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Instability of blanket bog slopes on Cuilcagh Mountain, N.W. Ireland

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INSTABILITY OF BLANKET BOG SLOPES ON CUILCAGH MOUNTAIN, N.W. IRELAND

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DECLARATION

I declare that no material in this thesis has previously been submitted for a degree at this or any other University.

The whole surface of the bog, as far as we could see it in the dim light, became wrinkled, and then began to move in little eddies, such as one sees in a swollen river. It seemed to rise and rise till it grew almost level with where we were, and instinctively we rose to our feet and stood there awestruck, Norah clinging to me, with our arms round each other.

The shuddering surface of the bog began to extend on every side to even the solid ground which curbed it, and with relief we saw that Dick and Joyce stood high up on a rock. All things on its surface seemed to melt away and disappear, as though swallowed up. This silent change or demoralization spread down in the direction of Murdoch's house - but when it got to the edge of the hollow in which the house stood, it seemed to move as swiftly forward as water leaps down a cataract.

Instinctively we both shouted a warning to Murdoch - he, too, villain though he was, had a life to lose. He had evidently felt some kind of shock or change, for he came rushing out of the house full of terror. For an instant he seemed paralyzed with fright as he saw what was happening. And it was little wonder! for in that instant the whole house began to sink into the earth - to sink as a ship founders in a stormy sea, but without the violence and turmoil that marks such a catastrophe. There was something more terrible - more deadly in that silent, causeless destruction than in the devastation of the earthquake or the hurricane.

The wind had now dropped away; the morning light struck full over the hill, and we could see clearly. The sound of the waves dashing on the rocks below, and the booming of the distant breakers filled the air - but through it came another sound, the like of which I had never heard, and the like of which I hope, in God's providence, I shall never hear again - a long, low gurgle, with something of a sucking sound; something terrible - resistless - and with a sort of hiss in it, as of seething waters striving to be free.

Then the convulsion of the bog grew greater; it almost seemed as if some monstrous living thing was deep under the surface and writhing to escape.

By this time Murdoch's house had sunk almost level with the bog. He had climbed on the thatched roof, and stood there looking towards us, and stretching forth his hands as though in supplication for help. For a while the superior size and buoyancy of the roof sustained it, but then it too began slowly to sink. Murdoch knelt, and clasped his hands in a frenzy of prayer.

And then came a mighty roar and a gathering rush. The side of the hill below us seemed to burst. Murdoch threw up his arms - we heard his wild cry as the roof of the house, and he with it, was in an instant sucked below the surface of the heaving mass.

Then came the end of the terrible convulsion. With a rushing sound, and the noise of a thousand waters falling, the whole bog swept, in waves of gathering size, and with a hideous writhing, down the mountain-side to the entrance of Schleenanaher - struck the portals with a sound like thunder, and piled up to a vast height. And then the millions of tons of slime and ooze, and bog and earth, and broken rock swept through the Pass into the sea.

From the novel 'The Snake's Pass' by Bram Stoker, first published 1890, pp. 229-230.

ABSTRACT

There are many accounts of slope failures on blanket bogs, but their nature and controls are poorly understood. This study investigates the mechanisms of blanket bog failure on Cuilcagh Mountain, north-west Ireland, and identifies the critical factors affecting the stability of peatland hillslopes. This is achieved by means of extensive field investigations involving hydrological monitoring, soil sampling and comprehensive laboratory analyses to determine the physical, hydrological and geotechnical properties of the blanket peat. The results from these investigations form the basis of hillslope hydrology and slope stability modelling using finite-element modelling programmes (commercial SEEP/W and SLOPE/W software).

A total of 47 failures scars were identified on Cuilcagh Mountain involving an estimated 300,000 m^3 of peat. Detailed field investigations revealed two main types of peatland slope failure: shallow translational peat slides associated with the failure of clay underlying the blanket peat, and bog flows in which failure occurs as a slurry-type plastic flow with the failure zone located within the peat. Peat slides were more prevalent on the steeper slopes (7.0-17.0°) of Cuilcagh, whereas bog flows were found exclusively on low gradient slopes (1.5-7.5°) with deep accumulations of peat (typically up to 2.5 m). Previously it had been suggested that bog failures were confined to steep slopes or peripheral areas of blanket bogs. However, on Cuilcagh Mountain they appear to be an integral part of the natural evolution of the main peatland, with the presence of many failure scars at different stages of re-vegetation and recovery.

Conventional methods of slope stability analysis (Factor of Safety using limit equilibrium methods) were found to be adequate for use on peat slide failures, but were not as suitable for analysing the slopes prone to bog flows. Sensitivity analyses indicate that cohesion of the failure material (i.e. the catotelm peat for bog flows and the underlying clay for peat slides) is the most critical factor contributing to slope failure. A reduction in cohesion is thought to be related to decomposition and/or progressive failure of the peat, or weathering and creep of the underlying clay. Increased overburden pressure from continuing peat accumulation is also an important factor in reducing the overall stability of a peatland slope. The initiation of bog flows and peat slides can occur from the progressive failure of the material in question, but there is more evidence to suggest that both types of failure are more frequently initiated as a result of a specific trigger event usually associated with high intensity rainfall.

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GLOSSARY/ABBREVIATIONS

Acrotelm: The upper aerobic layer of a bog (overlying the catotelm) made up of fibrous peat of low humification and the living vegetation layer.

Aelotropy: Horizontal banding or layering within a material.

AET: Actual evapotranspiration. The actual loss of moisture from the Earth's surface by means of direct evaporation together with transpiration from vegetation (Whittow, 1984).

Angle of internal friction (ϕ): The frictional resistance between constituent particles of a material, related to size, shape and orientation of particles, their resistance to crushing, and the number of contact points per unit volume.

Anisotropic: A material with physical properties that vary in different directions.

ASSI: Area of Special Scientific Interest.

ATV: All Terrain Vehicle.

Blanket bog: Ombrotrophic mire which can blanket large areas of upland and coastal regions, formed under conditions of high rainfall incidence and low evapotranspiration (Whittow, 1984).

Bog: Area of land with a deposit of decaying vegetable matter (peat) in waterlogged conditions.

Cation exchange ability (CEA): The potential for a soil to adsorb a particular cation (positively charged ion) at a given level of acidity (pH) (Clymo, 1983).

Cation Exchange Capacity (CEC): Total potential for soils to adsorb cations (positively charged ion) under chemically neutral conditions.

Catotelm: The lower, mostly anaerobic layer of a bog (underlying the acrotelm) comprising humified peat.

CMP: Cuilcagh Mountain Park

Cohesion (c): The inherent strength of a material derived from natural bonding and cementing.

Compressibility: Susceptibility of a material to change its volume and density when subject to pressure due to loading (Whittow, 1984).

Consolidation: Reduction in volume of a soil mass as a result of compression or applied load and involves a decrease in void ratio due to reduction in pore water (Whittow, 1984).

Creep: Slow mass movement of soil downslope in response to gravity.

cSAC: A candidate Special Area of Conservation.

Diplotelm: The two layered mire system comprising acrotelm and catotelm.

Dipwell: A perforated tube inserted vertically into an earth material in which the level of the water table can be determined and monitored.

Doline: A circular closed depression, formed by dissolution, collapse, or a combination of these.

Effective stress: Difference between total ground stress transmitted through interparticle contacts within a soil and the stress supported by pore water (Selby, 1993).

Elastic deformation: A temporary deformation of a material or body, after which it returns to its former shape once the stress has been released (Whittow, 1984).

ESA: Environmentally Sensitive Area.

ET: Evapotranspiration. The losses of moisture from direct evaporation and transpiration by vegetation.

Eutrophic: Mineral-rich.

Factor of Safety (F): The ratio of shear strength to shear stress.

Fen: A minerotrophic mire.

Flush: Area of land through which water is concentrated into channels, resulting in particular vegetation assemblages which reflect the nutrient flux and rheotrophic conditions.

Gelifluction: Type of solifluction associated with seasonally frozen ground.

GLE: General Limit Equilibrium

GWMM: Ground Water Mound Model.

Hag(g): Residual *in situ* block of peat formed by dissection of the peat mass.

Heath: A moorland landscape dominated by heather (*Calluna*) and other woody shrubs (Whittow, 1984).

Humification: The process of decay (or decomposition) which occurs by the biochemical oxidation of plant matter transforming it to humus.

Hydrosere: The wetland vegetation succession.

IPCC: Irish Peatland Conservation Council (not to be confused with the better known 'Intergovernmental Panel on Climate Change'.

Karst: A landscape created on soluble rock with efficient underground drainage.

k_{sat}: Saturated hydraulic conductivity.

Landslide: The downslope gravitational movement of rock or earth as a result of the failure of the material (Whittow, 1984). The term usually indicates an initial slide mechanism.

Liquefaction: Process by which sediments collapse due to a sudden loss of cohesion and the material is transformed into a fluid-like mass (Whittow, 1984).

Liquid Limit: Moisture content at which a soil passes from a plastic to a liquid state.

Macrotope: A mire complex that has been formed by the integration of individual mesotopes (Lindsay *et al.*, 1988).

Marsh: An area of wetland containing mineral soil partially under water (Hobbs, 1986).

Mesotope: A system developed as a single hydrological entity, such as a raised bog (Lindsay *et al.*, 1988).

Mesotrophic: Intermediate between eutrophic and oligotrophic (Hobbs, 1986).

Microform: Individual surface features within the patterning of a mire (Lindsay *et al.*, 1988).

Microtope: The small scale topographic features associated with the mire surface (Wheeler and Shaw, 1995).

Mineralisation: The breakdown of organic matter into inorganic components and carbon dioxide to produce nutrients (Wheeler and Shaw, 1995)

Minerotrophic: A supply of eutrophic water to the vegetation usually derived from mineral soils or rocks (Hobbs, 1986).

Mire: Peat producing ecosystem (Wheeler and Shaw, 1995).

Moor: Originally a German term for bog or fen, but now used more commonly for blanket bogs and heaths (Heathwaite *et al.*, 1993).

Mooratmung or 'Mire breathing': Changes in the level of the ground surface of mires (shrinking and swelling) in response to changes in the water content (Gilman, 1994).

Muskeg: A *sphagnum* dominated bog in the sub-Arctic latitudes of Canada and Alaska.

Oligotrophic: Mineral-poor.

Ombrogeneous: Peat formed under ombrotrophic conditions.

Ombrotrophic: Supply of water and nutrients exclusively from precipitation.

Paludification: The process of waterlogging as a result of restricted drainage at the margins of a former water body, allowing peat accumulating vegetation to encroach over the adjacent mineral ground (Wheeler and Shaw, 1995).

Peat: A biogenic vegetable deposit containing a high water content, slowly decaying under waterlogged conditions.

PET: Potential evapotranspiration. The potential losses of moisture from direct evaporation and transpiration by vegetation.

Piezometer: Equipment for measuring the pressure head of liquids within the ground.

Plastic deformation: Permanent change in the shape of a solid without rupture occurring.

Plastic limit: Water content of a soil as it passes from a rigid solid to a plastic state.

Pristine: A term used to describe areas of undamaged peatland that remain in a natural condition.

Pseudokarst: A landscape containing karst-like features such as caves and dolines, but not formed by bedrock dissolution as in true karst.

Raised bog: Mire with an elevated domed centre formed by the processes of terrestrialisation (hydrosere) and paludification.

Rheotrophic: Synonymous with minerotrophic.

Slurry: A mixture of water and fine solid that can flow as a highly mobile mass.

Solifluction: Slow downslope movement of soil as a result of heave, creep and gelifluction processes.

Soligenous: Peat formation under conditions of moving water (can be eutrophic, or oligotrophic).

Sphagnum: A genus of mosses with the ability to retain large amounts of water. A main contributor of peat formation.

Telmatic: Peat formation under conditions of periodic flooding (Hobbs, 1986).

Terrestrialisation: The process of mire formation by the filling of a water body with organic remains (Hobbs, 1986).

Thixotropy: A material which is solid when stationary and softens, or becomes liquefied upon remoulding, as a result of gradual re-orientation of the soil structure and water molecules to a more orderly structure (Mitchell, 1993).

Unit weight: Gravitational force per unit volume acting on a material.

SYMBOLS

β = Slope angle (°)

ϕ = Angle of internal friction (°)

γ_s = Unit weight at saturation (kN/m^3)

γ_w = Unit weight of water (kN/m^3)

c = Cohesion (kPa)

u = Pore water pressure (kPa)

m = Vertical height of the water table above the failure surface, expressed as a fraction of material depth (m)

z = Depth to the failure surface (m)

i = Hydraulic gradient

v = Darcian velocity (m/s)

q = specific discharge (m^3/s/m^2)

H = Total head

k_x = Hydraulic conductivity in the x-direction (m/s)

k_y = Hydraulic conductivity in the y-direction (m/s)

Q = Applied boundary flux (m^3/s)

t = Time (s)

θ = Volumetric moisture content

σ = Total stress (kPa)

u_a = Pore air pressure (kPa)

u_w = Pore water pressure (kPa)

k_{func} = Hydraulic conductivity function, the relationship between hydraulic conductivity and pore water pressure.

F_m = Moment equilibrium

F_f = Force equilibrium

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CHAPTER 1

INTRODUCTION

1.0 RATIONALE

Some 8.6% of the land surface of Britain and Ireland is covered by peatlands (Hobbs, 1986), most of which are classified as blanket bog (Taylor, 1983). The two principal types of ombrotrophic peatland in temperate regions are raised bogs and blanket bogs. The distinction between these is based on the mode of formation, which is determined by location, altitude and extent. This thesis is concerned with upland blanket bogs, phenomena which are common in Ireland, Wales, Northern England and Scotland. The principal landform/process assemblages associated with blanket bogs are surface patterning, peat piping and rapid mass movements. The controls and mechanisms of the latter have received relatively little attention and remain poorly understood. Hence, this research project is designed to investigate the different types and causes of slope failure in blanket bog peatlands in an area of North-west Ireland.

1.1 AIMS

Rapid mass movements of peat on slopes may be termed 'bog bursts', 'bog flows', 'bog slides', or 'peat slides' depending on the characteristics of the failure conditions and the state of the peat with depth. They are mainly natural phenomena that can occur in both blanket and raised bogs, but are a common feature of the blanket bogs of western and upland areas of Ireland where rainfall is high (Feehan and O'Donovan, 1996). 'Bog bursts' usually take the form of a rupturing of a surface area of bog with the flooding out of the more humified, liquid peat held at depth resulting in a 'bog flow'. The term 'bog slide' may be used to describe the movement of more coherent peat over a sub-stratum in the form of a shallow translational failure. The shear zone in the latter type of failure is usually located within or immediately below the peat layer. This differs from a 'peat slide' in which the mass movement is associated with the failure of the underlying material, usually clay. This distinction between bog bursts and flows, and peat slides is important as different mechanisms are involved. In the classification system of Hutchinson (1988), bog bursts and flows are contained within the category of debris flow, whereas peat slides are classed as translational slides. However, it has been suggested that there is a gradation of failure type from bog bursts and flows to slides (Carling, 1986).

Bog failures have been reported in many countries such as Germany, Switzerland, Canada, Australia and the Falkland Islands, but the majority is from within the British Isles, and in particular Ireland. However, most of these accounts are purely descriptive with only vague suggestions of mechanisms and causes. The most commonly reported destabilising factors contributing to individual failures include the presence of a break of slope (e.g. Bishopp and Mitchell, 1946; Alexander *et al.*, 1986), and an impermeable layer (e.g. Delap and Mitchell, 1939), with the trigger usually being identified as a high intensity rainfall event. This research project aims to add to the limited base of knowledge of hillslope failure in peatlands by integrating research on slope instability with the dynamic properties and characteristics associated with peat. Based on slope stability criteria, this form of hillslope failure is investigated in terms of the balance of forces acting upon peat covered hillslopes.

In general there is a lack of data concerning the physical characteristics of blanket bog peat and how these change with decomposition within the profile. Although for comparative purposes it will be necessary to use data from ombrotrophic raised bogs, this research aims to provide a detailed study of the changes in the physical state of blanket bog peat with depth from the surface.

This thesis will examine the susceptibility of blanket bog slopes to mass failure, and will attempt to establish which are the most critical environmental factors affecting the stability of peatland hillslopes. This will be carried out using a combination of approaches, in particular by examining the physical and geotechnical properties of blanket bog peat and by means of hydrological and slope stability modelling. Therefore, the main aims of this thesis are:

- To determine the changes in the hydrological and geotechnical properties of blanket bog peat with depth from the surface.
- To use hydrological and geotechnical data to model the stability of blanket bog slopes using a traditional 'limit equilibrium' approach.
- To determine the geotechnical controls on the stability of peat slopes in upland blanket bog environments.
- To study and gain a better understanding of the mechanisms of slope failure involved in rapid mass movements in blanket bogs (bog failures).
- To assess the importance of hillslope failure involving peat with respect to the development of an area of upland blanket bog.

This thesis will thus provide further insight into some general issues of landform evolution in peatlands, as well as presenting detailed knowledge about the physical properties of peat and the processes and mechanisms which combine to shape blanket bog environments.

1.2 IRISH PEATLANDS AND THEIR GLOBAL CONTEXT

It has been estimated that 3.4% of the Earth's land surface is peat covered, 297 Mha by bog and 210 Mha by swamp (Matthews and Fung, 1987). Peat accumulates wherever conditions are suitable irrespective of altitude or latitude; however, it tends to be most common in areas with a comparatively cold and wet climate (Hobbs, 1986). Table 1.1 shows estimates of the global distribution of peat resources. As a result of the specific conditions required for their formation, ombrotrophic blanket bogs are found in only a few regions, the British Isles containing approximately 10% of the total global resource (Tallis, 1997). In Ireland, ombrotrophic bogs once covered one-sixth of the country; however 94% of raised bogs and 86% of blanket bogs have been lost due to drainage, peat extraction and commercial developments (Foss, 1997). During the 1960's and 70's a period of environmental consciousness was brought about by a young generation of naturalists operating from

Table 1.1 Global distribution of the peatland resource.

(After Hobbs, 1986; Foss and O'Connell, 1996).

COUNTRY	HECTARES
Canada	129,500,000
U.S.S.R.	71,500,000
Finland	10,000,000
U.S.A.	7,500,000
Norway	3,000,000
Germany	1,618,000
U.K.	1,582,000
Sweden	1,500,000
Poland	1,500,000
Eire	1,176,000
Iceland	1,000,000
Indonesia	700,000
Cuba	200,000
Japan	200,000
New Zealand	166,000
Hungary	100,000
Netherlands	100,000
Denmark	60,000
France	60,000
Italy	60,000
Czechoslovakia	33,000
Austria	22,000
Romania	6,000
Israel	5,000
Others	400,000
Total	**231,988,000**

various universities, and with it arrived an awareness of the fact that bogs represented something more than a source of fuel and soil conditioner (Feehan and O'Donovan, 1996). The importance of conserving peatlands was recognised at the international level in the early 1980's and led to the formation of a number of protection and conservation-based bodies, such as the Irish Peatland Conservation Council (IPCC). The IPCC is a voluntary body whose principal aim is "to ensure the conservation of a representative example of Ireland's peatland heritage" (Foss, 1997, p.393), by means of conserving peatland habitats and wildlife, informing and educating the public, lobbying and fund-raising. The importance and value of bogs are summarised in Table 1.2. This conservation movement then proceeded to produce an abundance of conservation-based literature and campaigns to generate appreciation and recognition of peatlands.

1.2.1 Terminology and Definitions

The wide range of terms used to describe and classify bogs results from the differences in disciplines and languages used by researchers. Heathwaite *et al.* (1993) note that the complex nature of mire terminology is possibly the result of the diverse plant cover associated with peat producing ecosystems. Table 1.3 compares some of the terms used to describe mires in Europe and North America.

'Mire' originates from the old English word for bog, corresponding to the German term 'moor' for a bog or fen. Mire is perhaps the only internationally recognised term for a peat-producing ecosystem (Heathwaite *et al.*, 1993). 'Bog' is an Irish word that is derived from 'bogach', meaning soft ground (Feehan and O'Donovan, 1996). It is the general term for ombrotrophic mires, but is sometimes used colloquially for other types of wetland (Wheeler and Shaw, 1995). 'Fen' is the common term for minerotrophic mires. 'Marsh' describes a mineral soil with regular inundation of surface water, the movement of which with, or without, a nutrient input prevents the development of peat (Gilman, 1994). Peat is the term for the biogenic vegetable deposit containing a high moisture content (usually 85 to 95% by volume).

The peat mass can be looked upon as a two layered system, termed diplotelm. The uppermost layer is known as the 'acrotelm' that overlies the permanently waterlogged lower layer, the 'catotelm'. The physical characteristics and hydrological importance of these distinct layers is described in section 2.1.2. The specialist terminology used in this thesis is defined in the glossary.

1.2.2 Development of Ombrotrophic bogs

The properties of bog peat vary widely with depth beneath the surface, and are influenced by the variety of plant species forming the peat, the environment in which this accumulated, and by the changes within the peat column over time, essentially the transformation of organic matter into peat by the process of humification. It is therefore necessary to have knowledge of the developmental history and growth of the specific peat bog. There are three types of ombrotrophic peatlands in Ireland: raised bogs, upland blanket bogs, and lowland or oceanic blanket bogs.

Table 1.2 The importance and value of bogs.

Environmental Importance	**Education in the Peat Archive**
Habitat for flora and fauna	Pollen records of environmental change
Influence local climate	Archaeological records of man
Resource for healthcare e.g. *Sphagnum*	Biological indicators of climate change and pollution levels
Land resource for agriculture, recreation and water supply	
Atmospheric carbon sink	
Influence river regimes	
Filtering properties	

Table 1.3 The differences in terminology used to describe mires in Europe and North America (from Heathwaite *et al.*, 1993).

<table>
<tr><td rowspan="2">Terminology</td><td>North American</td><td colspan="5">Marsh</td><td>Bog</td></tr>
<tr><td>European</td><td>Swamp</td><td colspan="2">Marsh</td><td colspan="2">Fen</td><td>Bog</td></tr>
<tr><td rowspan="5">Characteristics</td><td>Vegetation</td><td>Reeds</td><td colspan="4">Grasses & sedges</td><td>Mosses</td></tr>
<tr><td>Hydrology</td><td colspan="5">Rheotrophic</td><td>Ombrotrophic</td></tr>
<tr><td>Soil</td><td colspan="4">Mineral</td><td colspan="2">Peat</td></tr>
<tr><td>pH</td><td colspan="5">Neutral</td><td>Acid</td></tr>
<tr><td>Trophic state</td><td colspan="2">Eutrophic</td><td colspan="3">Mesotrophic</td><td>Oligotrophic</td></tr>
</table>

Raised bogs occur widely across northern Europe, Asia and North America. They are so called because of their elevated domed centres whose rate of growth and morphometry are controlled by the hydrological processes of ground water flow within the peat mass (Heathwaite *et al.*, 1993). There are two processes involved in their formation. Firstly, terrestrialisation, which is the sequence of the hydrosere involving the succession of open water in a shallow lake to fen, then to fen woodland and finally to bog (Clymo, 1991). An illustration of the final climax stage in the formation of a raised bog is shown in Figure 1.1. Once the surface of the bog has grown beyond the maximum physical limits of groundwater an ombrotrophic plant community and peat accumulating system that is dependent on water and nutrients derived from direct precipitation develops (Heathwaite *et al.*, 1993). In this form, the peat itself within the mire acts as a reservoir. The second process that is important in the formation of raised bogs is that of paludification. Waterlogging can result due to restricted drainage at the margins of a former lake, allowing peat accumulating vegetation to encroach over the adjacent mineral ground (Aalen *et al.*, 1997).

In Ireland raised bogs are most common in central lowlands and towards the east originating from the shallow lakes and kettle holes left after the end of the last glaciation (c. 10,000 BP) (Foss and O'Connell, 1996). High water tables resulted in widespread flooding, particularly in the broad, shallow basins of the Shannon and Erne catchments (Aalen *et al.*, 1997). The development of stretches of open water and reed swamps into fen vegetation began approximately 9000 years BP, with the formation of raised bog about 7000 years BP (Aalen *et al.*, 1997).

Blanket bogs are climatic peatlands. Whereas raised bogs owe their existence to the particular history of landscape in which they have formed (Feehan and O'Donovan, 1996); blanket peat will develop and mantle the relief where the climate permits it. This will only occur where there is an excess of precipitation over evaporation in the colder and temperate regions of the earth (Hobbs, 1986). Peat accumulates and spreads laterally over the mineral soil and transgresses over surrounding, particularly ascending slopes (Heathwaite *et al.*, 1993). Eventually, the peatland converges to form a near-continuous blanket (Hobbs, 1986). Blanket peatlands usually develop over impermeable or nutrient poor soils or rock by the process of paludification, but they can also result from podsolisation. In areas subject to high rainfall with porous terrain, leaching results in the accumulation of impervious hummus colloids and an iron pan below the surface (Hobbs, 1986). The subsequent waterlogging and base deficient conditions creates an environment ideal for the formation and accumulation of ombrotrophic peat. A hypothetical section through a blanket bog is illustrated in Figure 1.2.

In Ireland, upland blanket bogs are usually situated in areas above 150 m in altitude, with more than 1250 mm of precipitation. These have been sub-divided into those heavily influenced by the proximity to the ocean (Atlantic sub-type) between 150 and 300 m which occur in the west and those which are formed on the mountainous areas above 300 m (montane sub-type) throughout Ireland (IPCC, 1990). The distribution of blanket bogs and raised bogs in Ireland is illustrated in Figure 1.3.

Figure 1.1 Hypothetical section through a raised bog (after Foss & O'Connell, 1996).

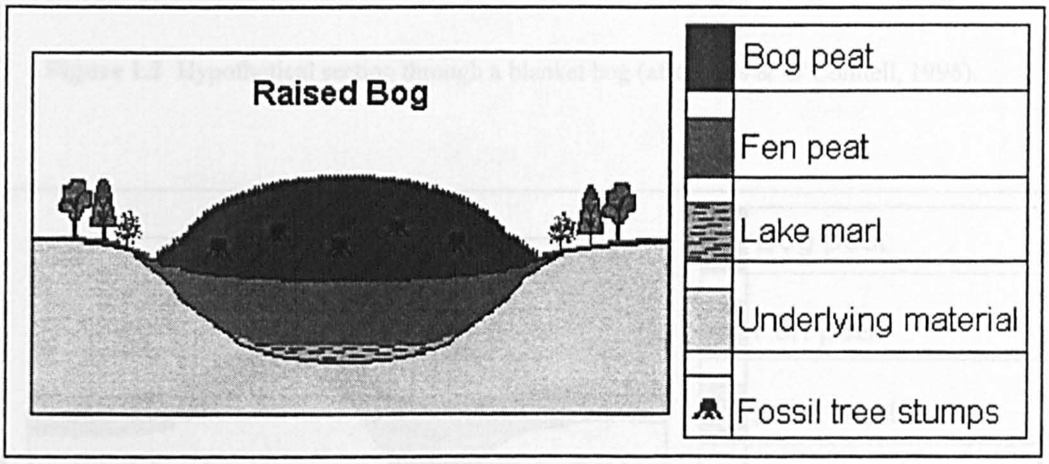


Figure 1.2 Hypothetical section through a blanket bog (after Foss & O'Connell, 1996).

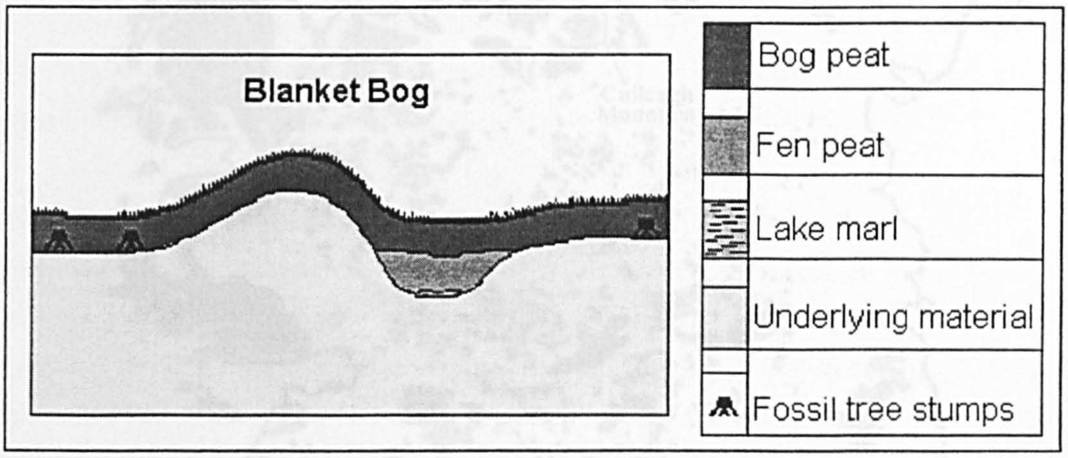
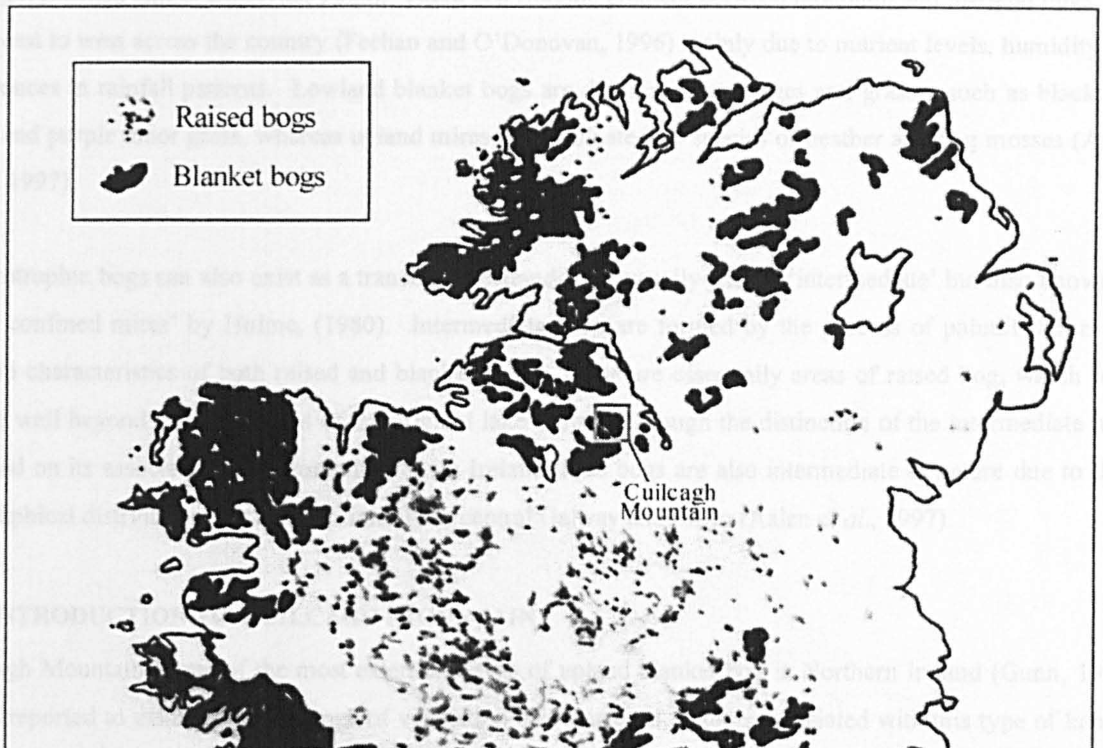


Figure 1.3 The distribution of blanket and raised bogs in Ireland (after Aalen *et al.*, 1997).



The Irish lowland blanket bogs are associated with generally flat land below 150 m in the west of the country. The presence of these bogs is almost entirely associated with the ocean and the main expanses are located in the low-lying coastal areas of counties Galway and Mayo, with further extensive parts of counties Kerry, Cork and Donegal (Feehan and O'Donovan, 1996). There is a floristic gradient between mountain and lowland bogs, and from east to west across the country (Feehan and O'Donovan, 1996) mainly due to nutrient levels, humidity and differences in rainfall patterns. Lowland blanket bogs are dominated by sedges and grasses such as black bog rush, and purple moor grass, whereas upland mires are dominated by species of heather and bog mosses (Aalen *et al.*, 1997).

Ombrotrophic bogs can also exist as a transition peatland-type, usually termed 'intermediate' but also known as 'semi confined mires' by Hulme, (1980). Intermediate bogs are formed by the process of paludification and contain characteristics of both raised and blanket bogs. These are essentially areas of raised bog, which have grown well beyond the boundaries of the original lake basin. Although the distinction of the intermediate mire is based on its associated floral communities, in Ireland these bogs are also intermediate in nature due to their geographical distribution, occurring primarily in central Galway and Mayo (Aalen *et al.*, 1997).

1.3 INTRODUCTION TO CUILCAGH MOUNTAIN

Cuilcagh Mountain is one of the most extensive areas of upland blanket bog in Northern Ireland (Gunn, 1995) and is reported to exhibit the full range of vegetation and structural features associated with this type of habitat (Environment and Heritage Service web-site, 2001). Previous research (e.g. Walker and Gunn, 1993; Gunn, 1995) has identified a high frequency of failure scars on the bog and in 1992 a large bog flow event caused disruption to Marble Arch Caves (discussed on page 14). Cuilcagh Mountain blanket bog is representative of other blanket bogs in north-west Ireland and therefore research into the controls and mechanisms of hillslope failure in this area is expected to have wider implications for peatlands in general.

1.3.1 Cuilcagh Mountain Blanket Bog

The characteristic plateau-block summits of Cuilcagh, Benbulbin, Dartry, Bricklieve and Slieve Anierin within the counties of Cavan, Leitrim, Sligo and Fermanagh have been grouped together to be known as Cuilcagh Plateau country (Herries-Davies and Stephens, 1978) (Figure 1.4). Upland blanket bog has developed on the slopes and foothills of these mountains to form an extensive peatland resource for the north-west region.

The fieldwork for this investigation has focused on the blanket bog covering the middle slopes of Cuilcagh Mountain. Cuilcagh Mountain (665m) is situated approximately 20 km south-west of Enniskillen and straddles the border between Northern Ireland (County Fermanagh) and the Republic of Ireland (County Cavan). Figure 1.5 illustrates the actual study area, which encompasses approximately 24 km^2 of blanket bog to the north and east of the summit. The slopes of Cuilcagh are characterised by a typical upland blanket bog environment and display a range of states from pristine bog to degraded sites, reflecting the history and land use of the environment. A wide range of failure types, of varying sizes, has also been recognised as playing an important

Figure 1.4 Cuilcagh Plateau country (after Herries-Davies and Stephens, 1978).

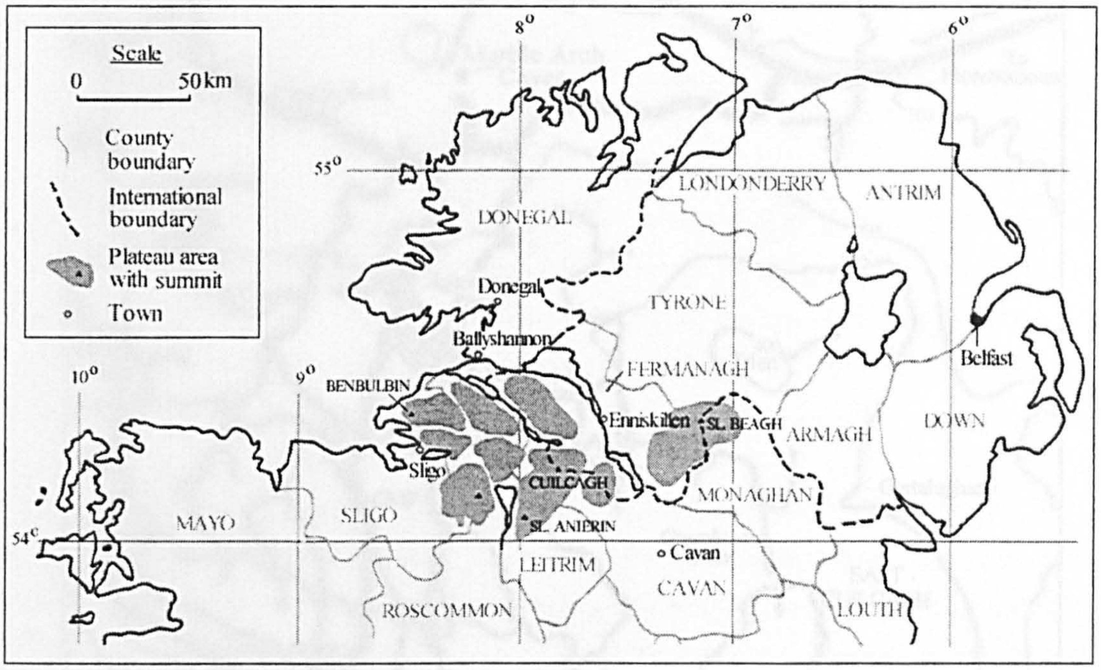
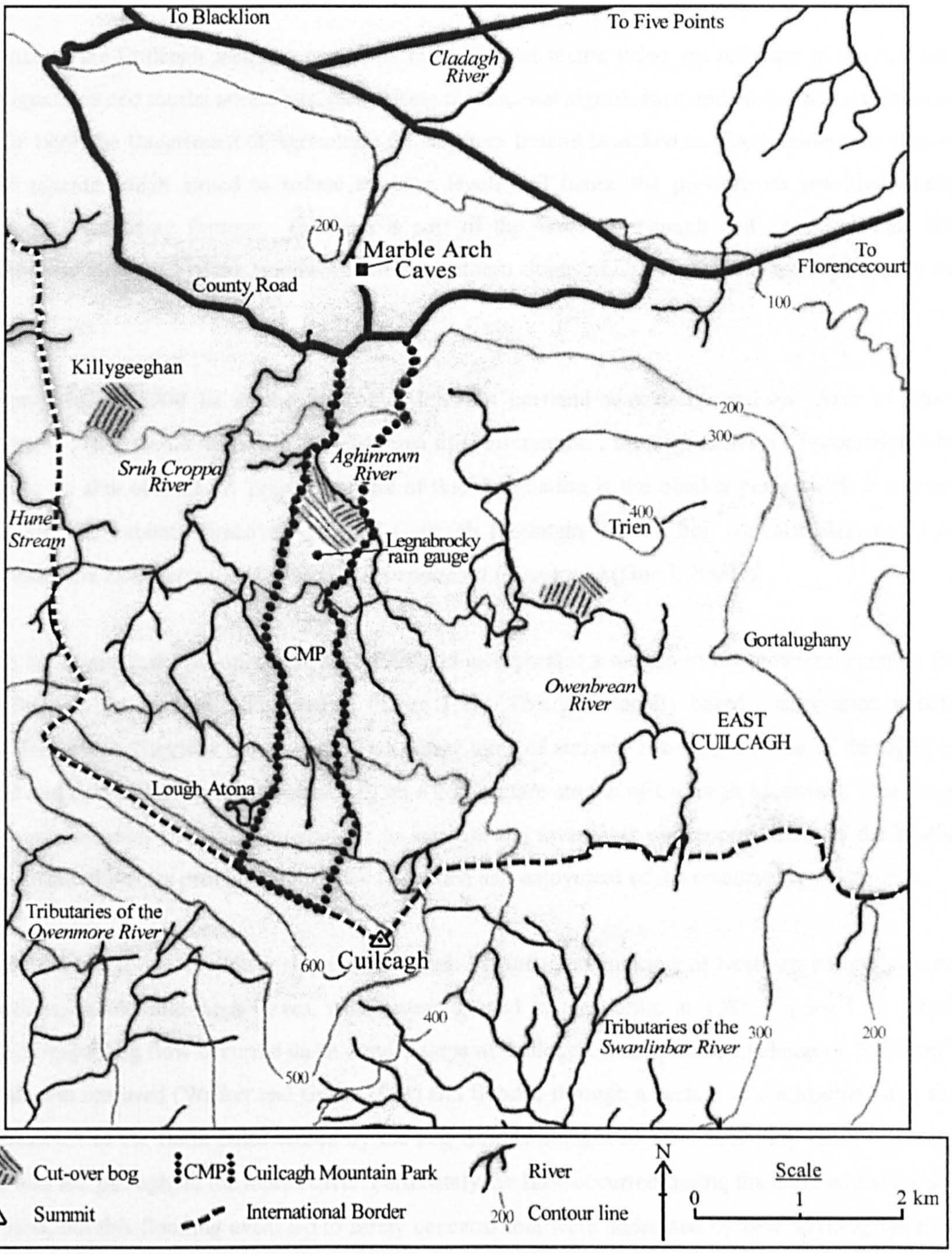


Figure 1.5 The study site: Cuilcagh Mountain.



role in the development of the blanket bog (Kirk and Dykes, 2000). Therefore, the variety and extent of bog failures make Cuilcagh Mountain an ideal setting for a detailed investigation into the stability of peat covered slopes.

The importance of the Cuilcagh area in terms of its scientific and scenic value are reflected in the number of statutory designations and tourist attractions, recognising the national significance and environmental interest of the region. In 1993, the Department of Agriculture for Northern Ireland launched an 'Environmentally Sensitive Area' (ESA) scheme which aimed to reduce stocking levels and hence the pressure on sensitive peatland environments by subsidising farmers. Cuilcagh is part of the West Fermanagh and Erne Lakeland ESA. Currently, approximately 50% of the landowners on the northern slopes of Cuilcagh Mountain have signed ESA agreements.

In 1994, approximately 3000 ha of the Cuilcagh Mountain peatland was designated an 'Area of Special Scientific Interest'. It is also a candidate 'Special Area of Conservation', the highest level of protection which can be given to an area of land. A primary feature of this designation is the blanket peat, which is a priority habitat under the EU habitats directive. In 1998 Cuilcagh Mountain blanket bog was also designated as a Ramsar site under the *Convention of Wetlands of International Importance* (Gunn, 2000a).

The Cuilcagh Mountain Park was opened in June 1999 and incorporates a section of the mountain running from the County Road to the summit (illustrated in Figure 1.5). This is a locally based conservation initiative managed by Fermanagh District Council, with the primary aims of actively restoring an area of damaged cut-over peatland and conserving areas of pristine bog on a 265 hectare stretch of Cuilcagh Mountain. The project includes an environmental education programme to increase the awareness and appreciation of the peatland habitat and wildlife as well as providing for public recreation and enjoyment of the countryside.

In addition to the blanket bog, the lower slopes of Cuilcagh Mountain contain one of Northern Ireland's premier tourist attractions, the Marble Arch Caves, which were opened to the public in 1985 (Figure 1.5). During August 1992, a major bog flow occurred on an eastern slope of Cuilcagh. An estimated volume of 20,000 m^3 of peat and water was removed (Walker and Gunn, 1993) and flooded through a section of the Marble Arch show cave. Transmission of the flood pulse caused by the bog flow is thought to have been very rapid and a thick layer of peat was left throughout the tourist cave. Fortunately the flow occurred during the night whilst the show cave was closed, but this flooding event led to safety concerns that were addressed by new warning systems at the stream sinks. Hence, the present research also has a practical application as it is hoped that it will facilitate identification of those areas of blanket bog in the cave's catchment which have the greatest risk of failure.

1.4 ENVIRONMENTAL SETTING

The environmental requirements for peat accumulation systems are primarily concerned with the promotion of waterlogging. Therefore, climate, geology, the permeability of the underlying substrate, topography and factors that independently affect the rate of microbial decomposition of dead plant remains are important. These are discussed with reference to present conditions on Cuilcagh Mountain. The general climatic criteria for the development of blanket bog are also discussed.

1.4.1 Climate

The climate of Cuilcagh is dominated by its position relative to the prevailing moist westerly airflow from the Atlantic. Adiabatic cooling occurs as the air passes over the high relief, delivering mild moist winters and cool, cloudy summers with a high average humidity (Gunn, 2000b).

Precipitation

Estimated isohyets for the northern slopes of Cuilcagh Mountain (Figure 1.6) indicate that the average annual rainfall increases with altitude from 1270 mm per year at Marble Arch Caves (at 175 m OD) to over 2000 mm per year at the summit of the mountain (665 m). The average number of rain days per year is approximately 250. Peak rainfall occurs in December, with March and April tending to be the driest months (Gunn *et al.*, 1993). Figure 1.7 has been compiled using data collected at a raingauge in the Aghinrawn catchment and at Marble Arch Caves and illustrates the cumulative annual precipitation for the north side of Cuilcagh Mountain for the years 1994 to 1999. Monthly rainfall totals ranged from 14 mm (August 1995) to 362 mm (December 1993), with annual totals of 2060 mm (1994), 1810 mm (1995), 1800 mm (1996) (Walker, 1998) and 1470 mm (1997) and 1850 mm (1998).

Temperature

Mean annual temperature for the Cuilcagh area is 9.0°C with a mean monthly range of 4.1°C in January to 14.8°C in July (Polley, 2001). For 1994, average monthly temperature ranged from 2.2 °C (February) to 13.7°C (July), with a mean of 7.7°C (Walker, 1998). The importance of seasonality in air temperature is related to low rates of evaporation and transpiration. At the micro-climatic scale, variations in wind speed and temperature are related to changes in relief and are reported to have an effect on the level of the water table (Walker, 1998).

Evapotranspiration (ET)

Total evapotranspiration that occurs in a bog environment is a combination of that from free water surfaces, bare peat surfaces and transpiring vegetation, therefore, the rate is a function of the depth of the water table and the vegetation type (Guertin and Barten, 1987) as well as meteorological conditions. Increased aerodynamic roughness, limited stomatal control of the plants and a greater surface area of vegetation means that the actual rate of evapotranspiration (AET) has been observed to be greater than estimates of potential evapotranspiration (PET) rates for areas of open water (Robinson *et al.*, 1991). The three dominant vegetation groups in a peatland community, *Sphagnum* mosses, heather and grasses, adapt very differently to seasonal variations. For

Figure 1.6 Isohyets of annual rainfall (mm) for the north slopes of Cuilcagh Mountain (Gunn, 2000a).

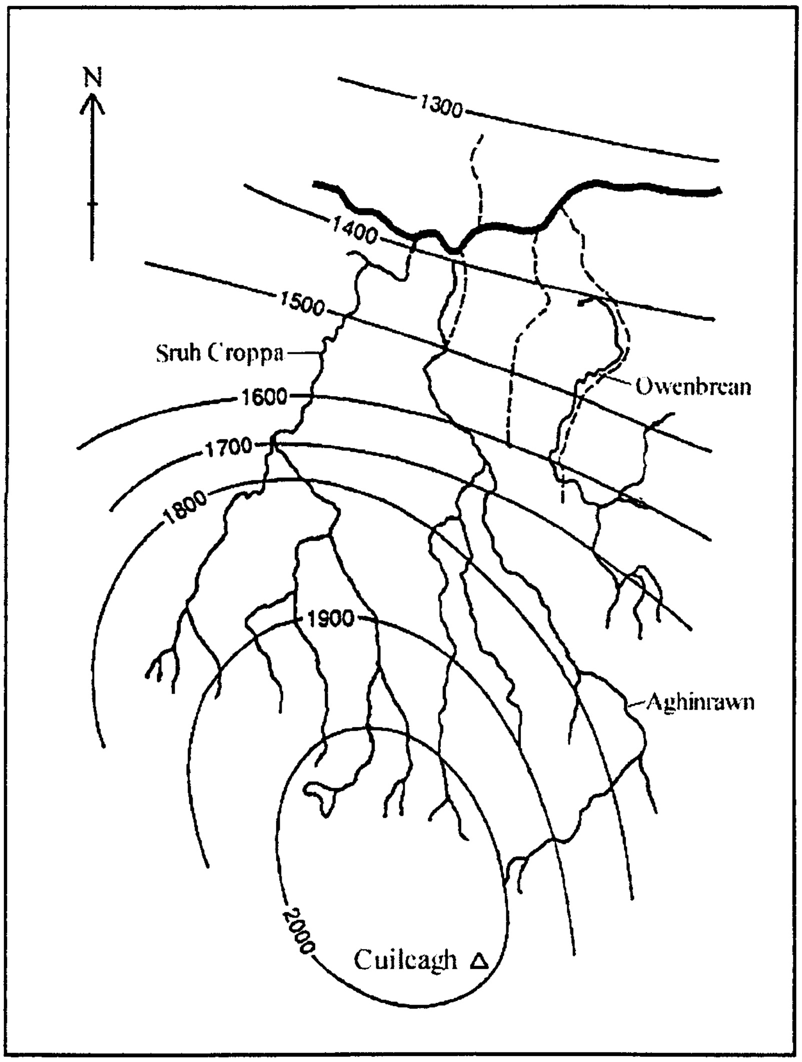
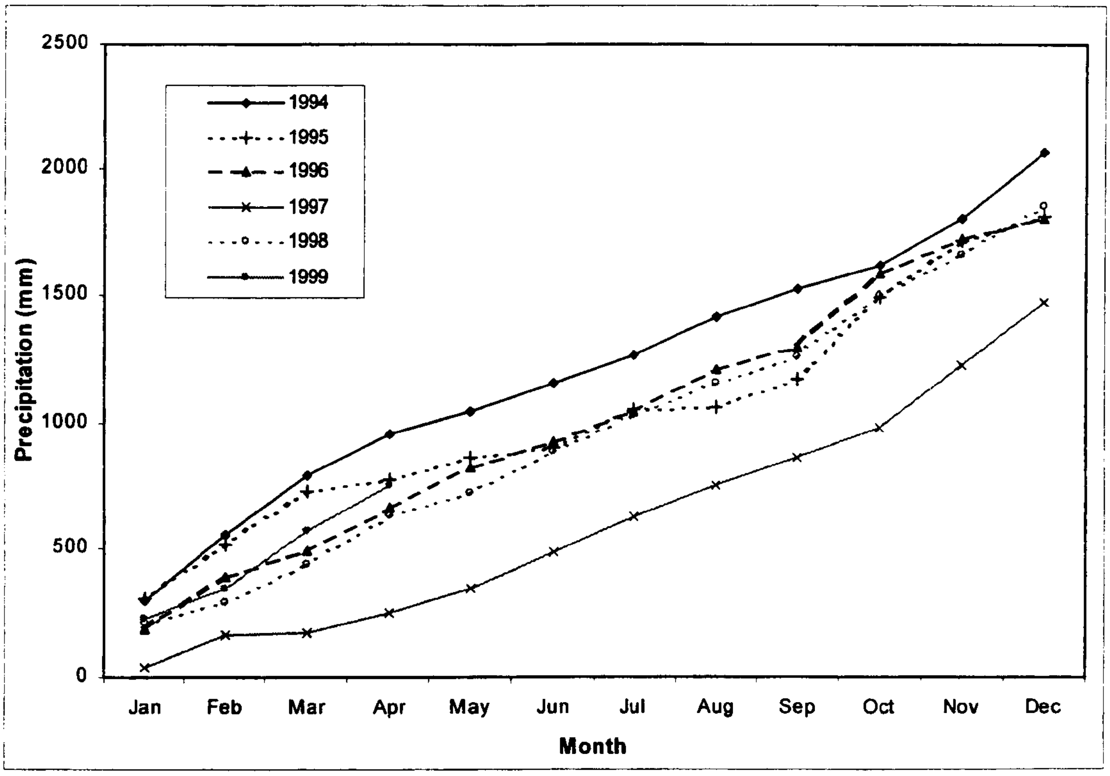


Figure 1.7 Cumulative annual precipitation for Cuilcagh Mountain (1994-96 data from Walker, 1998).



example, *Sphagnum* and heather can keep evapotranspiration rates lower than the PET rates during dry periods by reducing the albedo and through stomatal control respectively. In winter, these plants have effective evaporating surfaces. AET rates from grasses, on the other hand, can be significantly lower than the PET rates in winter (Heathwaite *et al.*, 1993). The AET rate compared to the PET rate depends therefore on the distribution and dominance of *Sphagnum* mosses and heather to grasses, and on seasonal variations related to temperature and water table depth (Walker, 1998), i.e. the overall ability of the peatland vegetation to regulate water loss.

Most water balance studies calculate PET and use this as the basis for estimated AET. Castle Archdale is the nearest meteorological station to Cuilcagh Mountain, approximately 32 km north of the summit and at an altitude of 66 m. Here, the mean annual PET is estimated to be 386 mm. In a recent study investigating the hydrological impacts of mechanised peat extraction on Cuilcagh Mountain, Walker (1998) compared and contrasted two sub-catchments consisting of a cut-over area, and a relatively undisturbed control area. An estimate of AET, calculated using three twelve month running totals of P-Q for an undisturbed sub-catchment on the lower slopes of the mountain was 580 ± 140 mm. This compared well with the 566 mm three-year average calculated using the Thornthwaite formula (Walker, 1998).

Climatic criteria for blanket bog formation

The environmental requirements for blanket bog formation are shown in relation to the most favourable conditions for peat formation in Table 1.4. An extreme tendency towards the three highlighted 'unfavourable' conditions of high temperature, high slope angle and good aeration are noted to prevent peat formation however suitable the other factors may be. Likewise, blanket bog formation requires an extreme tendency towards the highlighted 'favourable' factors (Lindsay *et al.*, 1988). The conditions for peat formation on Cuilcagh Mountain are also displayed in Table 1.4. Heathwaite *et al.* (1993) divide these factors which form the water balance for peatlands into four main components: atmospheric inputs, mire matrix, adjacent mineral soil and parent material, and the hydrological network. However, difficulties arise when monitoring the flux of water between different components, so the key water balance processes outlined by Ingram (1983) are generally used in evaluating the transfer of water in a peatland. These are precipitation, seepage, pipe flow, surface runoff, channel flow and evapotranspiration (Heathwaite *et al.*, 1993).

The most important climatic criteria for ombrotrophic bog development are the amount and distribution of precipitation as well as factors that affect evaporation and transpiration (wind, atmospheric humidity and air temperature). Cool, continuously wet conditions with predominantly gentle relief make it possible for the paludification of entire landscapes (Lindsay *et al.*, 1988). Paludification is the process whereby impeded drainage, leaching and waterlogging allows the development of a wetland directly over the mineral ground.

In Ireland, blanket bogs are found in areas with more than 1200 mm of precipitation per annum (Foss and O'Connell, 1996), but it is the quality (i.e. the persistence) rather than the quantity of rainfall that controls the distribution (Orme, 1970). The average annual number of rain days is a parameter of particular relevance to

Table 1.4 Factors affecting peat formation (after Lindsay *et al.*, 1988) and present conditions on Cuilcagh Mountain blanket bog.

Character	**Extreme Unfavourable Conditions**	**Extreme Favourable Conditions**	**Conditions on Cuilcagh Mountain**
Precipitation	Low	High	High 1270 - 2000 mm per year
Number of rain days	Low	**High***	High 250 per year (Gunn, 1995)
Atmospheric humidity	Low	**High***	High
Cloud cover	Low	High	High
Temperature range	High	**Low***	Low e.g. average monthly extremes 2.2 - 13.7°C for 1994 (Walker, 1998)
Mean temperature	**High***	**Low***	Low e.g. 7.7°C for 1994 (Walker, 1998)
Angles of slope	**High (90°)***	**Low (0°)***	Relatively low (0-35°)
Topography	Convex	Basin	Mixed relief
Substrate permeability	High	Low	Low
Substrate-water pH and base content	High	**Low***	Low pH 3.8 - 5.0 (Walker, 1998)
Substrate-water aeration	**High***	**Low***	Low
Nutrient status of vegetation	High	Low	Low

* Conditions considered most important (Lindsay *et al.*, 1988)

the growth of peat. A rain day is defined by the Meteorological Office as a 24-hour period during which at least 0.25 mm of precipitation is recorded. Lindsay *et al.* (1988) show a correlation between isopleths for 200 rain days and the limit of extensive peat formation for mainland Britain.

Although the combination of total annual rainfall and number of rain days can produce optimal conditions for blanket bog development, 'atmospheric flushing' occurs if the annual volume of precipitation exceeds the limits of this optimum, resulting in reduced rates of peat accumulation (Bellamy and Bellamy, 1966). This occurs due to the increase in the flux of oxygen and electrolytes through the surface layers with larger volumes of precipitation, which produces an increased rate of humification (Lindsay *et al.*, 1988).

1.4.2 Geology and Peat Formation

Early geological accounts have drawn comparisons between Cuilcagh Mountain and the hills of the Yorkshire Dales and English Pennines (Hull, 1878; Padget, 1953). The first published reference to the geology and geomorphology of Cuilcagh is that of Phillips in 1836 (cited by Padget, 1953, p 17) who likened Cuilcagh and the neighbouring plateaux summits of Benaughlin and Belmore to those of Penyghent and other hills in the Yorkshire Dales. Later, a more detailed account of the geology of the area by Hull (1878) again highlighted this comparison by documenting the Upper Carboniferous series of sandstones, shales and limestones as Millstone Grits and Yoredale Beds after the English Pennines and Yorkshire Dales respectively (Gunn *et al.*, 1993).

Figure 1.8 illustrates the solid geology of the northern slopes of Cuilcagh Mountain as published by the Geological Survey of Northern Ireland in 1991. The lower slopes are made up of the massively bedded Dartry Limestone Formation (in which the Marble Arch Cave system has developed), while the middle slopes are underlain by the Glenade Sandstone Formation. The upper slopes and summit ridge are made up of interbedded sandstones and shales and capped with a Namurian Sandstone Formation (Leitrim Series).

Cuilcagh summit ridge is thought to have been a nunatak (i.e. above the maximum extent of the ice) during the last Ice Age (Irish Midlandian, as British Devensian) (Gunn, 2000a). If this was the case then the upper slopes of the mountain would have been subject to periglacial and paraglacial activity, perhaps giving rise to the characteristic large boulder scree slopes and impressive cliffs of up to 30 m in height. Extensive mass movements have been responsible for the formation of large cracks that appear to follow structural lineaments on the summit ridge (Gunn, 2000a). Glacial drift of varying thickness is present on the middle slopes and provides an impermeable barrier which, together with the low permeability of the underlying sandstones and shales, has facilitated the development of the overlying peat. The drift geology of the northern slopes of Cuilcagh is illustrated in Figure 1.9.

A blanket bog of up to three metres in depth has developed directly on the mineral ground and drift deposits by the process of paludification during the Holocene, forming what has been described as one of the best examples of a blanket bog ecosystem in Northern Ireland (Gunn, 1995). Peat accumulation is associated with the

Figure 1.8 Solid geology of the northern slopes of Cuilcagh Mountain (from GSNI, 1991).

LKSF = Lackagh Sandstone Fm;
DVSH = Dervone Shale Fm;
DSM = Doobally Sandstone Mbr;
DARL = Dartry Limestone Fm;
GRLF = Glencar Limestone Fm;
Cuilcagh Dyke = Igneous Dyke (Tertiary).
GOS = Gowlaun Shale Fm;
KSM = Killooman Shale Mbr;
GAST = Glenade Sandstone Fm;
BBSF = Benbulben Shale Fm;
CASF = Carraun Shale Fm;
BCS = Briscloonagh Sandstone Fm;
BVF = Bellavally Fm;
MEF = Meenymore Fm;
KNM = Knockmore Limestone Mbr;
CLGL = Cloghany Limestone Mbr;

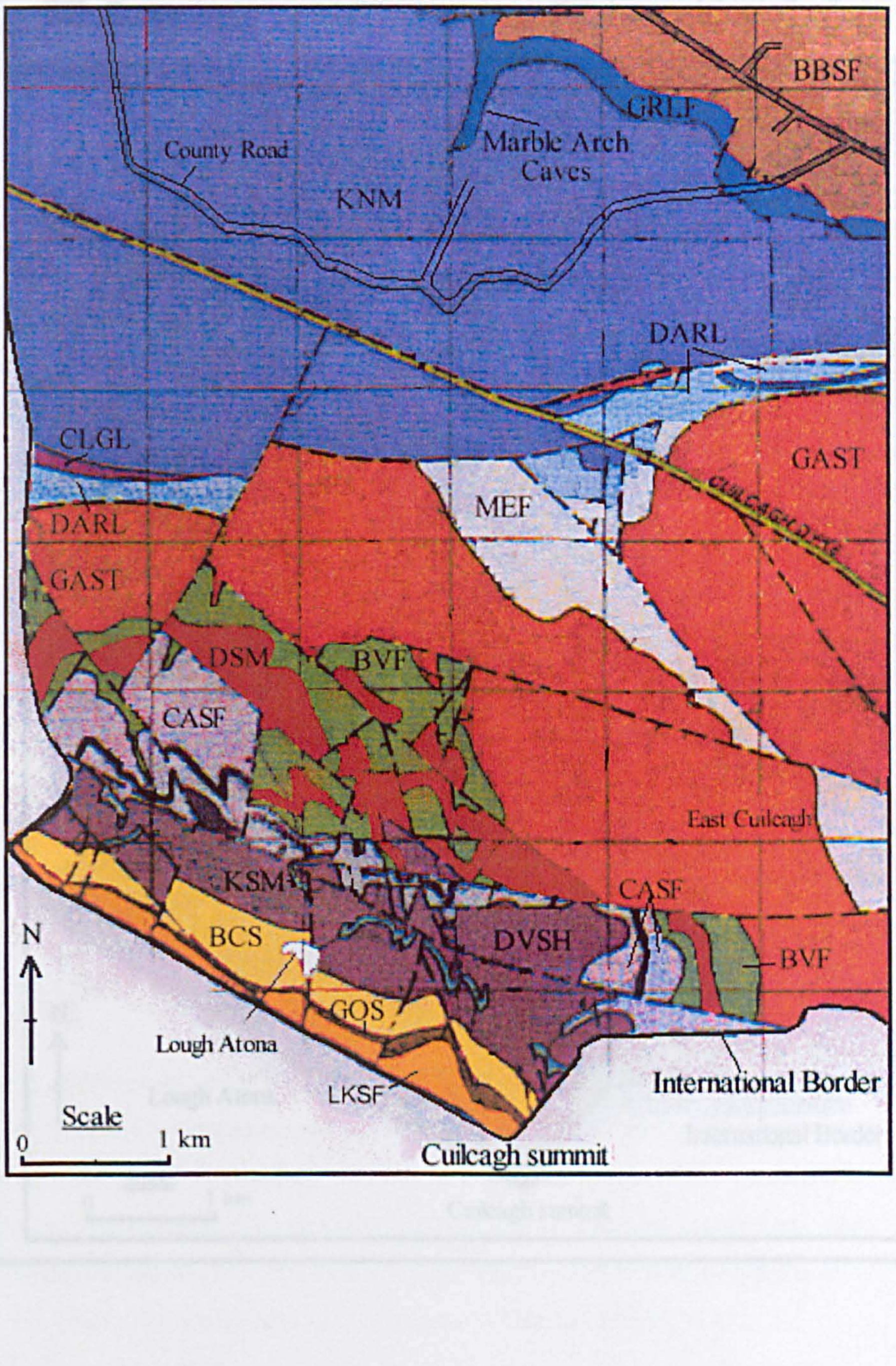
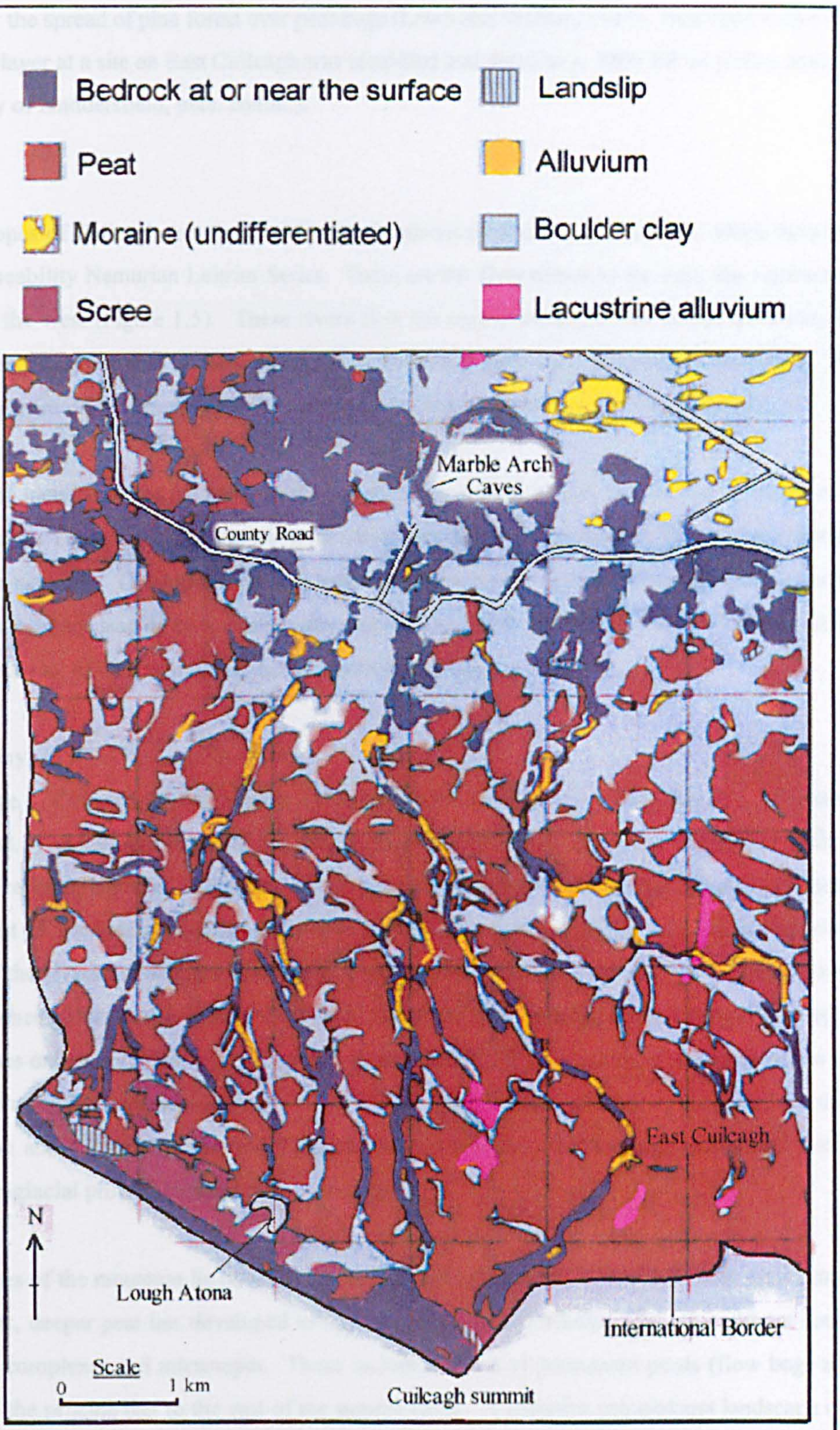


Figure 1.9 Drift geology of the northern slopes of Cuilcagh Mountain (from GSNI, 1989).



Atlantic and sub-Atlantic periods between 7000 and 5000 BP and between 2500 BP and the present, whereas the Boreal period between 9500 and 7000 BP and the sub-Boreal period between 5000 and 2500 BP were characterised by the spread of pine forest over peat bogs (Lowe and Walker, 1997). Pine bark found towards the base of the peat layer at a site on East Cuilcagh was identified and dated to c. 5000 BP by pollen analysis (Dr. C. Hunt, University of Huddersfield, pers. comm.).

1.4.3 Drainage

The northern slopes of Cuilcagh are dissected by three main rivers and their tributaries, which have their origin on the low permeability Namurian Leitrim Series. These are the Owenbrean to the east, the Aghinrawn and the Sruh Croppa to the west (Figure 1.5). These rivers flow for approximately 6 km before traversing the Dartry Limestone and eventually ending in the sinks of Pollasumera, Monastir and Cat's Hole respectively. The eastern slopes of Cuilcagh are drained to the east and south-east by two tributaries of the Swanlinbar River.

A rough index of 'dendricity' of the three rivers draining the northern slopes is provided by Gunn *et al.* (1993) and is displayed in Table 1.5. The Owenbrean catchment has a dominance of first order streams with an associated linear network. The Aghinrawn and Sruh Croppa networks are more dendritic; consequently runoff accumulates downstream leading to a more flashy response to the onset of heavy rain. The Swanlinbar River draining the south-east of Cuilcagh has a highly dendritic network.

1.4.4 Topography

The summit ridge of Cuilcagh Mountain runs from an altitude of 665 m at its north-east end for 4 km to 590 m at its western end. The northern slopes of the plateau are characterised by steep rock slopes and cliffs, with only a thin mantle of regolith in places. The upper slopes below the ridge lie between the 500 and 400 metre contour lines, and consist of predominantly concave slopes upon which the upper limit of peat has developed. The origins of all of the rivers draining the northern and eastern slopes of the mountain lie within this zone, and in their steeper reaches gullies deeply dissect the slopes. Lough Atona is situated immediately downslope of one of the steepest slopes on the north side of the Cuilcagh ridge. Gunn (1995) suggested that Lough Atona is probably the result of damming by terminal moraine, or a soliflucted head deposit. However, its position at the foot of a failed rock slope and its semi-circular basin suggests that it may be either a mass movement feature, or the remains of a paraglacial protalus rampart.

The middle slopes of the mountain lie between 400 and 250 m. As a result of the shallower gradients and gentle slope concavities, deeper peat has developed to form a typical upland blanket bog environment containing the associated mire complexes and microtopes. These include a series of permanent pools (flow bog) and areas of quaking bog on the pristine bog to the east of the summit ridge. A complex pseudokarst landscape of peat pipe networks with collapsed features has also formed on the areas of deeper peat within the middle slopes. These pipes range in size from a few centimetres to over a metre in diameter (Nield, 1993).

Table 1.5 The dendricity of stream networks, Marble Arch Caves drainage basin (Gunn *et al.*, 1993).

River	M Shreve Magnitude	N Strahler's Order	M:N Dendricity Index	Network Type
Owenbrean	15	3	5	Linear
Sruh Croppa	11	3	3.6	
Aghinrawn	9	3	3	Dendritic

Limestone underlies the lower slopes of Cuilcagh below 250 m, where only a thin coverage of peat remains. The main karst features comprise limestone pavements and cliffs, stream sinks, dolines, risings, and extensive cave systems including Marble Arch Caves (Figure 1.5).

1.4.5 Vegetation and Microtopography

Murray *et al.* (1991) surveyed the blanket bog vegetation on Cuilcagh Mountain for the Countryside and Wildlife Branch of the Department of the Environment (Northern Ireland). Most of the bog on Cuilcagh was classified as semi-natural vegetation of the 'wet bog' type. This is equivalent to the Nature Conservancy Council's Phase 1 habitat classification *Sphagnum* bog, dominated by ling heather, *Sphagnum* mosses and cotton grasses (Walker, 1998).

Some of the more gentle slopes of pristine bog found on Cuilcagh Mountain correspond to the characteristic bog hummock and hollow microtopography, particularly on the shallower slopes and plateau area of East Cuilcagh. Typically, this occurs where *Sphagnum* mosses are actively growing to form a system of hummocks and hollows with flat 'lawn' areas in between (Foss and O'Connell, 1996). The drier, hummocky areas are dominated by dwarf shrubs and graminoid species such as cross-leaved heath (*Erica tetralix*), heather (*Calluna vulgaris*), deer grass (*Trichophorum cespitosum*) and various bog cottons (*Eriophorum* spp.) (JNCC web site, 1999). Species such as *Sphagnum cuspidatum*, *Sphagnum fuscum* and *Polytrichum commune* correspond with distinctly wetter conditions. Flushes dominated by brown mosses or *Carex* species occur where water is concentrated into channels, reflecting the nutrient flux and rheotrophic conditions (Walker, 1998; Clymo, 1987). This illustrates that local variations within the microtope result in a diversification of habitats and species (microforms).

The vegetation in blanket bog environments is highly sensitive to change, particularly in land use practices. Concentrated grazing and more frequent use of ATVs (all terrain vehicles) has increased pressure on the lower and middle slopes of Cuilcagh Mountain, whereas patches on the upper slopes have been subject to intense burning in the past. These land uses have the effect of changing the composition and diversity of species (Feehan and O'Donovan, 1996), favouring a more widespread coverage of dry-based vegetation such as *Molinia* grasses.

The re-vegetation of areas subject to peat cutting activities can be divided into two categories, depending on the mining methods used. Firstly, areas which have been cut by hand in turbary plots form a pattern of large rectangular depressions colonised by *Sphagnum* species in the wetter areas (Gunn, 1995), and also grasses (*Molinia*) and bog cottons (*Eriophorum* spp.). These are separated by banks of uncut peat on which there is an abundance of heather (*Calluna vulgaris*) growth due to the drier, drained conditions. Machine cutting, however, can involve the complete removal of the surface vegetation and upper acrotelm to leave a surface of bare peat. In one area where this was the case, drier-bog based vegetation, such as *Eriophorum* spp. and an invading pioneer moss *Campylopus introflexus*, are now beginning to re-establish themselves on the bog surface (Walker, 1998). Other areas, in which the vegetation has been left in place but has been severely disturbed through the impacts of machine loading, have only a sparse coverage of *Eriophorum*.

1.5 ANTHROPOGENIC INFLUENCES ON THE CUILCAGH BOG

The role of man in changing the blanket bog environment is difficult to determine. However, this section reviews past and present land uses and peat extraction on Cuilcagh Mountain.

1.5.1 Land Use: Past and Present

Evidence for Neolithic farmers on Cuilcagh has been described by Gunn (1995), and includes the agricultural forest clearances at the beginning of the sub-Atlantic period (2500 BP). The removal of the protective forest cover, accompanied by climatic degeneration (i.e. persistent rainfall and lower evaporation rates) would have stimulated soil deterioration, particularly in the poorer upland soils (Orme, 1970). Further promotion of peat formation would arise due to the prevention of regeneration of shrubs and woodland, and continued agricultural malpractice.

In Medieval times, population densities were much higher, land was at a premium and habitation spread further up the mountain than is the case today (Gunn *et al.*, 1993). However, during and after the Potato Famine (1845-49) there was large-scale abandonment of the upper and middle slopes of the mountain (Gunn, 1995). Occupation of the mountain today remains minimal. At present, there are four main threats to the active blanket bog on Cuilcagh Mountain: overgrazing, burning, peat cutting and physical damage as a result of animal trampling, walking and ATVs.

Properties of the peat within the profile can not only exhibit characteristics of the variety of species forming the peat, but can also give an indication of changes in the environment in which it has accumulated and decomposed in the process of humification. Pollen analysis performed on peat cores from Cuilcagh Mountain has shown indirect evidence for the changing land-use of the blanket bog environment, particularly the intensity of apparent farming practices (Dr. C. Hunt, University of Huddersfield, pers. comm.).

1.5.2 Grazing and Burning

Farmers impose constraints on plant growth by stocking upland areas of blanket bog with sheep and in some cases cattle, and by attempting to improve the quality of the grazing through controlled burning of the vegetation and drainage of the peat (Tallis, 1997). During the 1980's sheep stocks on Cuilcagh increased dramatically and there were also periods of uncontrolled burning. The resulting overgrazing and lack of general management was noted to degrade the surface of the bog in many areas (Gunn, 2000b; R. Watson, Principal Officer for Countryside Management, Fermanagh District Council, pers. comm.).

Periods of controlled burning are intended to encourage growth of more palatable new shoots of heather and coarse grasses and are usually carried out on a rotational basis. Tallis (1997), working in the Pennines, states that although the overall vegetation composition is altered by the elimination of the more fire-sensitive species, there should be little long term damage if burning is properly controlled. Periods of uncontrolled burning, however, not only cause a destruction of the surface vegetation and the immediately underlying acrotelm, but also have been known to destroy the entire depth of peat, or at least cause irreversible damage by leaving the peat surface dry and bare. Subsequent further alteration occurs by rain and wind erosion, leaching and freeze-thaw processes (Maltby *et al.*, 1990). This is particularly important as recolonisation is slow and leaves areas of bare peat exposed to wind and rain, resulting in intensified erosion.

1.5.3 Peat Cutting

Evidence for peat being used as an historical source of fuel in Ireland includes the presence of half burnt sods under eight metres of bog in County Donegal, remains of early cutting equipment and old turf banks, and by occasional references in the Old Irish law texts in the 7th Century (Feehan and O'Donovan, 1996). Small scale turf cutting peaked in 1926 and then steadily declined until the Second World War, when peat had to replace two million tons of imported coal during the war years (Feehan and O'Donovan, 1996). After this period of more intense exploitation, cutting declined again and the Bord na Móna was established in the Republic in 1946 due to concern over the dependence on imported fuels. Its main aims were to produce and market peat and peat products commercially, mainly utilising the deep raised bogs of the Midlands. In 1981, the 'Turf Development Act' in the Republic and similar government schemes in Northern Ireland provided grants for individuals to obtain tractor-driven cutting machinery and exploit peat resources. The 'black devastation' (Aalen *et al.*, 1997) that followed also resulted in the exploitation of more blanket bog environments, and private production in the Republic increased from 350 000 tonnes p.a. to over 1.4 million tonnes between 1982 and 1990 (Bord na Móna, 1991). During this period there was also widespread dumping of farm and domestic rubbish onto bogs. In the Republic, an estimated 15% of blanket bog peatland has been cut away, and in Northern Ireland, almost half has been cut at some time in the past (Aalen *et al.*, 1997).

Hand cut areas in turbary plots are widespread on East Cuilcagh at Gortalughany and on areas of the lower northern slopes where access is made possible by a number of roads and tracks. It is thought that most of these hand-cuttings date from pre-1845 when population pressure was higher in the uplands (Gunn, 2000a). Large areas of cuttings of this nature, i.e. produced by the amalgamation of individual plots, have had sufficient time to become well re-vegetated, and as a result are much less intrusive on the landscape.

Machine cutting occurs on a fundamentally different scale to traditional hand cutting and creates a new blanket peat landscape characterised by horizontal expanses of exposed peat (Aalen *et al.*, 1997). The main area on Cuilcagh that was extensively mined by machines between 1986 and 1992 is situated to the north in the Legnabrocky Townland on the Aghinrawn River catchment (Figure 1.5). The area affected by actual mechanised cutting was 120 hectares (Gunn *et al.*, 1997), on the majority of which the surface of vegetation and upper acrotelm was completely removed to leave a bare surface of peat. A dense network of deep drainage ditches had also been excavated (Walker and Gunn, 1997). In this area, much of the cleared ground remained bare five years after the last period of extraction and there were many physical changes to the environment.

These included a drier surface allowing the invasion of different vegetation species, accelerated erosion, and the generation of higher flood peaks (Walker and Gunn, 1997). The effects of the removal of the surface vegetation, the extraction of the more calorific basal peat, the construction of deep drainage ditches, the splitting of the peat column into vertical tines (deep slits up of approximately 1.5 m in depth) during the peat removal process, and the weight and movement of the cutting machines result in the destruction of the usual structure and form of the bog. Peat cutting continues on a wide area at Killykeeghan on Cuilcagh Mountain (Figure 1.5).

Current restoration and management of cut-over peatland areas (as outlined by the Irish Peatland Conservation Council) involves the re-establishment of a high water table, as the damage to the bog from the various hand and mechanised cutting techniques and more importantly the construction of drains on and around the bog initiates a lowering of the water table (Tubridy, 1987). A section of cut-over bog on Cuilcagh Mountain is currently being monitored in a series of experimental sites on a catchment feeding the Marble Arch Cave system. There is a concern however, that an increased water level from the damming of drainage ditches and subsequent changes in vegetation will lead to a rise in pore water pressure and changes in various other stability factors, thereby reducing the shear strength of the already structurally altered peat, converting the slope into a more actively unstable condition. The restoration of this area therefore may directly affect the risk of flooding to the show caves and the degradation of the blanket bog.

1.6 SPECIFIC OBJECTIVES AND OUTLINE OF RESEARCH PLAN

This chapter has introduced the problems to be addressed in this thesis, i.e. the susceptibility of blanket bog slopes to mass failure, and the most critical environmental factors affecting the stability of peatland hillslopes. A review of the terminology and development of ombrotrophic bogs and an outline of the environmental characteristics of Cuilcagh Mountain blanket bog, which is regarded as being representative of other blanket bogs in north-west Ireland, have also been given. Therefore, to fulfil the aims of the thesis the following specific objectives are outlined:

1. To map and describe the morphometry of the peat slope failures on Cuilcagh Mountain and to determine the likely mechanisms of failure.
2. To determine the magnitude and frequency of failure events on Cuilcagh Mountain.
3. To investigate the physical properties of blanket bog peat and assess how these vary with depth from the surface.
4. To investigate the hydrological and geotechnical properties of blanket bog peat and assess how these vary with depth from the surface.
5. To model the stability of the blanket bog slopes on Cuilcagh Mountain using the determined geotechnical and hydrological properties of the peat.
6. To establish whether conventional methods of slope stability analysis are suitable for blanket bog environments.

7. To investigate the geotechnical and hydrological controls and identify the various destabilising factors (preparatory, triggering and controlling) involved in converting the blanket bog slopes to an actively unstable condition.

The work presented in the following chapters is based on detailed field investigations, laboratory determinations and hydrological and slope stability modelling. Chapter 2 comprises a review and assessment of research into peat hydrology, geomorphology and slope stability to provide a framework for the analysis of hillslope failure in peatlands. Field methods and results and a detailed examination of the physical and geotechnical properties of the Cuilcagh peat are presented in Chapters 3 and 4. These results form the basis for an analysis of the stability of peat slopes given in Chapter 5. Chapter 6 examines the factors that affect the stability of peat slopes by integrating the results of studies of the physical and geotechnical properties of the Cuilcagh peat and the hydrological and slope stability modelling. In Chapter 7, the conclusions of the research are presented. The implications of these findings for blanket bog evolution and the management and restoration of peatlands are then outlined.

CHAPTER 2

PEATLAND RESEARCH AND HILLSLOPE STABILITY

2.0 INTRODUCTION

Assessing the stability of hillslopes in peatlands is a complex exercise, not only because the physical and structural properties of peat differ from the more uniform soils more commonly the subject of slope stability analyses, but also because the geotechnical properties and hydrological behaviour of the peat are difficult to determine due to the variable nature of the material. At present there is no fully integrated study of the stability of slopes in peatlands. This is extraordinary considering that 'thresholds of critical instability' are often mentioned in relation to erosion in mires (Bower, 1961; Tallis, 1965a) and the peat mass has been termed 'an inherently unstable system' (Hobbs, 1986, Lindsay *et al.*, 1988) which becomes even more unstable with continued peat accumulation (Tallis, 1997). The framework for the analysis of hillslope failure in peatlands initially requires a review and assessment of research into peat hydrology, geomorphology and slope stability, before an integrated and holistic approach to the study can be achieved.

Firstly, the importance and abundance of peat are described and the nature and scope of peatland literature are examined. Specifically, this section describes the classification of peatlands, the physical, structural and geotechnical properties of ombrotrophic peat and types of peatland erosion. This is followed by a brief review of the common characteristics reported in bog failure events. In the second section, types and mechanisms of slope failure and methods of slope analysis are outlined and reviewed. This includes methods of measuring the shear strength of the soil, and the assumptions and limitations associated with modelling approaches.

2.1 PEATLAND RESEARCH

2.1.1 Introduction

Peat is of interest to workers in many fields: agriculture, horticulture, engineering, mining, chemistry, medicine and ecology (Clymo, 1983). As a result, peat literature as a whole is extremely fragmented in nature. The few accounts concerning the strengths and geotechnical properties of peat and organic soils are usually closely associated with engineering studies and in particular the construction of roads in North America and Canada (e.g. Adams, 1965; Landva and La Rochelle, 1983). The techniques of undisturbed sampling and the compression and shear deformation of some peats are described in some detail by Landva *et al.* (1983) and Landva and La Rochelle (1983), but have not yet been used to assess peat slope stability within a natural geomorphological context.

The majority of literature on peat, particularly in the UK, dealing with conservation, ecology, growth rates and the workings of the peat mass, is based on research specifically from raised bogs (Ingram, 1978, 1983; Clymo, 1984a, 1991; Wheeler and Shaw, 1995). However, there are also many reports on the blanket bogs of the English Pennines and the Flow Country of Caithness and Sutherland in northern Scotland, which are mainly concerned with types and causes of erosion and surface patterning (e.g. Bower, 1960, 1961, 1962; Tallis, 1964, 1965a, 1985; Lindsay *et al.*, 1988). Although there are studies of the distribution of peatland vegetation and erosion in Ireland (Tomlinson, 1981a, 1984; Bowler and Bradshaw, 1985), disregarding the literature on specific bog failure events, studies of Irish bogs tend to be associated either with peat as a resource or various ecological and conservation issues (Cruikshank *et al.*, 1995; Corbett and Seymour, 1997; Gunn *et al.*, 1997).

Classifications

Peatland classifications are generally based on one of three main criteria: hydrological setting; *in situ* peat stratigraphy; and the ecological history of the site (Burt *et al.*, 1990). Based on the hydrological setting, the autogenic terrestrialisation of open water (Wheeler and Shaw, 1995) (i.e. wetland succession) is known as the 'hydrosere'. The terminology used in the three main stages of the hydrosere (from Hobbs, 1986) are: 'rheotrophic' – the initial stage in which a mire begins to develop in mobile water; 'transitional' – the mire is at a stage in which upward growth of the water level relies more on precipitation and less on the input of nutrients; and 'ombrotrophic' – the mire is dependent entirely on atmospheric precipitation. The classification system of Moore and Bellamy (1974) divides European mires into eleven zones based on climatic conditions and mode of formation. This includes the distinction between 'primary', 'secondary' and tertiary' peatland systems describing their development in relation to the water supply. Minerotrophic peatlands are supplied by water that is usually rich in nutrients and minerals from the surrounding soils and rocks, while ombrotrophic (rain-fed) peatlands tend to be 'oligotrophic' i.e. have a low nutrient content. Studies of the vegetational development and ecological history of mires using macro-fossil and pollen analysis have indicated responses to known climate changes, identifying periods of formation, rates of accumulation (Conway, 1954), and phases of erosion (Tallis, 1965a; 1985).

Peatlands can be categorised according to scale (Ivanov, 1981). At the smallest scale, a mire 'microform' is an individual surface feature within the patterning of a mire, such as a single pool or hummock (Lindsay *et al.*, 1988). A mire 'microtope' describes the small scale topographic features (i.e. the arrangement of microforms) associated with the mire surface (Wheeler and Shaw, 1995). A mire 'mesotope' is equivalent to a mire massif or unit and describes a system developed as a single hydrological entity (Lindsay *et al.*, 1988), such as a single raised bog. At the largest scale, a mire 'macrotope' encompasses composite units formed by the fusion of individual isolated mire mesotopes, which originated from separate centres of mire formation. The extensive blanket bogs of Britain and Ireland have been described as ultimate expressions of macrotopes (Lindsay *et al.*, 1988).

2.1.2 Diplotelm Dynamics

The existence of two distinct layers in bogs was recognised by the Russian mire hydrologist Ivanov in the 1950's. Later these were discussed by Romanov in 1968 as it became firmly established that the upper and lower layers in a bog differ significantly not only in structure but also in function (Ingram, 1978). The literal translation of the Russian terms 'active' as the upper layer, and 'inert' for the lower layer were deemed inappropriate due to the same terms being used in other fields with different meanings (Clymo, 1991). Ingram (1978) suggested two different terms for the layers: acrotelm, meaning uppermost mire surface; and catotelm, meaning underlying mire layer. The term diplotelmic system is used to describe the two layered effect.

The acrotelm is the upper surface layer (usually about 50 cm in depth) and includes the living surface of vegetation. It is characterised by higher relative hydraulic conductivity and the most active water movement as it is this layer in which the water table fluctuates (Lindsay *et al.*, 1988). The surface layer is largely oxygenated and aerobic bacteria and micro-organisms facilitate rapid decomposition and transformation into peat. The roots of plants and low degree of humification of organic matter mean that this layer is highly fibrous and forms a skin or crust to the bog.

The catotelm, the layer underlying the acrotelm, is permanently saturated and typically makes up the bulk of more mature bogs. On Cuilcagh, this layer is up to two and a half metres in depth. Water movement is very slow (usually 3-5 orders of magnitude slower than the acrotelm) (Lindsay *et al.*, 1988) due to the compressed nature of the peat and the high degree of humification with depth. This layer is characterised by very slow anoxic decay due to its saturation and absence of aerobic micro-organisms. The basal peat has a tendency to be amorphous in nature with a high degree of humification. Gas may take up as much as 10% of the volume in the lower layer of the peat (Clymo, 1984b).

The distinction between the acrotelm and catotelm is usually not as pronounced in blanket bogs as it is in undamaged raised bogs. The greater variety of vegetation forming the peat in blanket bogs results in variations in the intensity of the humification process, as certain parts of the plants are more resistant to breakdown than others. This can affect the structure of the peat greatly and can result in a more multi-layered effect within the diplotelm. This type of aelotropy (banding) in peat results during deposition or from stress applications, rather than true stratification (Landva and Pheeney, 1980).

2.1.3 Physical and Structural Properties of the Peat

The two 'key characters' that are responsible for the great diversity that exists in peat are the botanical composition and the degree of humification (Clymo, 1983). The botanical composition can indicate the chemical state and origin of the peat, and the degree of humification (decomposition) can determine the physical properties (Clymo, 1983). However, difficulties can arise when comparing and contrasting results from different peatlands, as slight variations in the ecosystem and climatic regime in which they develop can affect the development of the bog, resulting in each individual peatland possessing its own characteristics and identity. Although the physical and structural properties of peat will vary with the mode and timing of peat formation, the properties are highly interdependent, and together are important in determining the height of the water table (Burt *et al.*, 1990).

Hobbs (1986) lists some of the properties of peat which give an indication of state and condition as: - moisture content; bulk density; organic content; liquid and plastic limits; and degree of decomposition. Table 2.1 shows the physical properties of blanket and raised bog peat in Ireland (from Galvin, 1976).

Moisture Content

The moisture content of peat can range from 200 to 2000% by dry weight (Hobbs, 1986) and can vary over small distances both vertically and horizontally. This is related to the nature of the plant species and the different

Table 2.1 Physical properties of Irish blanket and raised bog peat given by Galvin (1976, p.209)

Property	Blanket Peat	Young *Sphagnum* Peat	Older *Sphagnum* Peat
Field Moisture Content			
% dry wt.	1,057	1,607	995
% by volume	88.9	91.3	88.9
Degree of Humification (von Post)	H_8	H_2	H_8
pH	4.1	4.2	4.7
Ash Content (%)	1.5	1.6	1.0
Specific Gravity	1.31	1.36	1.36
Void Ratio	17.8	23.0	15.0
Porosity (%)	94.7	95.8	93.7
Bulk Density (g/cm^3)			
Field	1.02	1.01	1.02
Dry	0.07	0.06	0.09
Hydraulic Conductivity (mm/day)			
Laboratory	13	208	5
Field	6	209	28
Infiltration (mm/day)	4	61	3
Specific Yield (ml/ml)	0.16	0.38	0.17

degrees of decomposition in the peat mass. As a general rule, moisture content decreases with humification and mineral soil has the effect of reducing both moisture content and its variability (Hobbs, 1986).

Bulk density

The bulk density is the dry mass of material per unit of field bulk volume and is recognised as being an important physical parameter of soil and peat analysis. The dry bulk density of peat is low and variable in comparison with mineral soils, with reported values ranging from 0.07 g/cm^3 at the surface of the bog to over 0.1 g/cm^3 at depth (Clymo, 1983). It is related to the organic content and void ratio of the peat (Hobbs, 1986). The dry bulk density of peat is another useful indicator of the nature of a given body of peat.

Organic Content

The purity of peat is an important property (Hobbs, 1986) and depends on the amount of mineral matter present in the material. This is determined by measuring the organic content of the peat. Typically, pure *Sphagnum* peat comprises 99% organic matter, with most bog peat containing less than 20% inorganic matter (Clymo, 1983). The water holding capacity of peat depends greatly on the organic content. However, this relationship is often over-simplified, as humification influences the state of the organic matter and hence the manner in which the material can hold water. The organic content can be successfully measured using the loss on ignition method, which determines the loss in mass of an oven-dried sample after ignition in a furnace (Gale and Hoare, 1991).

Atterberg Limits

The liquid limit is the empirically established moisture content at which a soil passes from a plastic state to a liquid state. Similarly, the plastic limit is the moisture content at which a soil becomes too dry to be a plastic (BS 1377, 1990). Together, the liquid and plastic limits determine the plasticity index, which provides a means of classifying cohesive soils. The liquid limit of peat depends on three main properties: botanical composition; the degree of humification; and the proportion of clay present in the sample (Hobbs, 1986). The liquid limit of peat is noted to decline with increasing humification, as the decomposers break down the plant tissue. For example, the liquid limit of peat falls from 800% for low humification, to about 300% for strong humification (Hobbs, 1986). The plastic limit of peat can only be measured on samples containing some clay soil (Hobbs, 1986). Consequently, little has been published on the plasticity of peat.

Degree of Humification

The great diversity observed in peat structure and type, and which ultimately determines its stress and strain behaviour arises from the variety of plant species residues contributing to peat formation, and from the environmental conditions in which humification takes place. Humification is the process of decay (or decomposition) which occurs by the biochemical oxidation of plant matter. The principal physical changes in peat due to the process of humification are: - a reduction in total moisture content; an increase in specific gravity; an increase in compaction; a decrease in pore space; an increase in degree of decomposition; an increase in calorific value; and changes in colour towards a dark brown to black (Lüttig, 1986). It is primarily the change in structure of the peat (its morphology and texture) due to humification which is responsible for these changes and which ultimately differentiates one type of peat from another (Hobbs, 1986). Therefore, the classification that determines the stage of decomposition of the plant remains is considered to be one of the most important in the identification of peat types.

Various methods for the determination of fibre content and degree of decomposition of peat have been reviewed and evaluated by Malterer *et al.* (1992). The most generally accepted field technique for this classification in Europe is that developed by von Post in the early 1920's. This method attempts to describe the structure of mainly *Sphagnum* peat in quantitative terms. Although this is a primitive and seemingly crude technique, it is relatively easy to carry out in the field and if performed correctly, acceptable results may be obtained. The technique itself involves the squeezing of a small handful of peat and noting the nature of the material being extruded between the fingers, the residue and the visual identification of any plant structure and amorphous material. This is graded on a scale of 1 to 10 (with 1 describing no decomposition and 10 being completely humified) and designated H_1 to H_{10}. Table 2.2 shows the von Post system of humification. Hobbs (1986) provides an extended system that correlates the types of peat with their respective physical, chemical and structural properties and therefore increases the value of the use of this system. This includes field estimations of some, or all of the following: moisture content; presence of fine fibres; coarse fibres; wood fragments; organic content; tensile strength-vertical and horizontal; smell (indicating fermentation under anaerobic conditions); plasticity; and acidity (Hobbs, 1986).

Landva and Pheeney (1980) studied the differences in the structure of *Sphagnum* peat at different degrees of humification using a Scanning Electron Microscope. At low levels of humification (H_1-H_2) the Sphagnum leaves and stems consist of a series of hollow cells and appear more or less as they do when they grow. At H_3 to H_5, the membranes on both sides of the leaves and stems are at least partially decomposed, leaving a relatively open framework of cell walls. At H_5 to H_8 it is no longer possible to detect distinct leaf structures and at H_8 to H_{10}, the material would be expected to be completely decomposed and be amorphous in nature (Landva and Pheeney, 1980). Therefore, the breakdown of the plant structure by the process of decomposition has the effect of reducing the water holding capacity and hence water transmittability of the peat.

2.1.4 Geotechnical Properties of Peat

It is reported that the fibrous nature of the peat gives bogs significant shear strength, despite their high moisture content (Lindsay *et al.*, 1988). Also, the great physical stability of the peat mass is derived from the immense cation exchange ability (CEA) of *Sphagnum* peat (Hobbs, 1986). The cation exchange capacity (CEC) is the quantity of cations adsorbed on a soil particle surface per unit dry mass of soil under chemical neutral conditions (Hillel, 1971). The CEC of ombrotrophic bog peat varies noticeably with botanical composition and is very dependent on pH; therefore, Clymo (1983) prefers the term CEA to represent the measured capacity at a particular pH, and with a particular cation. Consequently, the term CEC in the case of peat is reserved for the maximum reached when all exchange groups are ionised (Clymo, 1983). Three types of water are recognised as forming part of the peat matrix: - intracellular water held within the internal cells (macro-pores); inter-particle water held by capillary forces (micro-pores); and intra-particle adsorbed (bound) water (Lindsay *et al.*, 1988). The proportions of these depend on the structure and morphology of the various plants present, and on the degree of humification (Hobbs, 1986). It is one particular phase of bound water - the adsorbed water adhering to

Table 2.2 Determination of degree of humification using the von Post system (from Landva and Pheeney, 1980).

SCALE	DESCRIPTION OF DECOMPOSITION	PLANT STRUCTURE	AMORPHOUS MATERIAL	NATURE OF EXTRUDED MATERIAL	NATURE OF RESIDUE
H_1	None	Easily identified	None	Clear, colourless water	
H_2	Insignificant	Easily identified	None	Yellowish water	
H_3	Very slight	Still identifiable	Slight	Brown, muddy water; no peat	Not pasty
H_4	Slight	Not easily identified	Some	Dark brown, muddy water; no peat	Somewhat pasty
H_5	Moderate	Recognisable, but vague	Considerable	Muddy water and some peat	Strongly pasty
H_6	Moderately strong	Indistinct, more distinct after squeezing	Considerable	About one third of peat squeezed out; water dark brown	
H_7	Strong	Faintly recognisable	High	About one half of peat squeezed out; any water very dark brown	
H_8	Very strong	Very indistinct	High	About two thirds of peat squeezed out; also some pasty water	Plant tissue capable of resisting decomposition
H_9	Nearly complete	Almost not recognisable		Nearly all peat squeezed out as a fairly uniform paste	
H_{10}	Complete	Not discernible		All the peat passes between the fingers; no free water visible	

the surface of the tissue - which is involved in the stability process. The characteristics of this water zone are governed by the CEA of the tissue and the chemistry of the water containing the nutrient supply. Therefore, the higher the CEA, the stronger the adsorption complex and the greater the inter-particle adherence (Hobbs, 1986).

Hobbs (1986) lists the engineering properties of peat as being: hydraulic conductivity, compression and consolidation, and shear strength.

Hydraulic Conductivity

Crucial to the understanding of peat hydrology is the transmission of water through the different layers of the peat mass. The hydraulic conductivity (k) of peat varies throughout the bog structure with notable differences occurring in and between the acrotelm and catotelm, both horizontally and vertically. The importance of hydraulic conductivity of peat is discussed in section 2.1.5 in relation to ombrotrophic bog hydrology.

Compression and Consolidation

The extremely compressible nature of peat results from the high moisture content, and has important time dependent characteristics due to the porosity and the manner in which pore water is held and expelled from the structure (Hobbs, 1986). Therefore, the distribution of water within the peat matrix has a considerable influence on the consolidating behaviour of peat. Compression and consolidation of peat involves two main processes: the expulsion of pore water; and the structural re-arrangement of particles (Hobbs, 1986). In the first stage, termed primary consolidation, both processes occur simultaneously. Secondary compression follows, with structural re-arrangement and expulsion of interparticle water, which continues as a creep-like process (Hobbs, 1986). Landva and La Rochelle (1983) note the difficulty in distinguishing between the primary and secondary processes in practice. However, they report that the consolidation process of *Sphagnum* peat consists of a combination of an initial elastic behaviour, followed by plastic, non-reversible structural compression (creep). The rate of creep is reported to be governed by the flattening of the open peat lattice rather than that of individual particles of organic matter. Results presented by Hobbs (1986) and Landva and La Rochelle (1983) suggest that within the context of peat, secondary compression is the dominant process of consolidation, as it continues almost indefinitely. Edil *et al.* (1986) suggest that compression can be divided into four components: instantaneous strain, primary strain (developing over one minute), secondary strain (developing over the next 100 minutes), and tertiary strain (appearing over the next 10,000 minutes). As with other physical and structural properties of peat, variability in compression exists due to differences in the type of peat, degree of decomposition and moisture content.

Shear Strength

There are only a few accounts of the shear behaviour of peat. These are concerned primarily with engineering problems of road embankments and test fill sites (e.g. Landva and La Rochelle, 1983), and are associated more with the compression and consolidation characteristics discussed above. The remainder is mainly related to the accessible acrotelm peat in the upper part of the peat profile. In this zone, fibres within the peat have been found to affect the geotechnical behaviour of the peat by providing an internal lateral resistance to shear deformation (Landva and La Rochelle, 1983). Less information is available on the shear characteristics of highly humified peat, although Mitchell (1993) suggests that while the strongly adsorbed water modifies the strength properties, undrained strength is reduced as a result of high moisture contents and plasticity. Methods of determining shear strength are discussed in section 2.2.5.

2.1.5 Ombrotrophic Bog Hydrology

The hydrological behaviour of a system may be described in terms of the characteristic pathways and volumes of water (Baird *et al.*, 1997), by means of the inputs, outputs, storage and importantly water movement within the system. The movement of water through peatlands has been described as a controlling ecological factor, since it determines the transport of solutes, growth rates of plants, and profoundly influences decomposition rates and peat redox status (Hemond and Goldman, 1985). Therefore, the understanding of peatland hydrology is essential in its conservation and management.

Peatland water balance

The water balance for a peatland comprises the inputs, outputs and storage changes in the hydrological system, i.e. the terrestrial phase of the water cycle. Unlike a drainage basin, however, the wetland is not defined by no-flow boundaries, and its water budget must include terms to represent groundwater and surface water inflows as well as outflows (Dooge, 1975; Gilman, 1994). The water balance for a wetland site was expressed by Gilman (1994):

$$P + G_{in} + Q_{in} = E + G_{out} + Q_{out} + \Delta s \tag{2.1}$$

Where: P is precipitation,

G_{in} is the groundwater inflow,

Q_{in} is surface inflow,

E is actual evapotranspiration from the wetland,

G_{out} is the groundwater outflow,

Q_{out} is the surface outflow, and

Δs is the change in water storage, usually seen as a change in water level or the water table.

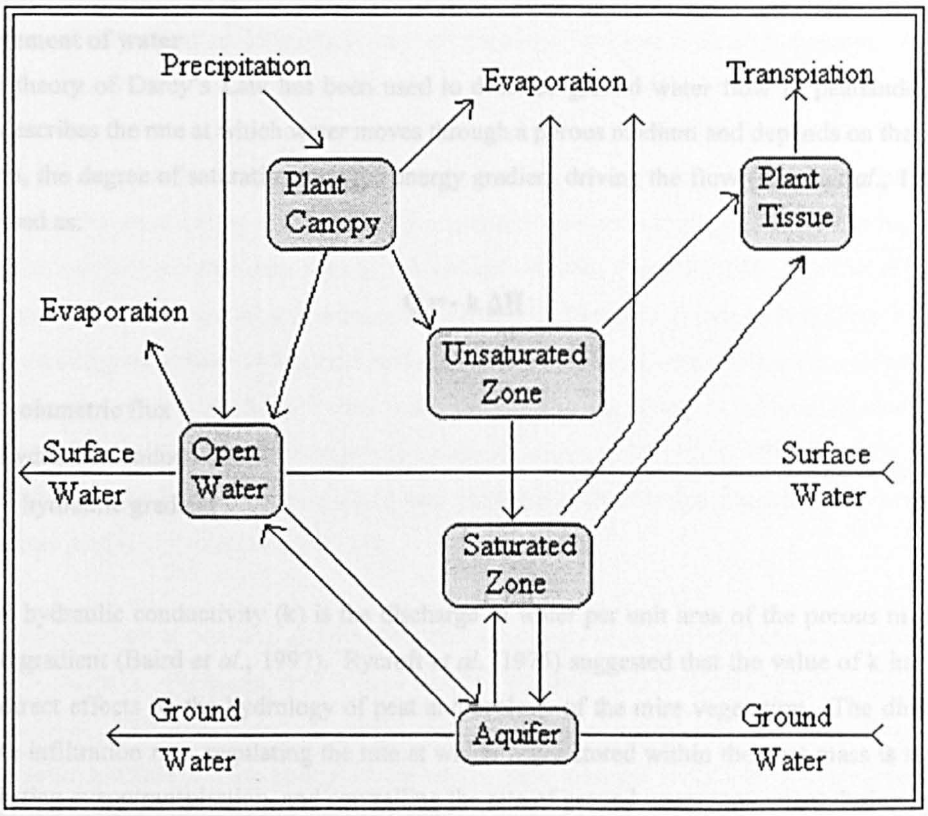
The lateral flows of surface and groundwater have an incoming and outgoing component, therefore they are regarded as throughputs of the system (Gilman, 1994).

Storage

Peatlands have a large water storage capacity, which is usually either full, or almost full (Burt *et al.*, 1990). Water which is stored in the peat mass takes the form of permanent open water bodies or temporary flooding, and retention in the unsaturated (acrotelm) and saturated (catotelm) zones (Gilman, 1994). Figure 2.1 illustrates the various components of flow and storage within a peat mass. Within the saturated zone, moisture can be held as intracellular, interparticle or adsorbed water; only the first of these flows under gravity (Burt *et al.*, 1990).

'Mooratmung' is the phenomena of 'mire breathing' in which the peat acts as an 'elastic' aquifer (Burt *et al.*, 1990), shrinking and swelling in response to changes water storage within the peat mass. The resulting

Figure 2.1 Components of water storage in the mire water balance.
(after Gilman, 1997)



movement of ground level with the water table has been measured in terms of both seasonal and long-term trends, and has been noted to complicate the measurement of water levels in mires (Gilman, 1994). Ground movement in fen peat has been studied by Gilman (1994), who has demonstrated that the main cause is due to changes in buoyancy forces which support the surface peat when it is saturated, but not when it is above the water table. Shrinking of the dewatered peat above the water table was noted to have had a less pronounced effect on ground level.

Movement of water

The classical theory of Darcy's Law has been used to describe ground water flow in peatlands (e.g. Ingram, 1978). This describes the rate at which water moves through a porous medium and depends on the pore structure of the medium, the degree of saturation, and the energy gradient driving the flow (Baird *et al.*, 1997). Darcy's Law is expressed as:

$$Q = -k \frac{\Delta H}{\Delta l} \tag{2.2}$$

Where: Q = volumetric flux

k = hydraulic conductivity

$\frac{\Delta H}{\Delta l}$ = hydraulic gradient

Therefore, the hydraulic conductivity (k) is the discharge of water per unit area of the porous medium under a unit hydraulic gradient (Baird *et al.*, 1997). Rycroft *et al.* (1975) suggested that the value of k has a number of direct and indirect effects on the hydrology of peat and ecology of the mire vegetation. The direct effects are controlling the infiltration rate, regulating the rate at which water stored within the peat mass is supplied to the acrotelm, affecting evapotranspiration, and controlling the rate of ground water movement during drainage. The most important indirect effect involves the last factor that influences the behaviour of artificially drained peatlands (Rycroft *et al.*, 1975).

A conceptual model of ground water flow in raised mires was developed by Ingram in 1978 on the basis of a simplification of Darcy's Law. The Ground Water Mound Model (GWMM) is based on the assumption that the poorly decomposed peat in the acrotelm has a high hydraulic conductivity, whereas the highly decomposed and compressed peat of the catotelm has a much lower hydraulic conductivity, and is relatively impermeable. Therefore, there is more or less steady state water table behaviour in the catotelm, which also gives the mire its overall shape (Eggelsmann *et al.*, 1993). Although this model concerns raised bogs, some of the main principles can be applied to the acrotelm and catotelm in blanket bogs.

Rycroft *et al.* (1975), working on the transmission of water through peat concluded that at that time, the understanding of the complex behaviour of water movement through more humified peat was evidently inadequate. This questioning of the applicability of Darcy's Law in peatland research led to numerous studies and much conflicting evidence. It is now accepted that peat of low humification can be expected to yield results that are consistent with Darcian behaviour (Ingram, 1983). However, for the highly humified peat within the catotelm, the results are inconsistent, although Rycroft *et al.* (1975) and Hemond and Goldman (1985) both state that an order of magnitude value can be obtained. Burt *et al.* (1990) suggest that non-linear flow through the catotelm may result from pore blocking, which reduces the rate at which water can by transmitted through the peat structure. Pore blocking can be caused by entrapped air (Galvin and Hanrahan, 1967) and microbial activity (Waine *et al.*, 1985). Also, Baird and Gaffney (1995) identified a relationship between positive pore water pressures and the hydraulic conductivity of peat soils. Compression and expansion of methane gas bubbles with variations in pore water pressure, due to a change in level of the water table would reduce the permeability of the peat (Baird *et al.*, 1997). This could partially explain the deviation from Darcian behaviour of the basal peat where decomposition is almost complete and a higher concentration of gas exists as a result. Hemond and Goldman (1985) suggest that a large component of reported non-linear flow in humified peat could be explained by the large elastic storativity of the peat, which renders some analytical methods inappropriate. In addition, variations in hydraulic conductivity are thought to result from the anisotropic nature of the bog, producing a higher horizontal hydraulic conductivity than in the vertical direction (Hobbs, 1986; Baird *et al.*, 1997). It has also been suggested that presence of gas produced by anaerobic decay occupying pore space below the water table raises the question of whether catotelmic peat should be treated as a saturated medium (Baird *et al.*, 1997). Nevertheless, it is generally accepted that hydraulic conductivity varies widely in different peats and is related to biological composition, degree of humification and physical characteristics (e.g. Clymo, 1983; Hobbs, 1986). More precisely, k is reported to decrease regularly with increases in overburden pressure, bulk density, substance volume and decomposition (Rycroft *et al.*, 1975).

An important characteristic of peatland hydrology is the occurrence of subsurface pipes and related pseudokarst landforms within the peat. The pipes, which can be over a metre in diameter, are thought to play an important role in the response of streams to storm rainfall, as they provide a network for the quick transmission of throughflow (Gerrard, 1981). Also, many of the larger pipe systems are noted to have overlying surface channels that act as storm overflow streams (Gunn, 2000a). Jones (1978) suggests that pipe formation in upland peat is a function of high rainfall, immature surface stream networks and high hydraulic gradients. They are thought to develop from macropores that act as zones of higher permeability, or 'percolines' (Gilman and Newson, 1980).

Evapotranspiration

Evapotranspiration is a very significant component of the water balance in ombrotrophic peatlands and is reported to represent the greatest loss from undamaged blanket bogs (Baird *et al.*, 1997), most notably with a decline of the water table in summer (Gilman, 1994). The importance of evapotranspiration has been discussed in section 1.4.1 in relation to the climatic criteria for ombrotrophic bog formation.

Runoff

The rate and route that water takes through the peatland will affect the timing and volume of runoff (Baird *et al.*, 1997). As the storage capacity of a peat mass is usually full, available storage is limited (Burt *et al.*, 1990). As a result, saturation-excess (as opposed to infiltration-excess) overland flow occurs and water is yielded rapidly into streams, to give a 'flashy' response (Baird *et al.*, 1997). This highlights the inaccuracy of the 'sponge analogy' in peatland behaviour, and suggests that the runoff regime from peat covered catchments is poorly regulated. However, there is some seasonal variation as during periods of dry weather the water table lowers and subsequently available storage increases.

2.1.6 Theory of Erosion in Peatlands

There are two main theories for erosion in peatlands: (1) Erosion is a result of unnatural damage to the normal peat accumulation system, and (2) erosion is the representation of a natural culmination in growth of the peat-accumulating system (Tallis, 1995). Unnatural damage to peatlands usually results from human interference and includes such pressures as grazing, burning and pollution. For the latter, in which erosion is associated with the final state of growth and development of a bog (Mitchell, 1938; Bower, 1962), the peat mass is perceived as an inherently unstable system which can only achieve stability by the loss of its contained water, either via gullying or by bursting (Conway, 1954; Pearsall, 1956; Colhoun *et al.*, 1965). Therefore, erosion may be occurring as a natural endpoint to peat development due to the crossing of a critical stability threshold. This was first discussed by Mitchell in 1938 (p 54) to explain a peat failure in Co. Wicklow: "Growth rendered the bog unstable and the burst acted as a safety valve to restore equilibrium, with such bursts occupying a definite position in the cycle of development of bogs resting on sloping surfaces." Alternatively, Clymo (1984a, 1991) has suggested that peatland growth and development acts as a system of inputs (organic material) and outputs (decay) and therefore has a 'limiting height'. This is determined by its physical properties, local climate and by the rate of the systems processes (Tallis, 1995).

Types of Erosion

Erosion in mires has been studied extensively in the English Pennines, particularly in the southern Pennines where the blanket bog is accessible and actively eroding. Bower (1960, 1961, 1962) was the first to recognise and classify the types of erosion in the blanket peat, on the basis of different forms and patterns of features, which related to processes of erosion and the nature of the peat. The two main processes identified were erosion by water and erosion by mass movement. Water erosion was reported to attack the peat in three ways: dissection, in which gully systems develop into and within the peat mass by the direct action of running water; sheet erosion, occurring from the peat surface through the agents of rain, running water and wind; and marginal face development, which affects the thin peat at the margin of the peat mass (Bower, 1960). Mass movements were reported to take the form of tearing and sliding on slopes at a relatively small scale (Bower, 1961) and 'bog bursts' were believed to be marginal features which were responsible for diverting drainage at the edges of the peat mass (Johnson, 1957; Crisp *et al.*, 1964; Tallis, 1964, 1965a). Dissection accounted for the most significant type of erosion in the Pennines and was sub-divided into two categories: type I and type II. Type I dissection described the close network of freely and intricately branched gullies confined to the deep peat on flat areas, whereas type II dissection classified the open pattern of gullying on slopes (Bower, 1961). However, Barnes (1963) found that types I and II are end members of the distribution rather than discrete populations. Bower (1960, 1961 and 1962) states that the basic control on blanket peat development and erosion is climate, but she also highlights the importance of topography as a major factor of erosion in the Pennines as a whole. Radley (1962) argued that recent biotic activities are the key to explaining peat erosion. This has become the more favoured view by later workers who have reported on the effects of burning (Tallis, 1965b, 1997), grazing

(Evans, 1997), artificial drainage and air pollution (Tallis, 1964, 1965b) as mechanisms of disruption to the vulnerable protective layer of bog vegetation in the Pennines. This damage is particularly severe in areas carpeted by the sensitive *Sphagnum* mosses as it reduces the species' ability to hold water and therefore to maintain waterlogged anaerobic conditions vital to peat accumulation. As a result, the surface of the bog dries out, shrinks and cracks which allows air penetration into the acrotelm. Erosion by rain and wind then forms channels on the surface of the bog which quickly erode further, forming the network of deep gullies and haggs described by Bower (1961) as forms of dissection. Once this dissection process is initiated, it is self-reinforcing and has the ability to degrade entire landscapes of plateau blanket bog (Brookes, 1985). The erosion caused by sheltering sheep can further accelerate the undercutting of the peat haggs.

Similar patterns and types of eroded mire have been reported by Tomlinson (1981a) in three upland areas within Northern Ireland, and by Bradshaw and McGee (1988) in Donegal and Wicklow. Although Tomlinson (1981a) prefers descriptive terminology rather than that used by Bower, dissection by anastomosing channels (type I) and by parallel or sub-parallel gullies (type II), remain the two most extensive forms of eroding blanket peat. However, the importance of underlying topography and drainage beneath the peat is highlighted, and it is suggested that in areas of deeper peat, the anastomosing channels may develop from the base of the peat, rather than from the surface (Tomlinson, 1981a). Water movement through the peat in natural subterranean pipes and the collapse of overlying peat, is believed to be a secondary process in the development and extension of hagg slopes.

Tallis (1985, 1997) has suggested that the approach and attitudes of researchers to the problem of blanket bog erosion may limit the generality of their findings. This criticism is focused on the assumption that erosion is an unnatural feature of the landscape due to specific human agencies, and hence is a sign of poor management. He states that peat erosion may be the result of processes which are an inevitable consequence of the upland environment, rather than specific agencies (Tallis, 1985).

The few researchers who have tried to quantify catchment peat erosion (e.g. Gardiner, 1983; Francis, 1990; Labadz *et al.*, 1991), have concentrated on suspended sediment in streams, the sedimentation of reservoirs, peat surface sediment traps and erosion pins on banks, rather than monitoring large scale mass movements. For example, Labadz *et al.*, (1991) provided an estimate of short-term sediment yield of 55 t km^{-1} yr^{-1} for a blanket peat catchment in the Southern Pennines using stream sediment sampling. The extent to which mass movements involving peat have influenced the development of blanket bogs has been largely ignored.

2.1.7 Bog Failures

Terminology and Definitions

Early accounts of slope failures in peatlands in Irish literature, such as a report on a failure in County Kerry (Sollas *et al.*, 1897), used the term 'bog burst' to describe the outburst and flood of escaping fluid peat from an area of ruptured bog. It is clear from this account and others like it (e.g. Delap *et al.*, 1932) that a genuine burst and flow failure is being described. Subsequently, this resulted in any form of mass movement involving peat being termed a 'burst' (e.g. Conway, 1954; Johnson, 1957). Even in some more recent literature (e.g. Tallis,

1985) there is little recognition of the differentiation between slides, flows and the traditionally named 'bursts' although Tomlinson and Gardiner (1982) make the important distinction and highlight the different mechanisms involved.

In this thesis, the terms 'bog burst' and 'bog flow' refer to the rupturing of an area of the less humified acrotelm and the flooding out of the more humified catotelm peat. A 'bog slide' is the movement of more intact peat over a sub-stratum located within, or immediately below the peat layer, whereas a 'peat slide' refers to a mass movement associated with the failure of the underlying material, usually clay.

Reported events

There are over 60 reports of failure events in bogs around the world. They are found in a range of sources, covering a variety of disciplines, including historical literature and reviews, newspaper articles, and agriculture, forestry, geology and geography journals. As a result, these accounts are catered for the specific interests of the readers and contain different emphasis. For instance, the majority of newspaper articles and the older accounts (pre-1930) are concerned primarily with descriptions of the event and the impact on local communities. Sollas *et al.* (1897, p.476) describes 'the lamentable loss of life' and damage caused by the 1896 Killarney bog flow in County Kerry. Sollas *et al.* (1897) also briefly reviews other bog failures by describing the size of bog affected and the damage, including loss of lives, livestock and agricultural land. However, local reports can be prone to exaggerations. For example, Praeger (1906), after reading of a great disaster and havoc caused by a bog burst in a Dublin newspaper, travelled immediately to the scene where he discovered the remains of a small slippage within a cut-over area.

Table 2.3 shows details of reported bog failures. The frequency of these events highlights their importance, particularly in Ireland. It is apparent that there were many failure events in *raised bogs* between 1750 and 1900 (mostly described by Sollas *et al.*, 1897). However, it is questionable whether this represents a period of accelerated natural mass wasting of ombrotrophic bogs in general, as: (i) human interference during the drainage and hand cutting of large raised bogs during this time may have initiated many failures, and (ii) failures may have been reported more readily as a result of a larger population working and/or living on, or near bogs at this time. Since 1906, all but one of the reported failure events in Britain and Ireland occurred in blanket bogs. The main difference between failures in raised and blanket bogs is the failure mechanism. In raised bogs, only bog flows occur whereas in blanket bogs, bog flows, bog slides and peat slides have been reported.

The criteria for determining the type of failure in peatlands are: topographic setting; nature of peat and underlying material; and failure form and location of the shear zone. These are discussed in relation to slope stability analysis in section 2.2. From the numerous descriptive accounts of slope failures in ombrotrophic bogs, it is evident that three main categories exist: shallow gradient slope failures; steep slope failures; and plateau-type failures. As with all landslide classifications, combinations of failure types also exist as a complex intermediate/transition category. Shallow gradient slope failures are associated with burst and flow mechanisms on raised bogs and areas of deep blanket peat. In these cases, slow mass movement in the form of creep-like deformation and liquefaction are reported to be important factors in contributing to slope failure. Examples of

Table 2.3 Details of known bog failures.

TIME OF FAILURE	LOCATION OF FAILURE (numbers refer to Figure 2.2)	PEATLAND TYPE	FAILURE TYPE	SOURCE
January 1526	Chat Moss, Derbyshire	Raised bog	Bog flow	Crofton (1902)
January 1633	White Moss, Lancashire?	Raised bog	Bog flow	Crofton (1902)
Pre 1640	Clougher, Co. Tyrone **(1)**	Blanket bog	Bog flow	Feehan and O'Donovan (1996)
June 1689	Upper Teesdale, Northern Pennines	Blanket bog	Bog flow	Camden (1772)
1697	Kapanihane Bog, Co. Limerick **(2)**	Blanket bog	Bog flow	Feehan and O'Donovan (1996)
1708	Castlegarde Bog, Co. Limerick **(3)**	Blanket bog	Bog flow	Sollas *et al.* (1897)
March, 1712	Clougher, Co. Tyrone **(4)**	Blanket bog	Bog flow	Feehan and O'Donovan (1996)
March, 1745	Dunmore, Co. Galway **(5)**	Raised bog	Bog flow	Sollas *et al.* (1897)
Autumn, 1763	Treuenfeld, Germany	?	Bog flow	Sollas *et al.* (1897)
November 1771	Solway Moss, Cumbria	Raised bog	Bog flow	Gilpin (1808)
1786	Slieve Bloom, Co. Laois **(6)**	Blanket bog	Bog flow	Feehan and O'Donovan (1996)
March, 1788	Dundrum, Co. Tipperary **(7)**	Raised bog	Bog flow	Sollas *et al.* (1897)
May, 1788	Knocklayd, Co. Antrim **(8)**	Blanket bog	Bog flow	Feehan and O'Donovan (1996)
December, 1809	Bog of Rine, Co. Longford **(9)**	Raised bog	Peat slide?	Sollas *et al.* (1897)
January, 1819	Erris, Co. Mayo **(10)**	Blanket bog	Bog flow	Sollas *et al.* (1897)
June, 1821	Clara, King's Co. **(11)**	Raised bog	Bog flow	Griffith (1821)
September, 1821	Joyce, Co. Galway **(12)**	Blanket bog	?	Sollas *et al.* (1897)
December, 1824	Ballywindelland, Co. Coleraine **(13)**	Raised bog	Bog flow	Sollas *et al.* (1897)
January, 1831	Geevagh, Co. Sligo **(14)**	Blanket bog	Bog flow	Sollas *et al.* (1897)
September, 1835	Randalstown, Co. Antrim **(15)**	Raised bog	Bog flow	Sollas *et al.* (1897)
January, 1840	Kanturk, Co. Cork **(16)**	Blanket bog	Bog flow	Sollas *et al.* (1897)
1867	Belmullet, Co. Mayo **(17)**	Blanket bog	Bog flow	Feehan and O'Donovan (1996)
December, 1870	Castlereagh, Co. Roscommon **(18)**	Raised bog	Bog flow	Sollas *et al.* (1897)
October, 1873	Dunmore, Co. Galway **(19)**	Raised bog	Bog flow	Sollas *et al.* (1897)
1879?	Falkland Islands	Blanket bog	Bog flow	Bailey (1879)
January, 1883	Castlereagh, Co. Roscommon **(20)**	Raised bog	Bog flow	Sollas *et al.* (1897)
January, 1883	Newtownforbes, Co. Longford **(21)**	Raised bog	Bog flow	Sollas *et al.* (1897)
1887?	Falkland Islands	Blanket bog	Bog flow	Barkly (1887)
January, 1890	Loughatorick, Co. Galway **(22)**	Blanket bog	Bog flow	Sollas *et al.* (1897)
August, 1895	Dungiven Bay, Co. Derry **(23)**	Blanket bog	Peat slide?	Sollas *et al.* (1897)
December 1896	Killarney, Co. Kerry **(24)**	Raised bog	Bog flow	Sollas *et al.* (1897)
1900	Lisdoonvarna, Co. Clare **(25)**	Blanket bog	Bog flow	Feehan and O'Donovan (1996)
June, 1906	Ballycumber, Co. Ofally **(26)**	Raised bog	Bog flow	Feehan and O'Donovan (1996)
1909	Kilmore, Co. Galway **(27)**	Blanket bog	Bog flow	Feehan and O'Donovan (1996)

(continues on following page)

Table 2.3 Details of known bog failures (continued).

June 1930	Upper Teesdale, Northern Pennines	Blanket bog	Peat slide?	Huddleston (1930)
February 1931	Glencullin, Co. Mayo **(28)**	Blanket bog	Bog flow	Delap *et al.* (1932)
October 1934	Co. Clare **(29)**	Blanket bog	Bog flow	Mitchell (1935)
January 1937	Co. Wicklow **(30)**	Blanket bog	Bog slide	Mitchell (1938)
Spring, 1937	Mullaghcleevaun, Co. Wicklow **(31)**	Blanket bog	Bog flow	Feehan and O'Donovan (1996)
August 1938	Yorkshire.	Blanket bog	Bog flow	Hemmingway and Sledge (1946)
July 1939	Powerscourt Mountain, Co. Wicklow **(32)**	Blanket bog	Bog slide	Delap and Mitchell (1939)
1945	Straduff, Co. Sligo **(33)**	Blanket bog	Bog flow	Alexander et al. (1985)
January 1946	Meenacharvy Townland, Co. Donegal **(34)**	Blanket bog	Bog slide	Bishop and Mitchell (1946)
1954	Derrylea, Co. Kildare **(35)**	Raised bog	Bog flow	Feehan and O'Donovan (1996)
November 1959	Isle of Lewis, Outer Hebrides	Blanket bog	Bog slide	Bowes (1960)
July 1963	Cockburnspath, Berwickshire	Blanket bog	?	Butler (1963)
July 1963	Upper Teesdale, Northern Pennines	Blanket bog	Peat slide	Crisp *et al.* (1964)
November 1963	Co. Antrim **(36)**	Blanket bog	Bog flow	Colhoun *et al.* (1965)
November 1963	Barnesmore, Co. Donegal **(37)**	Blanket bog	Bog flow	Feehan and O'Donovan (1996)
January 1965	Slieve Rushen, Co. Cavan **(38)**	Blanket bog	Bog slide	Colhoun (1966)
1973	Slieve Bloom, Co. Ofally **(39)**	Blanket bog	Bog flow	Feehan and O'Donovan (1996)
November 1979	Carrowmaculla, Co. Fermanagh **(40)**	Blanket bog	Bog flow	Tomlinson (1981b)
August 1980	Slieve-an-Orra Hills, Co. Antrim **(41)**	Blanket bog	Peat slide	Tomlinson and Gardiner (1982)
Spring 1982	Prince Rupert, British Columbia, Canada	Artificial Spoil/dump	Bog flow	Hungr and Evans (1985)
July 1983	Hermitage Water, Roxburghshire	Blanket bog	Peat slide	Acreman (1991)
July 1983	Teesdale and Weardale, Northern Pennines	Blanket bog	Peat slide	Carling (1986)
October 1984	Straduff Townland, Co. Sligo **(42)**	Blanket bog	Bog flow	Alexander *et al.* (1985); Thorn (1985)
May 1985	South-east Sligo **(43)**	Blanket bog	Bog flow	Alexander et al. (1986)
June 1986	Yellow River, County Leitrim **(44)**	Blanket bog	Peat slide	Coxon *et al.* (1989); Large (1991)
September, 1987	Mouille de la Vraconne National Park, Switzerland.	Blanket bog	Bog flow	Eggelsmann *et al.* (1993)
1988	Slieve Bloom, Co. Laois **(45)**	Blanket bog	Bog flow	Feehan and O'Donovan (1996)
July 1989	Ballacorrick Forest, Co. Mayo **(46)**	Blanket bog	Bog flow	Hendrick (1990)
November 1991	Skerry Hill, Co. Antrim **(47)**	Blanket bog	Bog slide	Wilson and Hegarty (1993)
February and August 1992, March 1993	Maquarie Island, South Pacific Ocean	Blanket bog	Peat slide	Selkirk (1996)
August 1992	Cuilcagh Mountain, Co. Fermanagh **(48)**	Blanket bog	Bog flow	Walker and Gunn (1993)
1993	Tierra del Fuego, Argentina	Blanket bog	Peat slide	Gallart *et al.* (1994)
January 1995	Upper Teesdale, North Pennines	Blanket bog	Peat slide	Warburton and Higgitt (1998)
October 1998	Cuilcagh Mountain, Co. Fermanagh **(49)**	Blanket bog	Peat slide	Dykes and Kirk (2000; 2001)
1998	Australia	Fen	Bog flow	Proctor (1998)

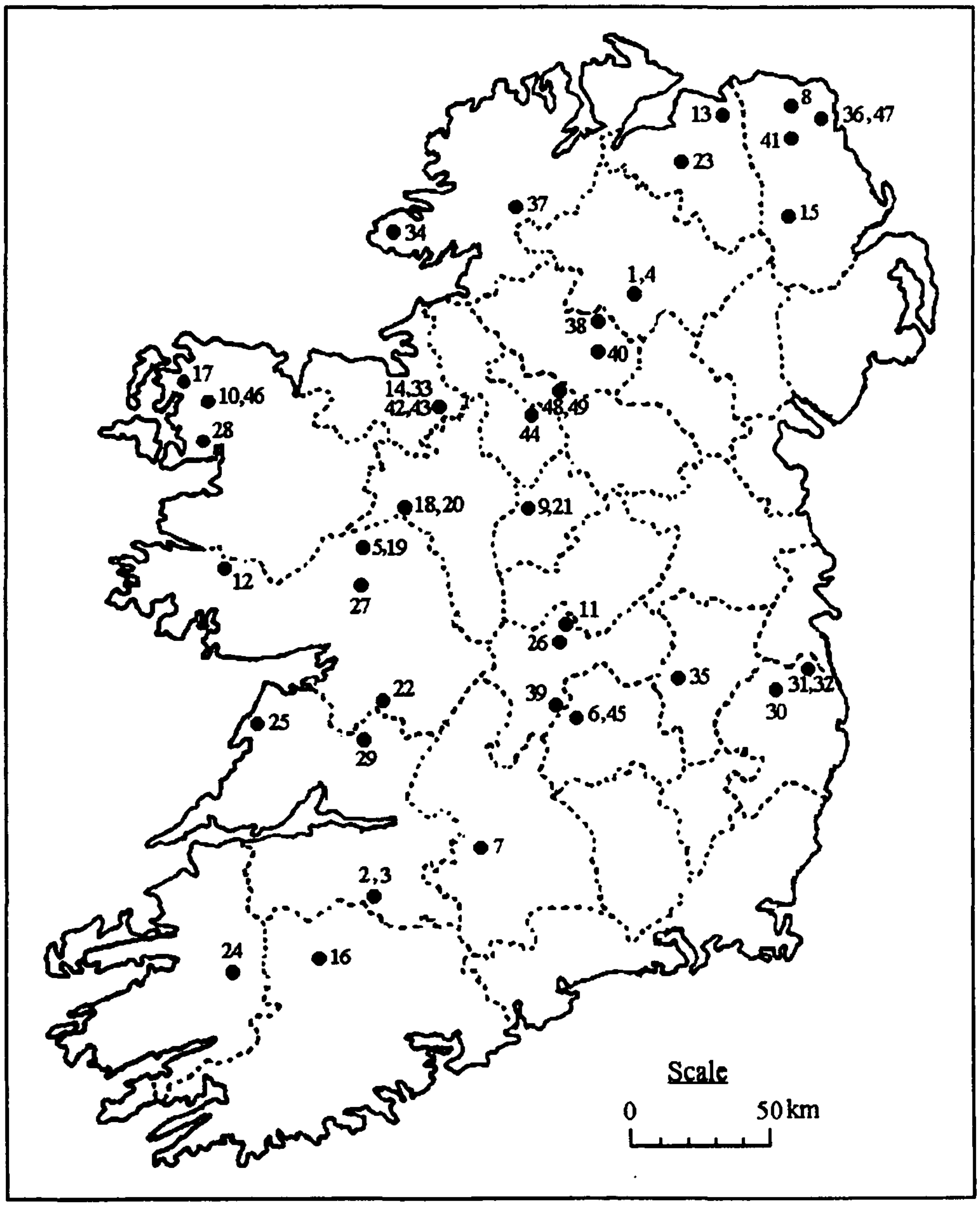
this include the 1896 Co. Kerry burst (Sollas *et al.*, 1897) and the 1931 Co. Mayo flow described by Delap *et al.*, (1932). Steep slope failures involve the sliding of a shallower depth of blanket peat, usually in a translational manner, either as a bog slide or a peat slide (depending on the location of the shear plane). Examples of peat slides are described by Tomlinson and Gardiner (1982) in Co. Antrim, and Crisp *et al.* (1964) and Carling (1986) in the northern Pennines. An example of a bog slide in Co. Leitrim has been studied by Coxon *et al.* (1989) and Large (1991). The third category involves the failure of a blanket peat slope over a plateau or escarpment. Mechanisms described in this type of failure include an initial slide movement over the edge of a slope, which acts as an outlet inducing a failure feed-back upslope. This has been reported to take place in the form of a flow (Alexander *et al.*, 1985) and has the ability to drain large areas of deep bog that has accumulated on the relatively flat plateau top. This has occurred several times at Geevagh in Co. Sligo, in 1831 (Sollas *et al.*, 1897), 1945 and 1984 (Alexander *et al.*, 1985; Thorn, 1985), and c. 1998 (Kirk and Dykes, unpublished data).

A wide range of peatland slope failure characteristics have been reported in literature. For example the rate of failure and release of material, ranges from an instantaneous outburst and flood event, to the slow oozing (likened to lava) which has been reported to continue for days (Sollas *et al.*, 1897), lowering the surface of the bog. The latter has been associated with the failure of both large raised bogs (e.g. Sollas *et al.*, 1897) and areas of blanket bog (e.g. Bailey, 1879). However, slope failures in blanket bog peat are more commonly reported to be rapid events. Sollas *et al.*, (1897) state that the rate of movement is a function of slope angle and viscosity of the failed material. The morphological units of bog failures differ according to the type of mechanisms involved. Three major units of a bog slide in Co. Cavan were recognised by Colhoun (1966) and described as the head, erosion track, and the depositional toe, or lobe. Bog bursts and flows usually consist of a large proportion of subsided and cracked peat around the margins of the failure scar. These have been referred to as 'floes' and 'crevasses' in early accounts (e.g. Sollas *et al.*, 1897, Delap *et al.*, 1932), and are differentiated from cracks found around the margins of many landslides formed by tearing apart of the soil. This type of subsided bog is associated with the release of highly humified peat at depth within the bog, and the stretching and tearing apart of the upper acrotelm and vegetation. A large depositional area at the foot of the scar consisting of rafts of intact peat, separated by pools of peat slurry and water is also a characteristic of flow type failures. The various destabilising factors reported to be of importance contributing to peat failure in the form of flows and slides are discussed in section 2.2.9.

Distribution of Bog Failures

Figure 2.2 illustrates the location of approximately 50 reported bog failure events in Ireland, details of which are given in Table 2.3. The distribution of failures is widespread in Ireland and areas of blanket bog containing more than one failure are also fairly common, such as Geevagh in Co. Sligo. Elsewhere in the British Isles, prior to drainage and cutting, a few accounts describe large failures in raised bogs, such as Solway Moss in Cumbria. More recently, a number of failures have been reported in the blanket bogs of the English Pennines. In general however, disregarding the early raised bog failures, bog flows are mainly confined to the deeper blanket bogs of Western Ireland, whereas peat slides are more common on steeper blanket bog slopes. This distribution reflects the importance of topography, as depth of peat is closely related to gradient (Bower, 1960).

Figure 2.2 The distribution of reported bog failures in Ireland (updated from Alexander *et al.*, 1985). (Numbers refer to Table 2.3)



On a global scale, bog failures have been reported in Germany, Switzerland, Canada and also in the Southern Hemisphere (Falkland Islands, Tierra del Fuego, Australia and subantarctic Macquarie Island). The majority of these are peat slides on relatively steep blanket bog slopes (e.g. Selkirk, 1996) and share the same characteristics as those reported in Britain and Ireland.

2.2 SLOPE STABILITY

2.2.1 Introduction

A great diversity of slope movements arises from the variability of form, behaviour, volume and type of material involved. The study of slope stability represents a research theme common to a variety of workers, namely: - geotechnical engineers, geologists and geomorphologists. This has led to the development of an interdisciplinary approach to research (Brunsden and Prior, 1984). The collaboration has been made possible by the fact that it is the objectives of analysis of slope stability rather than the methodology that distinguishes engineering and geomorphological approaches (Anderson and Richards, 1987). The engineer is primarily concerned with the stability of specific slopes, whereas the interest for the geomorphologist is the role of slope failure processes in the longer term slope stability and evolution.

The main recognised aims of slope stability analysis identified by Chowdhury (1978) are:

- To assess the stability of different types of slopes under given conditions;
- To assess the possibility of landslides involving natural or man-made slopes;
- To analyse slips and landslides that have already occurred and to assist in the understanding of failure mechanisms and the influence of environmental factors;
- To enable redesign of failed slopes, and planning and design of preventive and remedial measures where necessary;
- To enable the study of exceptional loading on slopes such as from earthquakes;
- To understand the development and form of natural slopes and the processes that have been responsible for different natural features.

Background information and thorough site investigation to determine factors such as topographic setting, geological condition, nature of soil material and movement types, are essential as they form the basis for slope stability analysis. Once the soil and ground water conditions have been established, a method of analysis which is appropriate to the anticipated mechanism of failure can then be chosen (Nash, 1987). The study of previously failed slopes, together with experience and thoroughness of the examiner, can result in an appropriate idealisation of ground conditions and the development of a realistic model.

2.2.2 Definition and Classification of Slope Movement

A variety of terms exist which describe different types of slope movement. Although the term 'landslide' has in the past been applied to all manner of slope movement events, regardless of processes involved (Hansen, 1984), the term itself indicates a distinct plane, or zone of sliding, so it usually does not include falls, topples and creep.

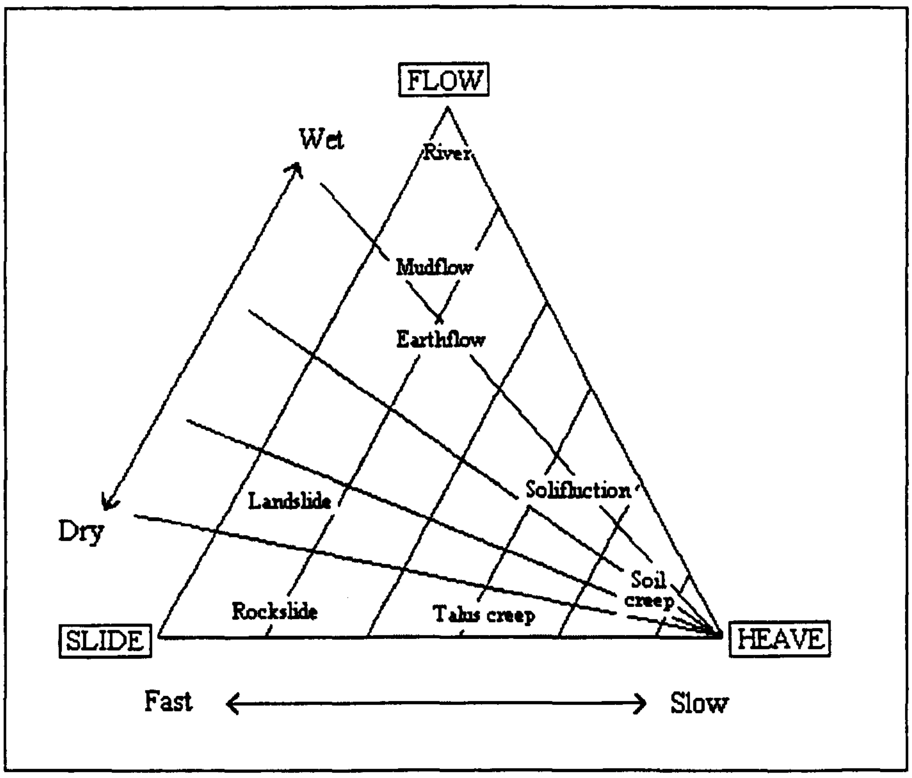
Varnes (1978, p 34) has defined slope movement as "a downward and outward movement of slope-forming materials under the influence of gravity". The terms 'mass wasting' (Selby, 1993) and 'mass movement' (Brunsden 1984) have been used to describe the process which does not require a transporting medium such as water, ice and air, and therefore is distinguished from mass transport. However, these agents are frequently involved in mass wasting processes by reducing the strength of slope materials, often by contributing to plastic and fluid behaviour of soils (Selby, 1993). The term 'mass movement' is used in this thesis as this encompasses the entire range of slope movements, including creep.

Three major classes of slope movement were identified by Nash (1987): falls, slides and flows. The category of creep may also be added to this group as, although it is widespread in occurrence, it can be linked quite closely with other forms of mass movement (Hansen, 1984). Details of the types of slope mass movement are given in Appendix 1.

The variety of slope movements is so great that Yatsu (1967) suggested that thorough classification systems were deemed hardly feasible, or at least not of much practical use. However, it has subsequently become generally accepted that although classifications are dependent on different landslide factors or the discipline of the researcher (Dikau *et al.,* 1996), if they are used in the correct context then they can be useful as a means of discovering some degree of order within a complex group of phenomena (Hansen, 1984). In reality, there is less distinction between groups of mass movements as a 'natural continuum' (Goudie, 1993) exists, causing further classification problems. The hierarchy of each classification varies with the interest of the user. For example, engineers tend to use the criteria of velocity of movement and type of material involved (bedrock or soil); whereas Carson and Kirkby (1972) as geomorphologists highlight the importance of water content and velocity of movement (illustrated in Figure 2.3). Selby (1993) considers at least the following criteria are necessary to distinguish between types of slope movement: velocity and mechanisms of movement; material; mode of deformation; geometry of moving mass; and water content. Hansen (1984) studied the basic discriminating factors used in published classification systems, and found the three most significant criteria to be: type of material and/or type of movement; morphology of the material moved or the surface of movement; and geotechnical properties. Hansen also suggested the following parameters for future studies:

- Age of movement
- Degree of activity
- Geographic type
- Geographic location
- Climatic type
- Type and size of material moved
- Underlying geology
- Type of movement
- Velocity of movement
- Water, air, and ice content
- Causes of movement, including trigger mechanism
- Morphology of deposited material and failure surface
- Geotechnical properties.

Figure 2.3 Classification of mass movements in terms of pure flow, slide and heave (from Carson and Kirkby, 1972).



Although there is no universally recognised classification system, Hutchinson (1988) has provided a comprehensive two part system (Table 2.4 a and b). The first identifies eight categories of slope movement based on morphology, mechanism, type of material and rate of movement; the second is a basic geotechnical classification.

The Cuilcagh peatland is characterised by the scars of slides and flows with failure planes located within and below the peat layer. The classification system of Hutchinson (1988) includes 'peat slides' and 'bog bursts and flows' in the categories of translational slide and debris flow respectively. Hutchinson (1968, p 691) describes bog failures generally as consisting of "... predominantly translational, downhill movements of masses of saturated peat". However a distinction is then made between bog failure types. Bog flows and bursts (associated with raised bogs) are described as occurring after receiving a sudden input of water which causes the bog to swell until some form of failure releases the inner, semi-fluid peat, whereas bog slides affect the thinner and more 'firm' blanket peat (Hutchinson, 1968).

2.2.3 Mechanisms of Failure

Slope forming materials have a tendency to move downslope under the influence of gravity. This tendency is counteracted by the mobilisation of shearing resistance (Brunsden, 1979). The margin of stability of a slope is given by the Factor of Safety, F, which is expressed as the ratio of shear strength (resistance) to shear stress. Therefore, F is dependent on the balance of disturbing and resisting forces acting on the mass of potentially sliding material (Franklin, 1984). Slope failure will only occur when the shearing resistance is not enough to counterbalance the forces tending to cause movement along any surface within the slope material (Chowdhury, 1978), i.e. when $F<1$.

Slopes can exist in one of three states determined by the ability of the transient forces to produce failure (Crozier, 1986). Where shear strength is significantly larger than shear stress ($F>1.3$), the slope is described as *stable*. An *actively unstable* slope describes conditions when the shear stress exceeds shear strength ($F<1$). *Marginally stable*, also sometimes referred to as *conditionally stable* slope conditions prevail when F lies between 1 and 1.3. This does not indicate failure of the slope is imminent, but suggests that transient changes in shear strength are responsible for occasional slope failure under these conditions. For example, the real F is influenced by such factors as stress-strain characteristics, pore-water pressure distribution, initial stresses and progressive failure (Nash, 1987).

Terzaghi (1950) considered two types of landslide causation with respect to F: - external, producing an increase in shear stress, but no change in the shearing resistance of the slope forming materials; and internal, leading to a decrease in shear strength (resistance) of a slope without a change in shear stress (Brunsden, 1979). External changes in slope conditions include alterations to slope hydrology, effects of loading and unloading and changes in the geometry of the slope. Internal changes involve an alteration in resistance and include progressive failure by strain softening, weathering and seepage erosion (Brunsden, 1979). Factors which contribute to external (increase in shear stress) and internal (decrease in shear strength) changes in slope conditions are shown in

Table 2.4a Classification system of slope movements by Hutchinson (1988)

I. CLASSIFICATION BY MORPHOLOGY WITH SOME CONSIDERATION OF MECHANISM, MATERIAL, AND RATE OF MOVEMENT.

A. REBOUND
Movement associated with:
  1. Excavations, from human activity
  2. Naturally eroded valleys

B. CREEP
  1. Superficial, predominantly seasonal creep; mantle creep:
    (a) Soil creep, talus creep (non-periglacial)
    (b) Frost creep and gelifluction of granular debris (periglacial)
  2. Deep seated, continuous creep; mass creep
  3. Pre-failure creep; progressive creep
  4. Post-failure creep

C. SAGGING OF MOUNTAIN SLOPES
  1. Single-sided sagging associated with the initial stages of landsliding:
    (a) of rotational (essentially circular) type
    (b) of compound (markedly non-circular) type
      (i) listric; (ii) bi-planar
  2. Double sided sagging associated with the initial stages of double landsliding, leading to ridge spreading:
    (a) of rotational (essentially circular) type
    (b) of compound (markedly non-circular) type:
      (i) listric; (ii) bi-planar
  3. Sagging associated with multiple toppling

D. LANDSLIDES
  1. Confined failures:
    (a) in natural slopes
    (b) in excavated slopes
  2. Rotational slips:
    (a) Single rotational slips
    (b) Successive rotational slips
    (c) Multiple rotational slips
  3. Compound slides (markedly non-circular with listric or bi-planar slip surfaces):
    (a) released by internal shearing toward rear:
      (i) in slide mass of low to moderate brittleness
      (ii) in slide mass of high brittleness
    (b) progressive compound slides, involving rotational slip at rear and fronted by subsequent translational slide
  4. Translational slides
    (a) Sheet slides
    (b) Slab slides; flake slides
    (c) Peat slides
    (d) Rock slides
      (i) Planar slides; block slides
      (ii) Stepped slides
      (iii) Wedge failures
    (e) Slides of debris:
      (i) Debris slides; debris avalanches (non-periglacial)
      (ii) Active layer slides (periglacial)
    (f) Sudden spreading failures

E. DEBRIS MOVEMENTS OF FLOW-LIKE FORM
  1. Mudslides (non-periglacial):
    (a) Sheets
    (b) Lobes (lobate or elongate)
  2. Periglacial mudslides (gelifluction of clays):
    (a) Sheets
    (b) Lobes (lobate or elongate, active or relict)
  3. Flow slides:
    (a) in loose, cohesionless materials
    (b) in lightly cemented, high porosity silts
    (c) in high porosity, weak rocks
  4. Debris flows, very or extremely rapid flows of wet debris:
    (a) involving weathered rock debris (except on volcanoes):
      (i) Hillslope debris flows
      (ii) Channelised debris flows; mud flows; mudrock flows
    (b) involving peat; bog flows, bog bursts
    (c) associated with volcanoes; lahars:
      (i) Hot lahars;
      (ii) Cold lahars
  5. Sturzstroms, extremely rapid flows of dry debris

F. TOPPLES
  1. Topples bounded by pre-existing discontinuities:
    (a) Single topples
    (b) Multiple topples
  2. Topples released by tension failure at rear of mass

G. FALLS
  1. Primary, involving fresh detachment of material; rock and soil falls
  2. Secondary, involving loose material, detached earlier; stone falls

H. COMPLEX SLOPE MOVEMENTS
  1. Cambering and valley bulging
  2. Block-type slope movements
  3. Abandoned clay cliffs
  4. Landslides breaking down into mudslides or flows at the toe:
    (a) Slump-earthflows
    (b) Multiple rotational quick-clay slides
    (c) Thaw slumps
  5. Slides caused by seepage erosion
  6. Multiple-tiered slides
  7. Multi-storied slides

Table 2.4b Classification system of slope movements by Hutchinson (1988).

II. GEOTECHNICAL CLASSIFICATION OF SLOPE MOVEMENTS BY SHEARING BASED ON SOIL FABRIC AND PORE-WATER PRESSURE CONDITIONS

A. **Soil Fabric** (*effects on* c', ϕ')

1. FIRST TIME SLIDES IN PREVIOUSLY UNSHEARED GROUND: soil fabric tends to be random (or partly orientated as a result of depositional history) and shear strength parameters are at peak or between peak and residual values.
2. SLIDES ON PRE-EXISTING SHEARS, associated with:
   (a) Re-activation of earlier landslides.
   (b) Initiation of landsliding on pre-existing shears produced by processes other than earlier landsliding, i.e.:
      (i) Tectonics
      (ii) Glaciotectonics
      (iii) Gelifluction of clays
      (iv) Other periglacial processes
      (v) Rebound
      (vi) Non-uniform swelling

In these cases the soil fabric at the slip surface is highly orientated in the slip direction, and the shear strength parameters are at, or about, residual value.

B. **Pore Water Pressure** (*conditions* on shear surface, effects on u)

1. SHORT TERM (undrained) – no equalisation of excess pore-water pressure set up by the changes in total stress.
2. INTERMEDIATE – partial equalisation of excess pore-water pressures. Delayed failures of cuttings in stiff clay are usually in this category.
3. LONG TERM (drained) – complete equalisation of excess pore-water pressures to steady seepage values.

Note that combinations of drainage conditions 1, 2, and 3 can occur at different times in the same landslide. A particularly dangerous type of slide is that in which long-term, steady seepage conditions (3) exist up to failure but during failure undrained conditions (1) apply, i.e. a drained/undrained failure.

Tables 2.5 and 2.6. These factors can alter the slope conditions at different rates, some over long timescales and others at a more rapid rate.

One of the main limitations associated with the factor of safety is that the result of an analysis may be sensitive to small changes in the assumed parameters (Nash, 1987) and so is prone to user error. Therefore, although any model is an idealisation of a given situation, a sensitivity analysis of the various factors which contribute to the factor of safety analysis is necessary to verify the choice of each parameter over which there is an uncertainty (Nash, 1987).

The Factor of Safety is relatively simple and straightforward to use, but it ignores the time factor, as the result gives no indication of likely rates of movement, or of possible deterioration of the slope material. This deterioration results in a reduction of F over time and may lead to progressive failure (Franklin, 1984). The alteration of a material from peak (maximum) to residual strength can occur after a notable shear strain or displacement for a material that is sensitive to structural breakdown (Mitchell, 1993). For example, Figures 2.4 and 2.5 illustrate a typical stress-strain curve and associated failure envelopes for this type of material.

2.2.4 Limit Equilibrium Analysis and Soil Strength

Quantitative stability analysis involves determining strength parameters and hydrological conditions within a slope and deciphering the likely shear surface (Crozier, 1986). This is usually carried out on a slope that has previously failed in order to determine which factors varied sufficiently to be responsible for converting the slope to an actively unstable condition. The importance of identifying a number of destabilising factors that could initiate movement as a result of more minor changes is highlighted, as the action of a single triggering factor may only partially explain slope instability.

Conventional methods of stability analysis are based on the concept of limit equilibrium (Chowdhury, 1978). Nash (1987, p 29), describes this as, "at the moment of failure, the shear strength is fully mobilised all the way along the failure surface, and the overall slope and each part of it are in static equilibrium." The concept of a failure surface, or slip surface along a discontinuity, is fundamental in limit equilibrium methods and can be considered as a hypothetical boundary separating two rigid bodies (Chowdhury, 1978). In reality, a single surface can be curved or linear, or failure may occur along a number of slip surfaces. As stability analysis considers a number of shear surfaces, the factor of safety for the slope is given by the value of F for the critical slope, identified as corresponding with the smallest calculated factor of safety (Nash, 1987). Each method of slope stability analysis is based on a different set of assumptions and is differentiated by the form of the shear zone, or failure surface within a slope. The three main types of this limit equilibrium analysis are: - the infinite slope analysis for planar failure surface; circular, rotational failure surface analysis; and a noncircular failure surface other than planar (Pearce and O'Loughlin, 1985).

There are many difficulties and limitations associated with applying stability analyses to natural slopes (Pearce and O'Loughlin, 1985):

- Degree of anisotrophy and heterogeneity of soil properties on natural slopes make estimation difficult,

Table 2.5 Factors which contribute to a high shear stress (Selby, 1993).

TYPES	MAJOR MECHANISMS	
Removal of lateral support	(i)	Stream, water, or glacial erosion
	(ii)	Subaerial weathering, wetting, drying, and frost action
	(iii)	Slope steepness increased by mass movements
	(iv)	Quarries and pits, and removal of toeslopes by human activity
Overloading	(i)	Weight of rain, snow, talus
	(ii)	Fills, waste piles, structures
Transitory stresses	(i)	Earthquakes – ground motion and tilt
	(ii)	Vibrations from human activity – blasting, traffic, machinery
Removal of underlying support	(i)	Undercutting by running water
	(ii)	Subaerial weathering, wetting, drying, and frost action
	(iii)	Subterranean erosion, squeezing out of underlying plastic soils
	(iv)	Mining activities, creation of lakes, reservoirs
Lateral pressure	(i)	Water in interstices
	(ii)	Freezing of water
	(iii)	Swelling by hydration of clay
	(iv)	Mobilisation of residual stresses
Increase of slope angle	(i)	Regional tectonic tilting
	(ii)	Volcanic processes

Table 2.6 Factors which contribute to a low shear strength (Selby, 1993).

Composition and texture	(i)	Weak materials such as volcanic tuff and sedimentary clays
	(ii)	Loosely packed materials
	(iii)	Smooth grain shape
	(iv)	Uniform grain sizes
Physio-chemical reactions	(i)	Cation (base) exchange
	(ii)	Hydration of clays
	(iii)	Drying of clays
	(iv)	Solution of cements
Effects of pore water	(i)	Buoyancy effects
	(ii)	Reduction of capillary tension
	(iii)	Viscous drag of moving water on soil grains, piping
Changes in structure	(i)	Spontaneous liquefaction
	(ii)	Progressive creep with re-orientation of clays
	(iii)	Reactivation of earlier shear planes
Vegetation	(i)	Removal of trees (a) reducing normal loads (b) removing apparent cohesion of tree roots (c) raising of water tables (d) increased soil cracking
Relict structures	(i)	Joints and other planes of weakness
	(ii)	Beds of plastic and impermeable soils

Figure 2.4 Stress-strain curve for peak and residual strength (Mitchell, 1993).

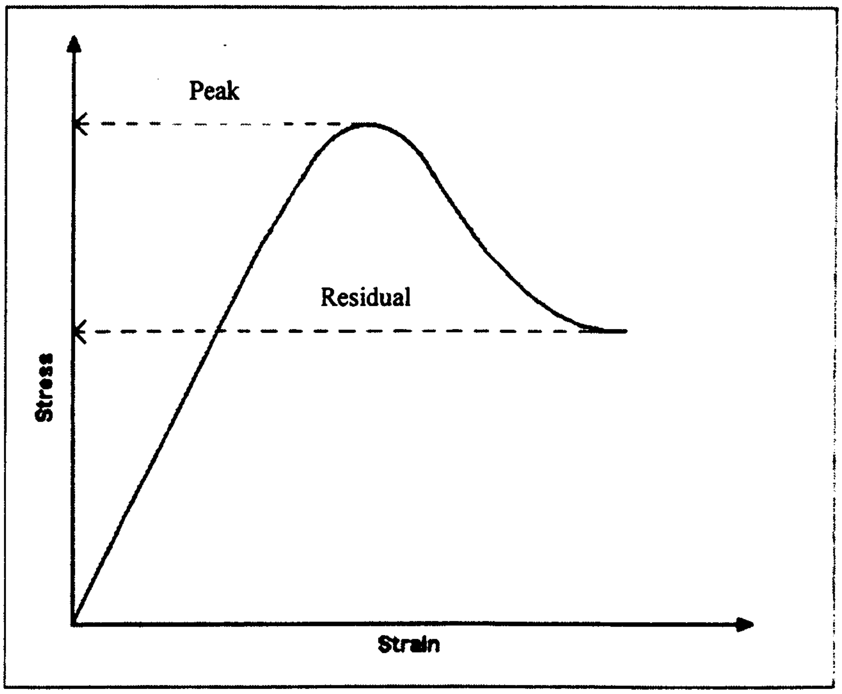
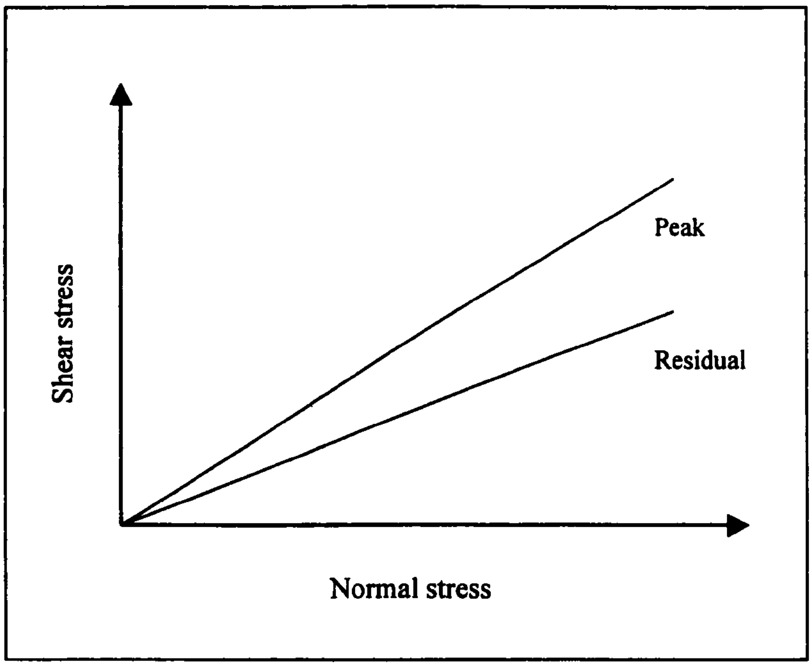


Figure 2.5 Failure envelope for peak and residual strength (Mitchell, 1993).



- Soil properties may also change progressively or seasonally,
- Under conditions of marginal stability, straining of soil materials (creep) theoretically causes the static limit equilibrium analysis to be an inappropriate technique,
- Detailed knowledge of the principal factors leading to failure is, in general lacking for natural slopes,
- Prediction and initiation of certain types of failure such as earthflows in which deformation takes place once failure has occurred is difficult,
- Natural slope stability is often closely influenced by the type and condition of the vegetation on the slope.

For peatlands, the most relevant problems are likely to be: - the high degree of anisotropy and heterogeneity in the peat properties; seasonal changes; straining of the slope forming materials during slow mass movement; fluctuations in pore water pressures; and the analysis of deformation once failure has occurred. Nevertheless, the theoretical representation of strength and stress in the application of a stability analysis is sound and can be used to explain how natural and human factors can either cause, or at least increase the risk of, failure (Crozier, 1986).

Components of Shear Strength

The shearing resistance of a soil depends upon many factors. Selby (1993) gives an incomplete equation as:

$$\tau_f = f\,(e, \phi, C, \sigma', H, T, \varepsilon, \varepsilon_r, S\ldots) \tag{2.3}$$

Where: τ_f = shearing resistance,
e = void ratio,
ϕ = frictional property of the material,
C = composition,
σ' = effective normal stress,
H = stress history,
T = temperature,
ε = strain,
ε_r = strain rate,
S = structure of the material.

Many of these factors are difficult to determine. However, the two most important parameters in providing strength are cohesion and internal friction, and these can be measured in conditions of controlled water contents, loads, and rates of loading (Selby, 1993). Cohesion (c) represents the inherent strength of a material which is present irrespective of any weight imposed onto the surface along which movement takes place, i.e. the amount of strength offered against shear stress, independent of normal stress (Crozier, 1986). Cohesion is derived mainly from bonding, particularly chemical bonding in which intermolecular forces are set up within mineral particles, but also from cementing materials and water within the soil (Selby, 1993).

The angle of internal friction (ϕ) indicates the extent to which 'friction' induced by weight of material acting directly at right angles to the shear plane (normal stress) contributes to shear strength (Crozier, 1986). The frictional resistance between mineral particles in contact represents the basic control on the strength of a soil (Selby, 1993) and therefore is related to the size of particles, their shape and orientation, resistance to crushing, and the number of contact points per unit volume. Overall, the amount of strength derived from internal friction is a function of the angle of internal friction and normal stress. Table 2.7 shows some typical values of unit weight, angle of internal friction and cohesion for some cohesionless and cohesive soils.

Gravitational load is a fundamental determinant of stability (Crozier, 1986) which contributes to resistance through internal friction and supplies a major distributing force by producing shear stress. It has two components. One acts parallel to the shear plane to constitute shear stress (τ). The other is normal stress (σ), which acts at right angles to the shear plane and contributes to frictional resistance. Figure 2.6 illustrates the variation in these components with changes in the angle of the shear plane (β).

Differences in pore water pressure (u) can either moderate normal stress or contribute to cohesion. Positive pressures occur when groundwater builds up above a shear plane and they act to reduce normal stress calculated from total weight. Negative pore water pressures arise during unsaturated conditions and the tension exerted by attached water provides an increment of strength (Crozier, 1986). The role of pore water pressures in stability calculations is expressed in terms of effective stresses.

The importance of cohesion and friction in determining the resistance to failure or shear strength (S) of a material is usually given by the Mohr-Coulomb equation, expressed as:

$$\mathbf{S = c' + (\sigma - u) \tan\phi'} \tag{2.4}$$

Where:-

c' = cohesion, with respect to effective normal stress.

σ = total normal stress.

u = pore water pressure.

ϕ' = angle of internal friction (shearing resistance), with respect to effective normal stress.

Therefore, the factor of safety (F) of the slope is calculated by:

$$\mathbf{F = \frac{c' + (\sigma - u) \tan\phi'}{\tau}}$$

(Crozier, 1986) (2.5)

Where:

τ = shear stress

2.2.5 Measuring the Shear Strength of Soil

It is necessary to have an accurate measurement of the shear strength of a soil to assess the present or past stability, or to predict future instability conditions (Petley, 1984) by performing limit equilibrium analysis of a slope. Tests to determine the strength characteristics of the soil involve simulating the magnitude of loads, loading rates and drainage conditions which occur as a slope fails (Selby, 1993). Selby (1993, p 50) highlights the importance of standard procedures and the correct choice of testing method by stating: "strength is not an absolute concept; measurements under compression, tension, and shear give different indications of strength, as do measurements made in the field compared to those made in the laboratory." He continues by suggesting that

Table 2.7 Published soil property values (after Selby, 1993).

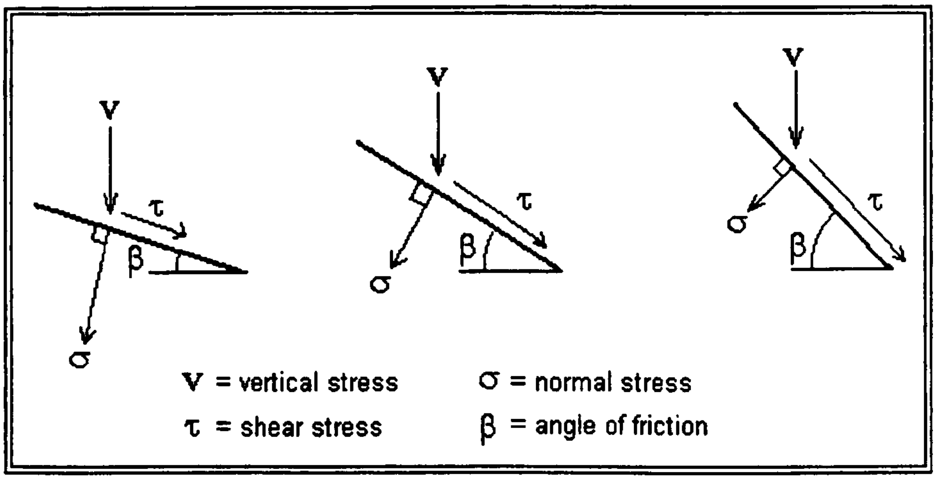
TYPE AND MATERIAL	UNIT WEIGHT (SATURATED/DRY) (kN/m^3)	ANGLE OF INTERNAL FRICTION (degrees)	COHESION (kPa)
COHESIONLESS			
Sand			
Loose sand, uniform grain size	19/14	28-34	
Dense sand, uniform grain size	21/17	32-40	
Loose sand, mixed grain size	20/16	34-40	
Dense sand, uniform grain size	21/18	38-46	
Gravel			
Gravel, uniform grain size	22/20	34-37	
Sand and gravel, mixed sand and gravel	19/17	48-45	
COHESIVE			
Clay			
Soft bentonite	13/6	7-13	10-20
Very soft organic clay	14/6	12-16	10-30
Soft, slightly organic clay	16/10	22-27	20-50
Soft glacial clay	17/12	27-32	30-70
Stiff glacial clay	20/17	30-32	70-150
Glacial clay, mixed grain size	23/20	32-35	150-250
Peat			
Raised bog peat[1]		27-32	2.4
Blanket bog peat[2]		36.6-43.5	5.5-6.1
Blanket bog peat[3]		34	4
(Basal) blanket bog peat[4]		13	8.7

[1] Landva and La Rochelle (1983) [2] Hanrahan *et al.* (1967)

[3] Hollingshead and Raymond (1972) (cited in Landva and La Rochelle, 1983)

[4] Carling (1986)

Figure 2.6 Variation in shear stress and normal stress with changes in angle of shear plane (Crozier, 1986).



"strength values can be as much a function of measurement process as a property of the material". Various field situations and suggested test parameters given by Selby (1993) are shown in Table 2.8.

Laboratory methods for determining shear strength aim to provide values applicable to the field situation. These methods can be divided into two types depending on whether changes in pore pressures are prevented (undrained) or permitted (drained). During laboratory tests, it is important that stress levels, moisture contents and the orientation of specimen are as close as possible to conditions occurring in the field. This is to ensure that the most representative and consistent test results can be obtained. The main problems concerned with laboratory testing are the difficulties associated with the extraction of reliable samples. Selby (1993) gives the four main areas of error involved in laboratory testing of repeat samples as:

- Selection of a representative sample for the whole body of material;
- Methods of specimen collection, which may affect the strength of the material;
- Storage of the specimen, which may affect moisture content and volume, and permit chemical and/or biological activity within it;
- Testing of the sample, which can be carried out at different levels of confining pressure, rate of stress application, uniformity of stress across the specimen, moisture content, and degree of control of drainage.

Another problem associated with the requirement for intact samples is that the samples are normally extracted from soil pits. This is an intrusive sampling technique, which causes general disruption to the area under investigation. Details of the various types of equipment that can be used in the laboratory determination of shear strength (direct, ring and triaxial apparatus) are given in Appendix 2.

In situ field tests are usually carried out when conventional sampling and laboratory testing procedures are unlikely to yield satisfactory results (Petley, 1984), either because of the degree of disturbance during sampling, or variable ground conditions. Field methods are most popularly used by engineers either to gain an initial assessment of ground conditions, or to analyse end-of-construction stability of slopes. These can be crude techniques (Petley, 1984) but considering the sensitive nature of some soils, extraction of samples for laboratory analysis may be inappropriate and so field techniques may be more suitable. In cohesionless soils the standard penetration test is commonly used, whereas a field shear vane and *in situ* shear box can be used for determining the total stress of undrained cohesive soils. With the exception of the latter (i.e. the *in situ* shear box), most field methods for indicating material shear strength are non-intrusive in that they do not require the use of a soil pit. The various field methods for determining the shear strength of a soil are also described in Appendix 2.

2.2.6 Shallow Mass Failure: The Infinite Slope Model

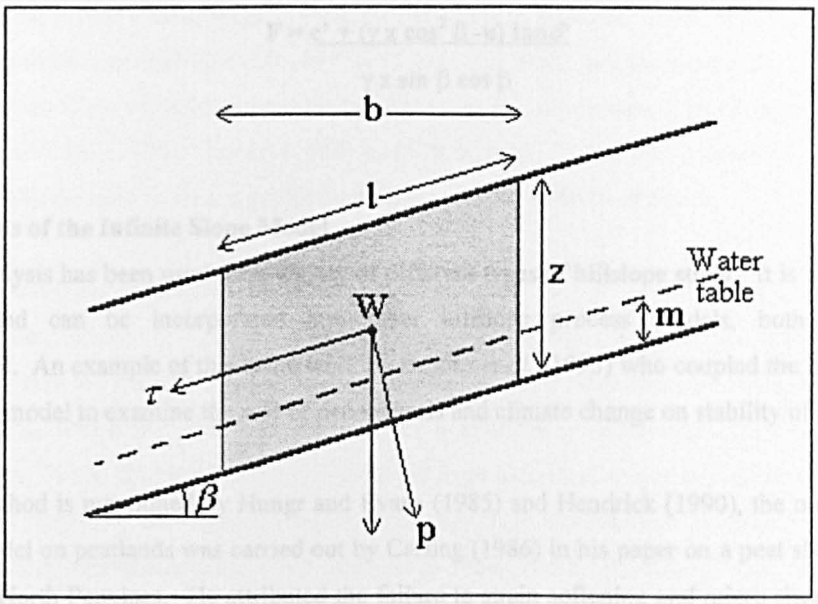
Translational slides are usually analysed using the infinite slope model (Skempton and DeLory, 1957). This is a two dimensional analysis of a cross section of a landslide, on the sides of which the forces are considered as being equal and opposite in both direction and magnitude (Selby, 1993). Two of the main assumptions of the infinite slope model are that the slope material is of uniform thickness and rests on a potential failure plane of constant angle and infinite extent (Skempton and DeLory, 1957). This is illustrated in Figure 2.7.

Table 2.8 Suggested shear strength tests for given field situations (Selby, 1993).

PROBLEM	PARAMETER	SHEAR STRENGTH TEST
Shallow translational landslide formed in prolonged wet season.	c'_p ϕ'_p	Consolidated undrained laboratory test, or field shear box test in saturated conditions.
Shallow translational landslide formed in dry season rainstorm.	c'_p ϕ'_p	Consolidated undrained laboratory test, or field shear box test at natural moisture content.
Long-term stability of clay slope subject to gradual toe removal, progressive failure, or first time failure in fissured clays.	c'_r ϕ'_r	Drained test, but for fissured over-consolidated clays $c'_r = 0$ and ϕ'_r parameters are appropriate.
Long-term creep of clay slope or slow mud flow.	c'_r ϕ'_r	Ring shear test.
Failure of slope in sand.	c_d ϕ_d	Drained test.

($_p$ = peak, $_r$ = residual, $_d$ = drained)

Figure 2.7 The Infinite Slope Model (Selby, 1993)



Where:-

W = Weight
β = Angle of shear plane
l = Length of slice
b = Length along specified axis
p = Normal stress
τ = Shear stress
m = Height of water table above shear plane
z = Depth of material

and

γ = Unit weight of material
γ_w = Unit weight of water
ϕ = Angle of internal friction
c = Cohesion

Using the components of geometry and characteristics of the soil mass, total normal stress (σ) and shear stress (τ) can be measured:

$$\sigma = \gamma z \cos^2 \beta \tag{2.6}$$

$$\tau = \gamma z \sin \beta \cos \beta \tag{2.7}$$

Therefore, the calculation of the factor of safety is:

$$F = \frac{c' + (\gamma z \cos^2 \beta - u) \tan \phi'}{\gamma z \sin \beta \cos \beta} \tag{2.8}$$

2.2.7 Applications of the Infinite Slope Model

Infinite slope analysis has been used for a variety of different types of hillslope study. It is inherently simple in its formation and can be incorporated into other hillslope process models, both hydrological and geomorphological. An example of this is the work by Brooks *et al.* (1993) who coupled the infinite slope model to a hydrological model to examine the role of pedogenesis and climate change on stability of slopes in Scotland.

Although the method is mentioned by Hungr and Evans (1985) and Hendrick (1990), the only other use of the infinite slope model on peatlands was carried out by Carling (1986) in his paper on a peat slide in Teesdale and Weardale in the North Pennines. He attributed the failure to strain softening and micro shearing of underlying clays. Laboratory analysis of the basal peat and the underlying clay included consolidated drained direct shear tests, and although analysis of the peat was erratic and produced an unsteady shear failure owing to its fibrous nature, satisfactory results were obtained (Table 2.7). Critical state stability curves for the clay with various overlying depths of peat were also calculated.

2.2.8 Hillslope Failure and Hydrology

Hydrological triggering, or more specifically triggering by rainfall, is commonly regarded as one of the principal initiation mechanisms of natural hillslope failure (Terlien, 1998). Consequently, many studies have investigated the relationship between hillslope failure and rainfall patterns (e.g. Garland and Olivier, 1993; Larson and Simon, 1993; Brooks and Richards, 1994), specific storm events (Dowdeswell *et al.*, 1988; Codebo *et al.*, 2000), or adverse groundwater conditions (Anderson and Kneale, 1980). Water infiltration and percolation from rainfall can result in increased pore water pressure along a potential slip surface decreasing the effective stress and reducing the shear strength, thereby reducing slope stability (Ng and Shi, 1998).

Prediction of hillslope failure triggered by rainfall is usually based on empirical methods that involve the recognition of landslide-prone areas and the identification of critical thresholds of rainfall intensity and duration (Iverson, 2000). For example, this method has been used on slope failures in South Africa (Garland and Olivier, 1993), Scotland (Brazier and Ballantyne, 1989; Brooks and Richards, 1994), Hong Kong (Finlay *et al.*, 1997), Italy (Pasuto and Sinvano, 1998), and New Zealand (Crozier, 1999; Glade *et al.*, 2000). Theoretical methods involve the development of models to predict the susceptibility of slope failure to variations in topographic, geologic and hydrological variables (Iverson, 2000). This is usually carried out using infinite slope analysis, relating the potential of slope failure to groundwater pressures. Ng and Shi (1998) used this method to investigate the stability of slopes in Hong Kong.

Brooks and Richards (1994) provide evidence which suggests that rainstorms of different synoptic origin produce varying hydrological responses because of the associated event characteristics: anticyclonic storms with high intensity rainfall promote large, rapid responses in F at shallow depths; and cyclonic storms with prolonged low intensity rainfall produce more gradual responses at depth as rainwater has time to infiltrate and percolate. Larson and Simon (1993) studied landslides in Puerto Rico and found that short duration, high intensity rainfall triggered shallow soil slips, while long duration, low intensity rainfall produced larger, deeper debris avalanches and slumps. Ng and Shi (1998), Crozier (1999) and Glade *et al.* (2000) also considered antecedent moisture conditions and storm duration to have a profound influence on the stability of slopes.

2.2.9 Causes of Instability in Peatlands.

Various destabilising factors may affect the balance between the shear strength and shear stress acting on a slope. These may take the form of a preparatory factor, in which the slope becomes susceptible to movement, a triggering factor, in which movement is initiated, or a controlling factor which dictates the condition of movement (Crozier, 1986). Table 2.9 has been compiled from individual accounts and shows factors considered to be important in explaining the occurrence of bog failures. The importance of an intense rainfall event as the main triggering factor in peat failures is clear from the available literature, although many factors contribute to preparing the slope, or converting it to an actively unstable condition.

Hulme and Blyth (1985), Carling (1986), Gilman and Newson (1980) and Wilson and Hegarty (1993) suggested that climatic preparation of the peat slopes is considered to be an important factor in contributing to instability. Failures are attributed to both high antecedent rainfall conditions and periods of drought followed by a high intensity rainfall event. Extreme wet conditions prior to peat failures have the effect of increasing the pore water pressures within the peat, and therefore can lead to reduced shear strength. On the other hand, droughts are important because irreversible changes occur in the peat when it dries out, resulting in the death of the surface vegetation. Dry periods also cause alterations to the hydrological regime of the slope as the water table drops and water flow is then focused in the lower, more humified catotelm. Periods of drought are also responsible for the formation of desiccation cracks on the surface of the peat, and with the onset of heavy rain there is a rapid transfer of water to either the base of the peat or within the peat layer resulting in an increased shear stress. The lateral pressure of water held within the cracks and the loading of the slope by the additional water may also contribute to the loss of strength of the peat and possible failure.

Changes in the hydrological regime of the slope are reported to be an important aspect of instability resulting from impeded drainage (Hendrick, 1990), a break of slope (Alexander *et al.*, 1986, Bishopp and Mitchell, 1946), the presence of an impermeable layer within the peat (Delap and Mitchell, 1939), or a difference in degree of humification (Wilson and Hegarty, 1993). The role of natural piping within the peat and underlying material has

Table 2.9 Factors considered to be important (✓) in explaining the occurrence of bog failures.

REFERENCE	DESCRIPTION			FACTORS CONSIDERED IMPORTANT							
	Season	Type	Slope	DD	PP	PCS	HA	LA	MS	PWP	Others
Acreman (1991)	Summer	PS			✓			✓	✓	✓	Cracks
Alexander *et al.* (1985)	Spring	BF	CX			✓	✓		✓	✓	Tines
Alexander *et al.* (1986)	Autumn	BF	CV					✓	✓		Cracks
Bailey (1879)[1]	Autumn	BF					✓				Steep slope
Barkly (1887)[1]	Summer	BF									Steep slope
Bishopp & Mitchell (1946)	Winter	BS	CX				✓				Snow melt
Bowes (1960)	Autumn	BS	CX					✓	✓		Cracks, Loch seepage
Camden (1722)	Summer	BF									Springs
Carling (1986)	Summer	PS	CX	✓	✓			✓	✓	✓	Cracks
Colhoun (1966)	Winter	BS					✓				
Colhoun *et al.* (1965)	Autumn	BF	CX	✓			✓				
Coxon *et al.* (1989)	Summer	PS	CX					✓	✓		
Crisp *et al.* (1964)	Summer	PS	CX				✓		✓		
Delap *et al.* (1932)	Winter	BF	CX					✓			Lake seepage
Delap & Mitchell (1939)	Summer	BS	CV			✓	✓				Stream undercutting
Dykes & Kirk (2000, 2001)	Autumn	PS		✓	✓				✓	✓	
Gambles (1995)	Autumn	BF		✓		✓	✓				
Gilpin (1808)	Autumn	BF				✓	✓				
Griffith (1821)	Summer	BF				✓		✓			
Hemmingway & Sledge (1946)	Summer	BF	CX							✓	Sudden, heavy rain.
Hendrick (1990)	Summer	BF	CV	✓			✓			✓	
Hungr & Evans (1985)	Spring	BF								✓	Undrained loading
Kinahan (1897)		BF				✓		✓			Cracks
Large (1991)	Summer	PS	CX		✓		✓		✓		
Mitchell (1935)	Autumn	BF	ESC	✓			✓				
Mitchell (1938)	Winter	BS	CX								Cracks
Proctor (1998)	Winter	BF				✓	✓				
Selkirk (1996)	Winter, Spring, Summer	PS					✓		✓		Seismic activity, flushes, cracks
Sollas *et al.* (1897)	Winter	BF	CX			✓	✓				Flush
Thorn (1985)	Autumn	BF	ESC				✓		✓		
Tomlinson (1981)	Autumn	BF		✓			✓				
Tomlinson & Gardiner (1982)	Summer	PS	CV	✓			✓		✓		
Walker & Gunn (1993)	Summer	BF									
Warburton & Higgitt (1998)	Winter	PS	CX	✓					✓		Flush, Cracks
Wilson & Hegarty (1993)	Autumn	BS		✓				✓		✓	Cracks

PS	Peat slide	PP	Peat pipe (or pipe in clay)
BS	Bog slide	PCS	Peat cut scarp
BF	Bog flow	HA	High antecedent rainfall
CX	Convex	LA	Low antecedent rainfall
CV	Concave	MS	Mineral substrate characteristics
ESC	Escarpment	PWP	Pore-water pressures
DD	Drainage or boundary ditches		

been highlighted by Carling (1986) and Dykes and Kirk (2001), while Gilman and Newson (1980) add that pipes may provide 'perforations' along which the ground tears during failure, and therefore may promote instability.

There are many early reports of human induced bog failures at peat cut scarps (for example those reported by, Gilpin, 1808; Sollas *et al.*, 1897; Mitchell, 1935; Delap and Mitchell, 1939). As a result of it these, it became common practice for peat cutters not to cut sections across slopes as this would release the reservoir of peat mud from the lower layers of the bog (Feehan and O'Donovan, 1996). Alexander *et al.* (1985) have described the importance of machine cut tines within the peat to facilitate the transfer of rainwater to the clay rich drift underlying the peat. Evidence from deposited rafts with vertical cut sides suggest that once failure occurred, the removal of peat was facilitated by pre-cut nature of the bog. Drainage ditches have also been reported to contribute to slope failure in peatlands (Table 2.9). Both longitudinal and transverse ditches (in either pristine or degraded states) have been associated with the occurrence of peat slides (Tomlinson and Gardiner, 1982; Carling, 1986; Dykes and Kirk, 2001) and bog slides (Wilson and Hegarty, 1993).

The most commonly reported external factor causing an increase in the shear stress of peat on a slope is a change in slope geometry as peat accumulation and transformation continues (e.g. Mitchell, 1935; Bishopp and Mitchell, 1946). This has the effect of loading the slope and changing the hydrological regime with respect to pore water pressures. Channel undercutting also has the effect of changing the overall height of the slope. Internal factors of particular relevance in decreasing the shear strength of the peat slope are the breakdown in fibrosity of the peat during the humification process, and the variation in vegetation making up the acrotelm 'crust' of the bog. The progressive failure of the slope in the form of longer-term mass movement by creep may also slowly alter the resistance of the slope, as has been discussed by Carling (1986) in relation to the presence of tension cracks within peat slopes. The significance of processes such as liquefaction and fluidisation of the basal catotelm are unclear, but their role is associated with decreasing the shear strength of the material.

2.3 SUMMARY

1. There is a considerable volume of literature concerning the distribution and causes of general blanket bog erosion, particularly with respect to the English Pennines.
2. Studies of the physical and geotechnical properties of peat are almost exclusively from raised bogs.
3. Peatland erosion is usually quantified using sedimentation of streams and reservoirs, peat surface sediment traps and erosion pins on banks. The role of rapid mass movement events in the evolution of peatlands tends to be largely ignored.
4. There is much literature concerning general slope stability research. The difficulties and limitations associated with applying stability analyses to natural slopes are also well documented.
5. There are many descriptive accounts of slope failure in peatlands, mainly occurring in Ireland. Many destabilising factors have been considered important in the initiation, preparing and controlling of these failures.

6. With the exception of the study of a peat slide on Cuilcagh Mountain (Dykes and Kirk, 2001), only one other complete slope stability analysis has previously been carried out on a bog failure, also a translational peat slide (Carling, 1986). To date there has been no thorough slope stability analysis carried out on a bog flow type failure.

CHAPTER 3

FIELD METHODS AND RESULTS

3.0 INTRODUCTION

One of the main aims of this thesis was "To assess the importance of hillslope failure involving peat with respect to the development of an area of upland blanket bog". In this chapter, the field investigations are described and results from them presented. The failures are then placed in their geomorphological and hydrological context by the study of their distribution, characteristics and hydrology. Detailed site investigations encompass a range of conditions on the blanket bog: (i) an area of 'pristine' peatland, i.e. without apparent slope movement or drainage, (ii) a site with slope movement but no failure, and (iii) two sites disrupted by failure events. The latter two sites are used to assess the degree of drainage and associated alterations of the strength characteristics of the peat as a result of failure.

3.1 FIELD EVIDENCE OF SLOPE INSTABILITY

3.1.1 Introduction

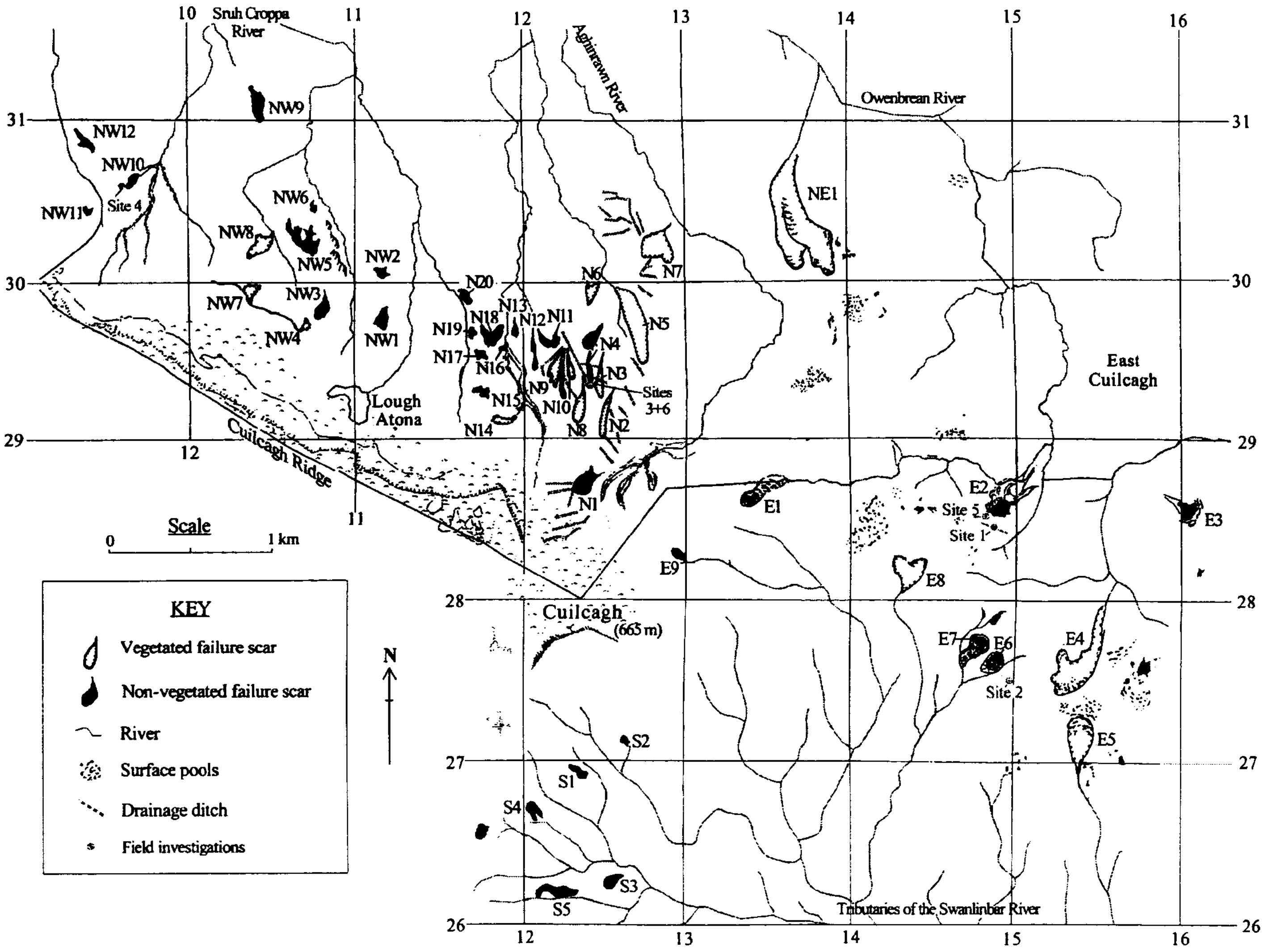
The middle slopes of Cuilcagh Mountain to the north and east of the summit comprise approximately 24 km^2 of blanket bog. Many failures are evident on the bog surface. The identification of these shallow translational failures is aided by the fact that they usually contain all, or most of the standard landslide features (Dikau *et al.*, 1996), such as: - crown; eroded scar area; scarp or headwall; body; flow track(s); and a depositional foot. The characteristics of these components are described below with examples of various failure events on the mountain. The appearances of these differ according to the age and degree of recovery of the failure and the type of failure.

3.1.2 Distribution and Variety of Blanket Bog Failures

A total of 47 individual failures have been identified on the middle slopes of Cuilcagh Mountain by use of aerial photography and field investigations (Figure 3.1). The various components of these failures, together with their slope hydrological characteristics have been studied and mapped using aerial photographs (approximately 1:10,000 scale) and a stereoscope. Sets of aerial photographs for the years 1981, 1989, 1991 and 1995 have been used to assess the changes that have occurred on the bog over this period.

Three main areas of slope failure involving peat can be identified on the slopes of Cuilcagh Mountain. The majority of failures (33) are situated north and north-west of the summit on the blanket bog between 340 and 500 metres OD. These failures drain into tributaries of the Sruh Croppa and Aghinrawn Rivers and have been named N1 to N20 and NW1 to NW12 (Figure 3.1). Flow failures including four recent failures (post 1985) are situated to the east of Cuilcagh at 350 m OD, two flowing north into the Owenbrean River, and the other two draining into tributaries of the Swanlinbar River from the east and south. The East Cuilcagh failures have been named E1 to E9. Five other failures are directed towards another tributary of the Swanlinbar River and

Figure 3.1 The distribution of blanket bog failures on Cuilcagh Mountain.



are situated immediately south of the summit at 450 m OD (S1 to S5). Table 3.1 summarises the type, location and age of all of the failures identified on Cuilcagh Mountain (as shown in Figure 3.1). On some of the vegetated failure scars on the northern slopes, it is difficult to distinguish between failure type (i.e. bog flow or peat slide). Also, two more recent failures (N1 and NW5) share similar characteristics to both types of failure and are thought to be transitional 'bog slide' failures. The failure planes in these cases are thought to be at the base of the peat layer immediately above the underlying clay. However, as a result of weathering of the scars and subsidence and drainage around the margins of these features since they occurred, the exact failure mechanism is difficult to determine. Given the general distribution of bog flows and peat slides, however, it seems probable that different areas and slopes of the mountain are prone to different types of slope failure. For example, on East Cuilcagh, all of the failures are bog flows situated around the 350 m contour line; whereas peat slides are more prevalent on the northern and southern slopes close to the 450 m contour line.

3.1.3 Case Studies of recent failures on North and north-west Cuilcagh

1998 Multiple Peat Slide, North Cuilcagh (N4)

A multiple peat slide occurred on a northern slope of Cuilcagh Mountain in late October 1998 and is described in detail by Dykes and Kirk, (2000, 2001). The event affected an area of 30,500 m^2, and comprised two distinct failures: an initial upper failure and subsequent failure of a lower section of slope. The morphological features, scale and profile of this slope are illustrated in Figure 3.2. The initial upper failure occurred on a slope of 7°, upslope of a degraded transverse drainage ditch. Peat depth around the scar was fairly constant at 70 cm, with local variations of up to $\pm$ 20 cm. This was underlain by a layer of pale clay that appeared to rest on a surface of darker coloured sandy clay. The failure surface was located at 110 to 120 cm below the original ground surface. Plate 3.1 shows the initial failure scar, which consists of a striated dark clay surface with a few sandstone clasts over which the peat mass had moved. Few rafts of peat remain on the surface, the headwall remains almost vertical and a few tension cracks are present parallel to the scarp. Rafts from the initial failure scar rode up onto *in situ* peat at the lower drainage ditch and slid up to 320 m down slope as the dominant grass vegetation provided an extremely low frictional surface. This left a large area of flattened vegetation (illustrated on Figure 3.2 and Plate 3.2) which has subsequently completely recovered. Although the lower failure is similar in nature to the upper scar, a deep erosion track (over 2.1m) has been excavated and more large rafts are present on its surface and towards the foot of the scar. The transported peat and eroded clay from the failure scars and flow tracks seems to have remained within the clearly defined depositional area (Figure 3.2), with no notable volumes being transported further by the stream at the foot of the slope.

The morphological evidence suggests a distinct sequence of events beginning with the failure of a segment of slope situated upslope of a degraded transverse ditch. It has been suggested that the failure zone in this case was located at or near the base of the pale clay layer immediately underlying the peat (Dykes and Kirk, 2000). This is based on evidence pertaining to the presence of various subsurface pipes within this clay layer, strength characteristics of the clay and peat, and subsequent slope stability analysis (Dykes and Kirk, 2001). Rapid

Table 3.1 Data for the blanket bog failures identified on Cuilcagh Mountain.
(* Details given in Table 3.2)

Failure Name	Grid Reference	Failure Type	Date
S1	12352695	Peat slide	Pre-1989
S2	12702715	Peat slide	Pre-1989
S3	12552620	Peat slide	Pre-1989 (well vegetated)
S4	12052670	Peat slide	Pre-1989 (well vegetated)
S5	12202620	Peat slide	Pre-1989
E1	13452870	Bog flow	1997-98
E2*	14952860	Bog flow	1992
E3*	16052860	Bog flow	Pre-1981
E4	15302760	Bog flow	Pre-1989 (well vegetated)
E5	15352715	Bog flow	Pre-1989 (well vegetated)
E6*	14902770	Bog flow	1997-98
E7*	14752775	Bog flow	Pre-1989
E8	14302815	Bog flow	Pre-1981 (well vegetated)
E9	12952825	Bog flow	Pre-1981 (well vegetated)
NE1	13703025	Bog flow?	Pre-1981 (well vegetated)
N1*	12302880	Transitional failure?	1986
N2	12502915	Peat slide?	Pre-1981 (well vegetated)
N3	12502935	Peat slide	Pre-1981 (well vegetated)
N4*	12452950	Peat slide	1998
N5	12852985	?	Pre-1981 (well vegetated)
N6	12452995	Peat slide	Pre-1981 (well vegetated)
N7	12853025	?	Pre-1981 (well vegetated)
N8	12352915	Peat slide	Pre-1981 (well vegetated)
N9	12152945	Peat slide	Pre-1981
N10	12352945	Peat slide	Pre-1981
N11	12202975	Peat slide	1981-1989
N12	12052955	Peat slide?	1981-1989
N13	11952980	Peat slide	1981-1989
N14	11902910	?	Pre-1981 (well vegetated)
N15*	11802935	Peat slide	1981-1989
N16	11902965	Peat slide	1981-1989
N17	11752960	Peat slide	1981-1989
N18	11852975	Peat slide	Pre-1981, 1981-1989
N19*	11752975	Peat slide	Pre-1981, 1981-1989
N20	11752990	Peat slide	Pre-1981
NW1	11202980	Peat slide	Pre-1981 (well vegetated)
NW2	11203005	Peat slide	Pre-1981
NW3*	12802980	?	1981-1989
NW4	12752975	?	Pre-1981 (well vegetated)
NW5*	12753020	Transitional failure?	Pre-1981, 1981-1989
NW6*	12803050	Peat slide	1981-1989
NW7	12302995	?	Pre-1981 (well vegetated)
NW8	12403030	?	Pre-1981 (well vegetated)
NW9	12403110	Peat slide	1981-1989
NW10*	13753065	Peat slide	2000
NW11	13353045	Peat slide	Pre-1981
NW12	13353090	Peat slide	1981-1989

Figure 3.2 The 1998 multiple peat slide on north Cuilcagh (N4).

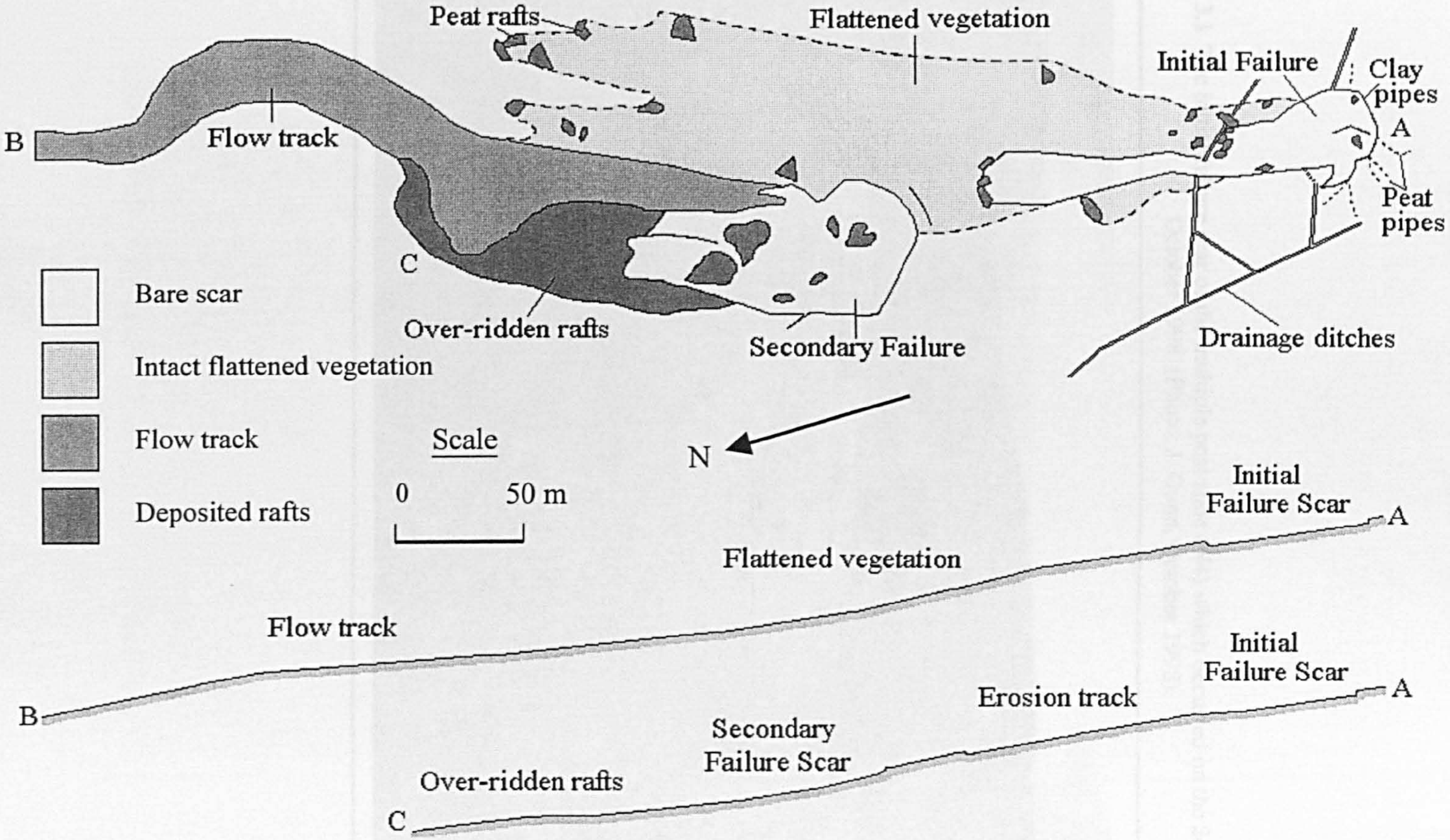


Plate 3.1 The initial failure scar of the multiple peat slide (N4) which occurred on the 24/25 October 1998. (Photo: J. Gunn, October 1998).

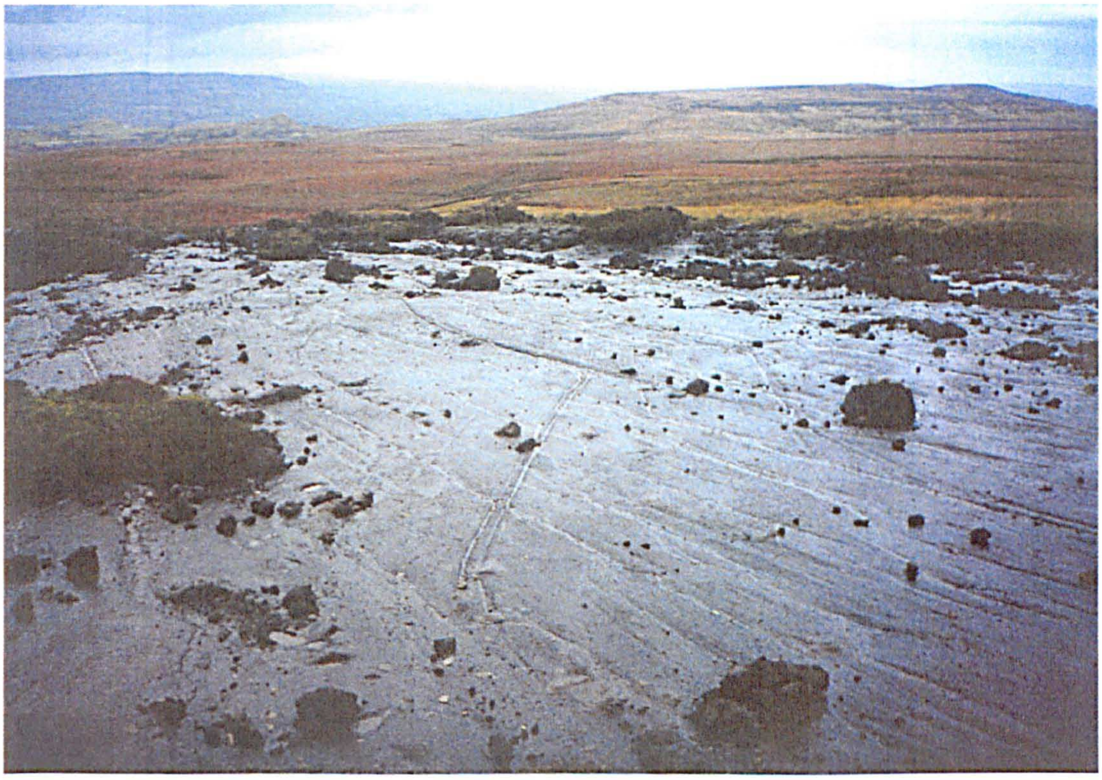


Plate 3.2 Vegetation flattened by the sliding of peat rafts from the initial failure scar of the multiple peat slide (N4), North Cuilcagh. (Photo: K.J.K., October 1998).

loading by sliding of peat from the upper failure and erosion track is thought to have led to undrained shear failure of clay beneath the peat further down the slope resulting in the deeply excavated channel. This in turn unloaded the toe of the steeper slope, which then failed to form the secondary failure scar.

2000 Peat Slide, north-west Cuilcagh (NW10)

The most recent failure on the mountain occurred during March 2000. This peat slide occurred on a north-west slope of Cuilcagh Mountain at an altitude of 380-390 m OD. The event affected an area of approximately 13,450 m^2, 4,625 m^2 of which was scar area. The failure was associated with high intensity rainfall event (48.6 mm falling over 24 hours on the 2nd March) after a relatively dry period. Figure 3.3 illustrates the morphological units of the peat slide. Like the 1998 multiple peat slide, the failure (or shear) zone was located in the clay underlying a shallow depth of peat (around 50 to 70 cm). A p.v.c. water supply pipe (approximately 12 cm in diameter) located towards the back of the scar ran transverse slope and was ruptured by the failure event. This was laid during the 1980's and is located approximately 40 cm from the surface within the peat. Evidence that the pipe failed from west to east was found as the join was located towards the western margin of the scar (Figure 3.3) and thrusting of the peat was noted on the east of the failure margin immediately upslope of the pipe. Local residents noticed a disruption to the water supply approximately two years previously and on investigation at that time discovered a slight movement had caused the water pipe to contort and rupture at the join. They also noted the presence of cracks within the peat upslope of the pipe (i.e. at the upper margin of the headscar).

3.1.4 Case Studies of recent failures on East Cuilcagh

1992 Bog Flow, East Cuilcagh (E2)

During August 1992, a major bog flow occurred on an eastern slope of Cuilcagh Mountain after a summer rainstorm event (57 mm of rainfall in 18 hours). The failure affected an area of 21,500m^2, of which 2,600m^2 was scar area (Figure 3.4) (Walker and Gunn, 1993). The post-failure scar was covered by a thin layer of peat suggesting that the failure zone was located within the peat mass. Plate 3.3 shows the bog flow five years after the failure. Over time, erosion of the scar by slope wash has resulted in the removal of fine clay material between the clasts to leave a pavement of sandstone blocks. Peat around the scar ranges from 1.2 to 1.5 m deep, reaching 2.1 m 20 m upslope of the headwall and is underlain by clay containing sandstone clasts. It is unclear whether this material is glacial till or *in situ* weathered debris.

Figure 3.4 shows a large area of subsided and cracked peat around the margin of the failure, particularly to the west. These features are unique to flow type failures in peat and can make up a large portion of the disrupted area. These were commonly referred to as 'floes' and 'crevasses' in previous studies (e.g. Sollas *et al.*, 1897; Delap *et al.*, 1932) and are differentiated from cracks found around the margins of many landslides that are formed by tearing apart of the soil. This type of subsided bog is associated with the release of highly humified peat at depth within the bog, with associated stretching and tearing of the upper acrotelm and vegetation.

Figure 3.3 The morphological units of a peat slide which occurred in March 2000 (NW10).

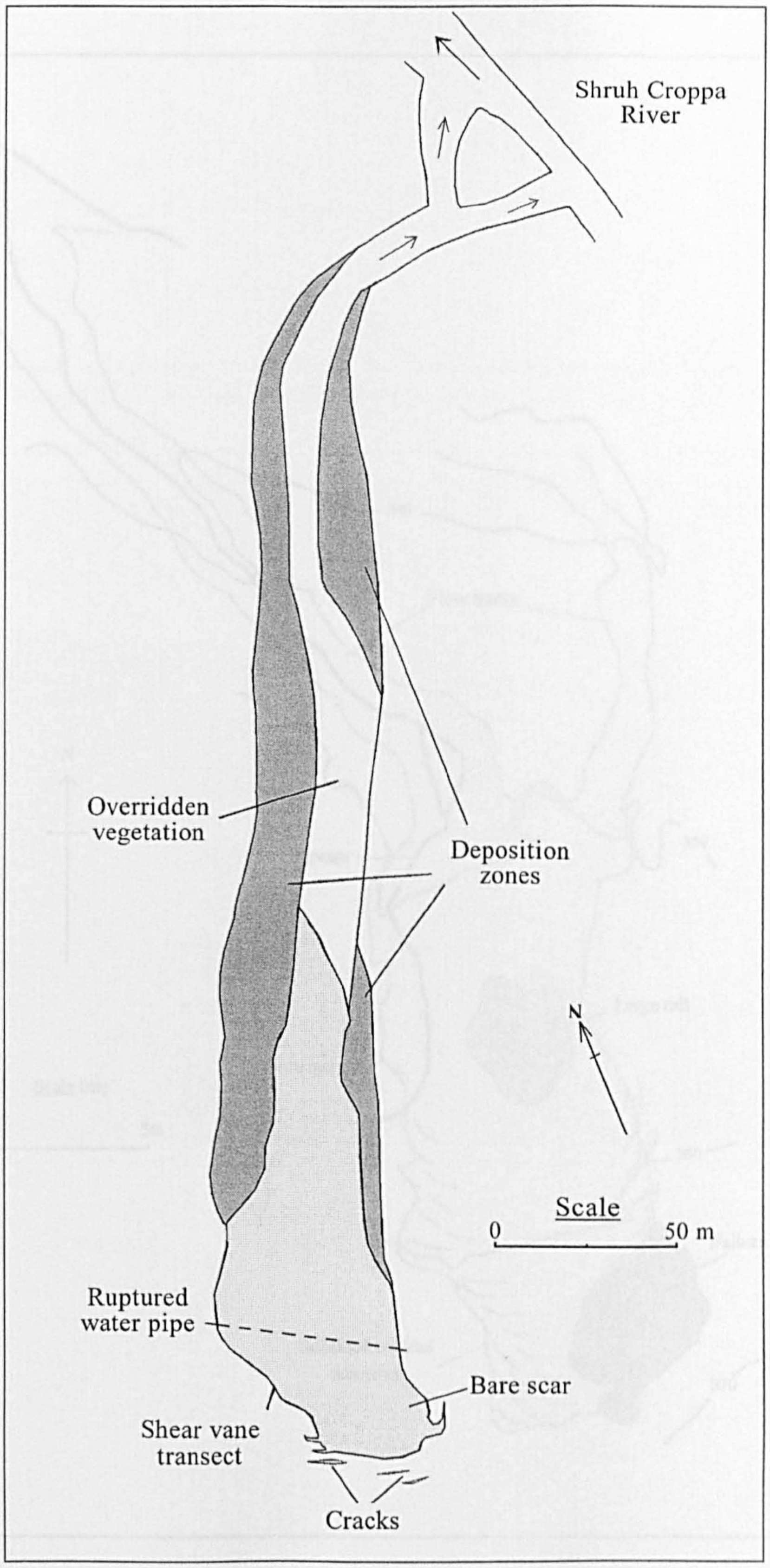


Figure 3.4 Morphological units of the 1992 bog flow on East Cuilcagh (E2)

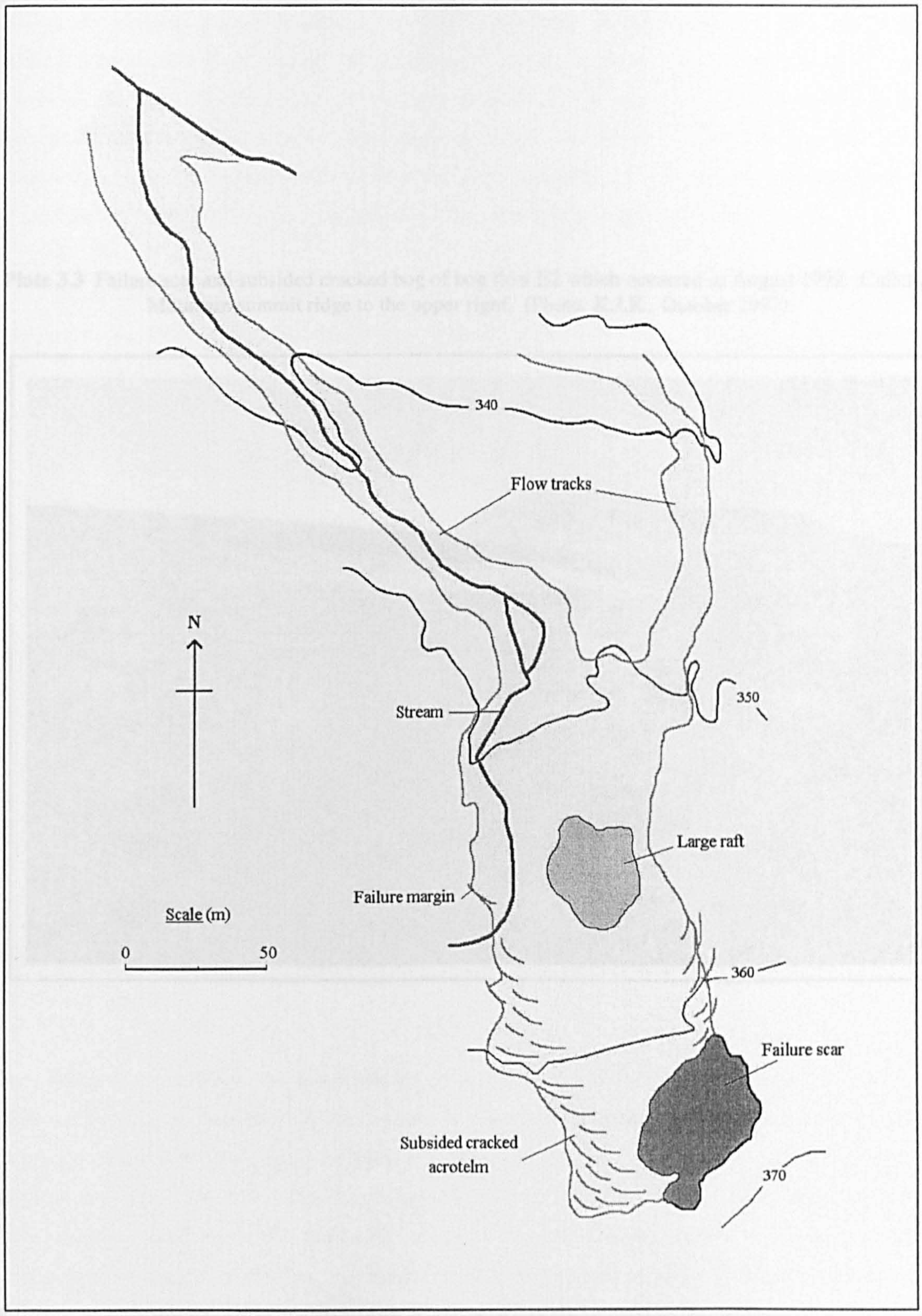


Plate 3.3 Failure scar and subsided cracked bog of bog flow E2 which occurred in August 1992. Cuilcagh Mountain summit ridge to the upper right. (Photo: K.J.K., October 1997).

The large depositional area at the foot of the scar consists of many rafts of intact peat separated by pools of peat slurry. In this case, two flow tracks entered and subsequently followed the course of the Owenbrean River and resulted in the deposition of liquid peat and rafts along the river corridor. This deposit of peat slurry was noted to re-vegetate relatively quickly (compared with the failure scar), although rafts from the event were still identifiable seven years later. Some 7.8 km downstream of the failure, the Owenbrean River sinks at Pollasumera. Here, the flood backed up at to a depth of 10 metres due to constrictions in the downstream cave system, which filled to the roof in places. Peak discharge 200 m downstream was estimated at 90-130 m^3/s and the transmission time for the flood pulse to reach the show cave system at Marble Arch (approximately 9 km from the failure scar) was estimated at approximately one hour (Walker and Gunn, 1993).

Other Failures on East Cuilcagh

Approximately one kilometre south of the 1992 bog flow lies an area of bog that contains several different forms of slope movement, including two flows and a slope with an apparent bulge in its middle section (discussed in Section 3.3.3). The most recent bog flow occurred during the winter of 1997-1998 (E6) and comprises one small scar (26 x 30 m) on a slope of 5.5° and a larger depositional area (1.5°) made up of crescentic shaped rafts separated by pools of peat slurry and water. It was noted that the majority of the rafts on the scar are elongated strips of acrotelm and upper catotelm that have been rotated through 90°. Plate 3.4 shows rafts torn from the headwall of the fresh flow (taken in February 1998). Towards the foot of the failure, the deposition of rafts is more chaotic as some have overridden one another in places. A well developed toe marks the downslope and eastern extent of the failure (Plate 3.5) formed by undercutting of the *in situ* peat by the failed rafts. Therefore, unlike the other flows and slides on the mountain, there is no evidence to suggest that the failure had caused a flood of water and peat. Peat around the scar ranges from 1.2 to 1.6 m deep, reaching 2.1 m in depth 20m upslope of the headwall. Plate 3.6 shows a tilted raft near the headwall of the scar. This raft (and others in the area) measured 0.9 m in thickness and so assuming a total peat depth of 2.1 metres prior to failure, indicates that 1.2 m of basal peat are absent. In the months following the failure, much of the exposed scar was covered with a shallow depth of 'sticky' peat, particularly around the headwall, and pools of peat slurry had dammed upslope of rafts at the downslope end of the scar. However, subsequent visits to the site have revealed erosion of the peat remaining on the scar and the formation of delta-like features as material washed from the scar has entered the pools of settled peat slurry.

A flow failure immediately to the east separated by a ridge just a few metres wide, occurred before 1989 (determined by aerial photographs). A small stream is located on its eastern flank. Although this failure only left a small bare scar area (27 x 36 m), it affected approximately 6,240 m^2, which is comprised almost entirely of transported large crescentic rafts. The failure appears relatively fresh on the 1989 aerial photographs with a well-defined flow track, suggesting the event occurred within the few years previous. Tension cracks are evident around the margins of the flow, particularly upslope of the headwall where drainage has led to damage to the cover of moss vegetation. Like other more recent flows on East Cuilcagh, the depth of peat 20 m upslope of the headwall was measured at 2.1 m. However, drainage and subsidence of the peat around the headwall has led to shrinkage of peat depth down to around 0.8 m. It is possible that bank collapse of the

Plate 3.4 Elongated rafts torn from the headwall of failure E6. (Photo: A.P. Dykes, February 1998).

Plate 3.5 A well defined toe which marks the downslope extent of failure E6 on East Cuilcagh. (Photo: A.P. Dykes, February 1998).

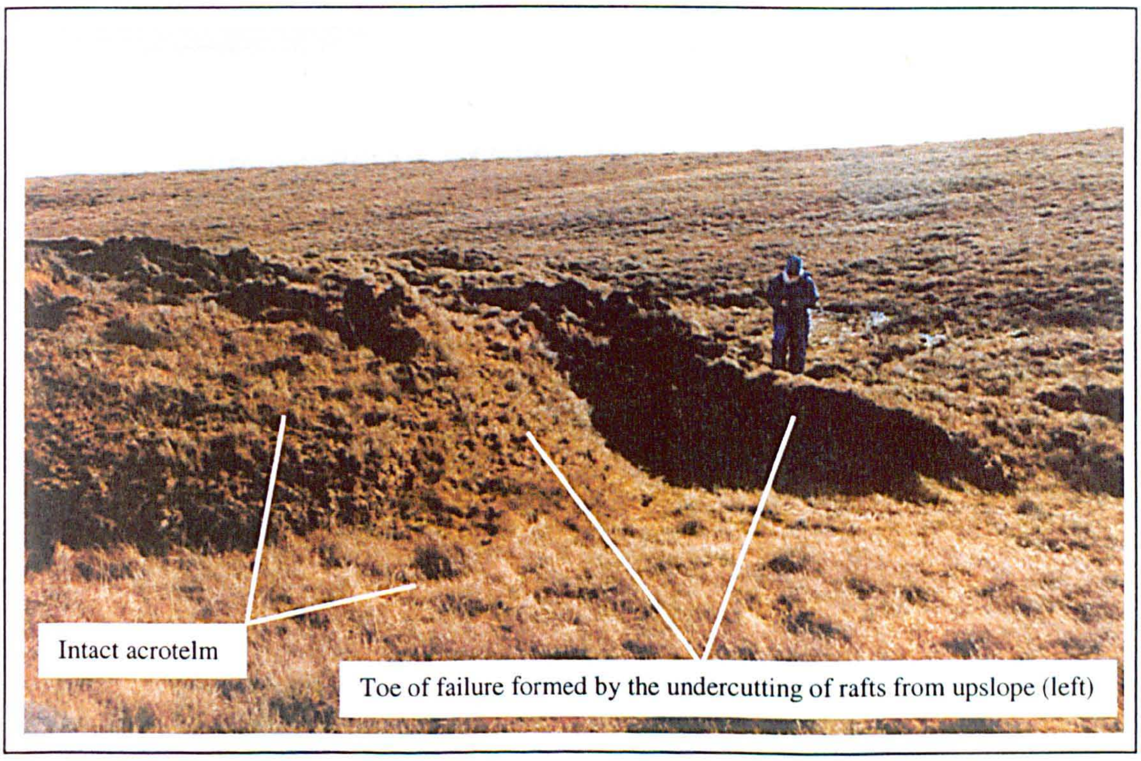


Plate 3.6 A tilted raft near the headwall of failure E6. (Photo: K.J.K., February 1998).

stream on the eastern flank of the slope initiated slope failure in much the same way as for the 1992 bog flow, either with a temporary block in drainage resulting in the formation of a dam, or by releasing the basal catotelm. It is evident that after the initial tearing and break-up of the over-riding acrotelm, the rafts were not transported far, whereas the catotelm seems to have flooded out altogether. This would have produced the distinctive dark coloured flow track that enters a tributary of the Swanlinbar River, as seen in the 1989 aerial photograph.

3.1.5 Older Failures on Cuilcagh Mountain

Plate 3.7 shows a section of the mountain north of the summit ridge. Clearly visible are the fresh scars of a multiple peat slide that occurred in 1998, a failure scar from an event in 1986, and also a much older failure scar. The headscar and flow track of this older failure remains identifiable, as there is a difference in vegetation covering the once bare scar. The dominant greener vegetation of *Sphagnum* mosses, grasses and reeds stands out from the surrounding brown, heather-based vegetation. Peat has accumulated to form a depth of 42 cm in the centre of the scar. The headwall is visible at surface level as a vegetated step, although it has degraded to a lower angle than on the fresh scars. A similar older re-vegetated failure is present on East Cuilcagh. However, as this was a flow type failure, a large portion of it is made up of re-vegetated subsided cracks. Fresh peat is beginning to accumulate due to *Sphagnum* re-colonisation, and has reached a depth of two cm in some areas of the headscar. Using estimated rates of peat accumulation (e.g. 6.5 to 16.5 cm in the last 150 years (Bowler and Bradshaw, 1985)), it is possible to estimate the relative age of older features, i.e. in the case of the latter, slope failure is likely to have occurred between 18 and 50 years BP. However, the date determined using these rates would give a lower age limit as there is a delay in the onset of peat accumulation by a period of erosion, particularly slope wash on the scar area. This is evident in more recent failures where re-colonisation of bare scar areas is occurring in small isolated clumps of vegetation.

As the cracks drain or re-vegetate, the rafts undergo an increase in the growth of heather (*Calluna vulgaris*) and diminution of *Sphagnum* mosses and grasses such as *Molinia* spp. Therefore, unlike the re-vegetation of scar areas, the deposited areas are recognisable, as they appear more brown in colour and darker than the surrounding bog vegetation. Praeger (1897, p. 202) visited the site of a bog flow failure in Co. Galway seven years after the event and found that "ridges and crevasses, hummocks of old surface and great lumps of old bog that had risen from below to fill the wider cracks, were all still evident".

The flow tracks that resulted from the failures differ according to the failure type and proximity to a watercourse. Flow (and transitional) type failures that involve the release of large quantities of liquid peat usually have a well-defined depositional track, with levees forming ridges along the high water mark of the flood. This is best shown in Plate 3.8, which depicts a vegetated flow track from a re-activated failure on North Cuilcagh (NW5). Flow tracks for peat slide failures are different in nature to those associated with bog flows, mainly due to the absence of peat slurry. Also, the peat moved in peat slide events is usually more coherent and forms large rafts which become deposited on, or near the scar area. Plate 3.9 shows a large area of flattened vegetation caused by the sliding of large rafts over the surface vegetation before coming to rest upon reaching

Plate 3.7 A section of North Cuilcagh showing the fresh multiple peat slide (N4), failure scar N1 and several re-vegetated scars including N2 and N3 (Photo: K.J.K., November 1998).

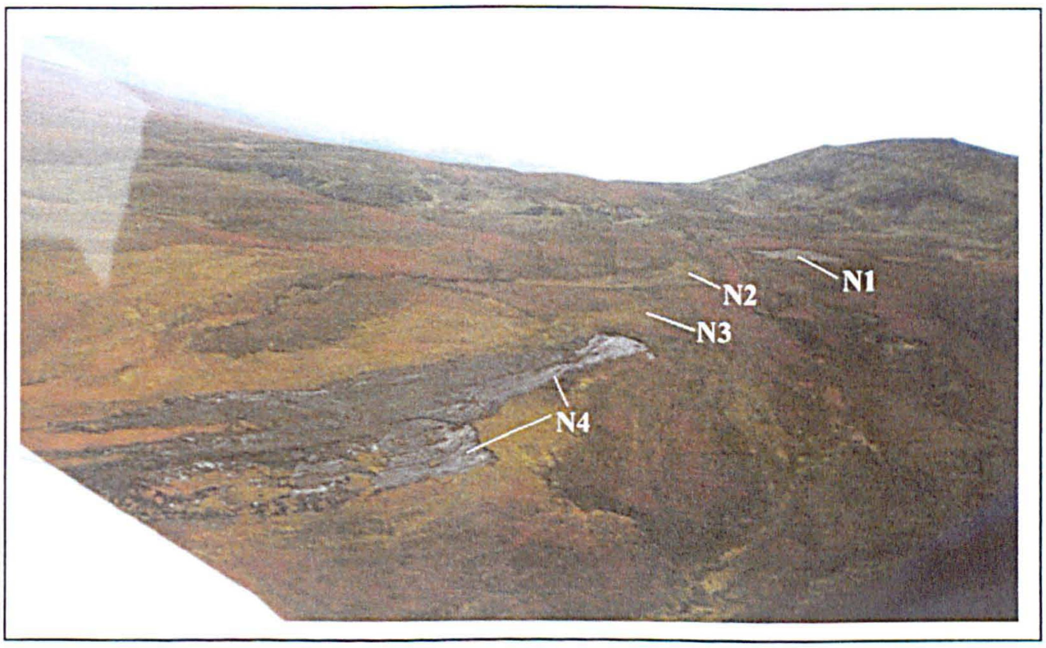


Plate 3.8 Flow track of failure NW5, with levees of deposited rafts (Photo: K.J.K., February 1998). (Approximate width of flow track = 12 m)

Plate 3.9 The extent of disruption caused by the multiple peat slide (N4). Photograph shows the vegetation flattened by the sliding rafts of peat and the secondary failure scar (to the right). (Photo: K.J.K., October 1998).

a shallower gradient. The water and sediment from this failure that occurred in late 1998 (N4) continued to flow into a tributary of the Aghinrawn River and together with the flood waters from the associated high rainfall event caused bank erosion and channel alterations further downstream.

3.1.6 Frequency of Occurrence

By comparing the various sets of aerial photographs and field investigations on the bog, it has been possible to examine the changes that have occurred since 1981. The relative ages of some of the older failures have been estimated by examining the degree of re-vegetation and general recovery of the failure scars and flow tracks. Recovering failures of various ages, together with recolonisation patterns have been described in only a few accounts of failure events (Praeger, 1897; Large, 1991; Alexander *et al.*, 1985; Selkirk, 1996). Figure 3.1 illustrates the abundance of failure scars identified within the study area, which suggests a relatively important role for mass movement of peat in the shaping of the blanket bog.

A total of 27 failures were identified on the 1981 aerial photographs, 18 of which are well vegetated suggesting they were at least 10 years old. Although some failures can be distinguished from scars caused by burning by studying their position on the slope and failure morphology (such as the presence of a degraded scarp and flow track), it is possible that older, more re-vegetated failures are now unidentifiable. The remaining 9 failures on the 1981 aerial photographs appeared relatively fresh and hence had probably occurred in the previous few years. Between 1981 and 1991, 18 individual failure events occurred, although only one or two of these are thought to have involved a flow mechanism. The majority of the others were the result of shallow failure of the underlying shaley clay on a relatively steep (10-18°) slope removing the entire depth of peat (only around 0.7 m). During the period 1991 to 2001, there were five main failures on the bog, three flows and two peat slides. The higher frequency of failure events during the 1980's compared with the 1990's may have been a result of disruption to the living vegetation and acrotelm. This accompanied increases in sheep stocking and periods of uncontrolled burning (see Section 1.5.2).

3.1.7 Magnitude of Failures

The magnitudes of bog failure events are highly variable. The scar areas alone range in size from 18 m by 27 m to 72 m by 135 m. Table 3.2 shows the volume of material removed from the scars of twelve major failures and Table 3.3 shows details of all failure events identified on Cuilcagh Mountain. Assuming an average peat depth of 2.0 m for the failures on East Cuilcagh and between 0.7 and 1.5 m on the northern and southern slopes (prior to drying out and subsidence), these have involved the movement of over 300,000 m^3 of peat from a total area of bog just under 200,000 m^2. Table 3.4 shows the magnitudes of failures within the given time periods. The well-vegetated scars on 1981 aerial photographs are relatively large in scale with an average area of 5,800 m^2 and volume of 9,600 m^3. The fresh pre-1981 failures and those occurring between 1981 and 1991 however, are smaller in scale with an average area around 2,500 m^2 and volume of less than 4,000 m^3. Between 1991 and 2001 there were fewer failures but these were larger in scale and are comparable to the pre-1981 vegetated failures. This is thought to be a reflection of the type of failure. On East Cuilcagh the four recent failures and older vegetated scars were bog flow events in which large areas of the bog are affected, although not all of it is

Table 3.2 Details of twelve major bog failures on Cuilcagh Mountain.

Failure	**Approximate dimensions of scar (m)**	**Present depth of peat and clay around scar (m)**	**Estimated depth at time of failure (m)**	**Estimated volume removed from scar (m^3)**	**Gradient (headscar towards toe)**	**Degree of re-vegetation**	**Date ***
E2	40 x 50	1.0-1.1	2.0	3,650**	7.5-2.5°	Very poor	1992
E3	54 x 54	0.8-0.9	2.0	5,832*	3.5-3.0°	Extensive	Pre-1900 (e)
E6	18 x 27	1.0-1.2	2.0	972*	5.5-1.5°	None	1997-98
E7	27 x 36	0.5-0.6	2.0	1,944*	4.5-5.0°	Poor	Pre-1989
N1	75 x 45	0.7-1.2	1.5	5,063*	7.0-6.0°	Poor	1986
N4	120 x 20 100 x 50	0.7-1.0	1.2	9,100**	7.0-17.0°	None	1998
N15	54 x 36	0.5-0.7	1.0	1,944*	7.0-8.0°	Poor	1981-89
N19	18 x 36	0.6-0.7	1.0	648*	9.0-16.0°	Moderate	1981-89
NW4	81 x 27	0.7-1.0	1.5	3,280*	8.0-9.0°	Moderate	1981-89
NW5	72 x 135	0.8-1.3	1.5	14,580*	6.0-12.0°	Poor	Pre-1981, 1981-89
NW6	45 x 27	1.1	1.5	1,822*	10.0°	Poor	1981-89
NW10	150 x 35	0.7	0.7	3,238**	10.0°	None	2000

e = Estimated.
* = Determined from aerial photographs and direct observation.
** = Determined from topographic surveys.

Table 3.3 Dimensions and estimations of total volumes of material involved in bog failure events.

Site	Length (m)	Width (m)	Area (m^2)	Depth of material (m)	Volume of material (m^3)
S1	54	27	1,458	1.5	2,187
S2	54	36	1,944	1.5	2,916
S3	99	45	4,455	1.5	6,683
S4	54	45	2,430	1.5	3,645
S5	45	27	1,215	1.5	1,823
E1	99	36	3,564	2.0	7,128
E2	153	63	9,639	2.0	19,278
E3	90	72	6,480	2.0	12,960
E4	180	81	14,580	2.0	29,160
E5	135	54	7,290	2.0	14,580
E6	72	45	3,240	2.0	6,480
E7	99	63	6,237	2.0	12,474
E8	108	90	9,720	2.0	19,440
E9	45	27	1,215	2.0	2,430
NE1	333	63	20,979	1.7	35,664
N1	72	45	3,240	1.5	4,860
N2	162	27	4,374	1.5	6,561
N3	135	27	3,645	1.2	4,374
N4	120 100	20 50	2,400 5,000	1.2	9,100
N5	234	45	10,530	1.2	12,636
N6	27	72	1,944	1.2	2,333
N7	126	90	11,340	1.5	17,010
N8	90	36	3,240	1.5	4,860
N9	90	45	4,050	1.5	6,075
N10	63	36	2,268	1.5	3,402
N11	72	45	3,240	1.2	3,888
N12	117	18	2,106	1.2	2,527
N13	45	27	1,215	1.2	1,458
N14	72	36	2,592	1.2	3,110
N15	54	36	1,944	1.0	1,944
N16	27	18	486	1.0	486
N17	45	36	1,620	1.0	1,620
N18	54	45	2,430	1.0	2,430
N19	18	36	648	1.0	648
N20	45	36	1,620	1.0	1,620
NW1	63	27	1,701	1.5	2,552
NW2	36	36	1,296	1.5	1,944
NW3	81	27	2,187	1.5	3,281
NW4	27	18	486	1.5	729
NW5	72	135	9,720	1.5	14,580
NW6	45	27	1,215	1.5	1,823
NW7	54	27	1,458	1.5	2,187
NW8	108	27	2,916	1.5	4,374
NW9	99	27	2,673	1.2	3,208
NW10	150	35	5,250	0.7	3,238
NW11	27	27	729	0.7	510
NW12	72	27	1,944	0.7	1,361
Total			195,328		307,575

Table 3.4 Details of the magnitude and frequency of failure events identified on Cuilcagh Mountain.

Period	Number of failures	Total area (m^2)	Average area (m^2) of failures	Volume of material moved (m^3)	Average volume of material moved (m^3)
Pre-1981 (Vegetated)	18	104,900	5,828	172,330	9,574
Pre-1981 (Fresh)	9	22,837	2,537	35,340	3,927
1981-1991	18	39,123	2,174	54,681	3,038
1991-2001	5	28,468	5,694	45,224	9,045
Total	**50**	**195,328**		**307,575**	

bare scar. Table 3.5 shows that the scar area for several bog flow events makes up only 15 to 45% of the total failure area (i.e. area from which peat has been moved). On the northern slopes, peat slide failures are more frequent but tend to be considerably smaller than the bog flow events. The average volume of material moved in peat slide events is around 3,000 m^3, compared to an average of 16,000 m^3 for the bog flows on East Cuilcagh.

3.1.8 Peat Failures in Other Areas

A variety of peat failures at different locations described in literature have been visited to assess the significance of the Cuilcagh flows and slides. Carling (1986) reported several peat slides in Teesdale and Weardale, North Pennines, and attributed the failure to strain softening and micro shearing of underlying clays. This failure is similar in cause and nature to the October 1998 slide on the north side of Cuilcagh Mountain (as described in section 3.1.3). A characteristic of these slides is the apparent strength and coherence of the peat layer due to its fibrous nature. This is evident in the abundance of large intact rafts of peat moved in the failure events and the absence of liquefied peat during the flood down the catchment.

Several flow failure sites were visited in spring 1998, including one on the Yellow River catchment, approximately 9 km west of Cuilcagh in Co. Leitrim described by Coxon *et al.* (1989) and Large (1991) and those reported by Alexander *et al.* (1985, 1986) at Straduff Townland in Co. Sligo. The latter area of blanket bog contains several previous flow scars adjacent to one another. These have all failed over an escarpment ridge and have been liquid in nature, causing much damage to the downstream catchment and townland. Upslope of the escarpment, basal catotelm peat has drained from the plateau, resulting in a large area of torn and subsided acrotelm and upper catotelm separated by pools of water and peat. A fresh failure approximately two hundred metres to the north-west of that reported by Alexander *et al.* (1986) was also found in 1998. This had flowed over the escarpment and down through a forested area, leaving some flattened trees, deposited rafts, and peat mud on the upslope side of the trees. The flow track was approximately 100 m in width and extended around 300 m from the escarpment edge before crossing a road and entering a river channel. Another recent escarpment flow located approximately 10 km south-west of Cuilcagh draining into Stony River on the Slieve Anierin plateau was discovered on a reconnaissance flight over the area. This had left a large area (approximately 150 x 80 metres) cracked and subsided upslope of the break in slope. Plates 3.10 and 3.11 show the large-scale disruption to the area of bog upslope of the escarpment ridge. These flow failures have similar characteristics to the flows on East Cuilcagh. However, they are not undercut by a river at the foot of slope, but are located some distance away from a watercourse. In this example, the flow continues for approximately 0.5 km from the escarpment before reaching the Stony River. This type of topography seems particularly prone to large-scale flow type failures as shallow gradients on the plateau result in a deep accumulation of peat.

Table 3.5 Proportion of scar to total failure area for four bog flow events.

Site	Dimension of failure scar (m)	Scar area (m^2)	Dimension of total failure area (m)	Failure area (m^2)	Area of scar as % of total failure area
E2	40 x 50	2,000	153 x 63	9,639	21
E3	54 x 54	2,916	90 x 72	6,480	45
E6	18 x 27	486	72 x 45	3,240	15
E7	27 x 36	972	99 x 63	6,237	16

Plate 3.10 Aerial view of an escarpment flow on the Slieve Anierin plateau.
(Photo: K.J.K., November 1998).

Plate 3.11 Width of the escarpment flow on the Slieve Anierin plateau (field assistant centre left for scale). (Photo: K.J.K., April 1999).

3.2 COLLECTION OF SAMPLES FOR LABORATORY ANALYSES

3.2.1 Introduction

Sampling and extraction of peat for laboratory analysis without causing severe disturbance is notoriously difficult. The usual method involves the analysis of a core removed from the peat with the use of an auger. Disturbance is caused by compression and smearing of the sensitive matrix of the peat, especially when it is well decomposed, or when it is highly fibrous. Calculations of the core volumes using this technique are also known to cause inaccuracies in the results. However, in this study it was not necessary to use an auger and instead samples were collected from the headwalls at the top of failure scars. A large rectangular block (approximately 100 cm in length and 75 cm in width) was cut into, and cleared from the headwall of the scar to obtain a clean-cut column of intact peat from which samples could be extracted. Samples were collected for analysis of physical properties (degree of humification, bulk density, organic content and field moisture content) and geotechnical properties (saturated hydraulic conductivity, Atterberg tests, consolidation and shear strength) to determine the characteristics of the Cuilcagh peat, to assess the changing properties with depth and to ascertain any differences between peat involved in the bog flows and peat slides. The methods and results of the analyses into the physical and geotechnical properties are described in the following chapter.

3.2.2 Samples for Analysis of Physical Properties

Samples were collected from eight areas of the Cuilcagh blanket bog for analysis of the physical properties of the peat. Sites were selected on East Cuilcagh adjacent to bog flow failures and on the northern and north-western slopes where peat sliding is more prevalent. The site selection took into account the variety of failure types identified in section 3.1.2, relatively recent events (which have occurred since 1986) and sites that were more accessible. On East Cuilcagh, samples were collected from bog flows E2 (1992), E6 (1997/98) and E7 (pre-1989). The sampled sites to the north and north-west comprised N1 (1986), N4 (1998), NW3 (1981-89), NW5 (pre-1981 and 1981-89), and NW10 (2000) (see Figure 3.1 for locations). The slope failures to the south of Cuilcagh were not sampled as these were more inaccessible and had similar characteristics to the failures on the northern slopes.

At each of the selected sites, four individual profiles (at least 50 cm apart) were sampled at approximately 30 cm intervals in depth to include samples from the root mat, acrotelm, transition zone, and catotelm. Therefore, approximately 8 samples were collected from each profile. Samples were collected using p.v.c. pipe sections made into core rings 5 cm in length and 4.7 cm in diameter.

3.2.3 Samples for Analysis of Geotechnical Properties

As with the samples for physical properties, samples for the analyses of geotechnical properties were collected from East Cuilcagh adjacent to bog flow failures and from the northern slopes adjacent to peat slides and transitional failures. Samples for saturated hydraulic conductivity were collected from East Cuilcagh at bog flow failure sites E2 and E6, and on the northern slopes at sites N4 and NW5. Samples were extracted from the root mat, lower acrotelm, and the middle and basal catotelm in p.v.c. pipe sections cut into core rings (10 cm in length, 10 cm in diameter). Samples for Atterberg tests (liquid and plastic limits) were collected from two sites E2 and N4 at different depths throughout the peat profile and hence representing different degrees of humification. Block samples of peat for consolidation and shear testing were collected from E2, and NW5 and were extracted from the acrotelm (at 30 cm), upper catotelm (at 60-70 cm), and the basal catotelm (at 120 cm).

3.3 FIELD INVESTIGATIONS OF SHEAR STRENGTH

3.3.1 Introduction

A field shear vane was used to determine the *in situ*, undrained shear strengths of the peat profile at sites on both the eastern and northern slopes. The equipment and techniques used have been outlined in Appendix 2. Shear strength readings were obtained from the root mat and at depths of approximately 50 cm intervals, to include both the acrotelm and catotelm. Accuracy of the shear vane is stated to be within 10 % of the reading (Geonor, 1966). Readings were taken in tm^{-2}, and converted into kPa. Eggelsmann *et al.* (1993) state that the *in situ* strength of peat varies between 4.5 and 19.5 kPa over a depth of 1.5 to 1.8 metres below the surface, and depends upon the structure of the peat, its mineral content and moisture content. Four sites were used in this investigation, each to determine a different aspect of the present condition of the peat structure. Briefly, site 1 is a pristine slope on East Cuilcagh; site 2 is a slope on East Cuilcagh which has undergone some deformation; site 3 is situated immediately upslope of the multiple peat slide (N4) which occurred in 1998 on North Cuilcagh; and site 4 is adjacent to the peat slide on north-west Cuilcagh which occurred in March 2000 (NW10).

3.3.2 Site 1 – Pristine slope on East Cuilcagh

Site 1 is situated to the south of the 1992 bog flow (E2) on East Cuilcagh (Figure 3.1). The measured transect runs west to east on a slope 140 m in length. This site was chosen as it is relatively accessible and is typical of other natural slopes on the eastern side of the mountain where the peat is generally over two metres in depth. There is no apparent disturbance to the surface vegetation, but the site is situated in an area of previous bog flows. Therefore, the investigation at Site 1 is used to determine the strength characteristics of relatively undisturbed deep peat in an area prone to slope failure. Readings were taken at 11 points adjacent to, and between, a series of installed dipwells (Section 3.4.2) along the slope transect.

Figure 3.5 illustrates the slope transect and depth of the peat at the tested points. Slope gradient is exaggerated in the diagram, but is 5.5° near the crest of the slope, 9° in the middle, and falls to 4° at the foot of the slope. Peat depths vary accordingly, reaching three metres at the top, decreasing down to two metres in the middle section and deepening to over three metres at the foot of the slope.

Figure 3.6 and Table 3.6 show the shear strength results for each point on the slope transect. Each result represents an average of three readings. Shear strength values ranged from 6.9 kPa (very low strength) recorded in the root mat to 36.9 kPa at the base of the peat profile. In general, the recorded *in situ* shear

Figure 3.5 Site 1, location of dipwells and shear test points on a pristine slope, East Cuilcagh.

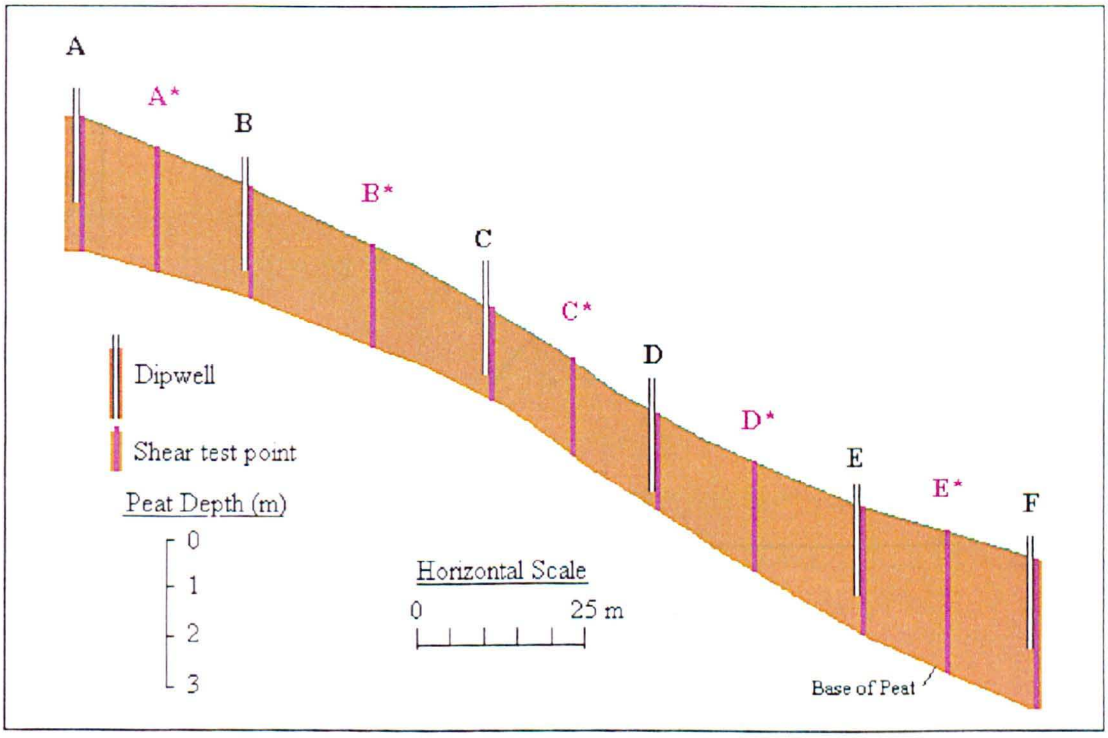


Figure 3.6 Shear vane results for the pristine slope on East Cuilcagh (Site 1)

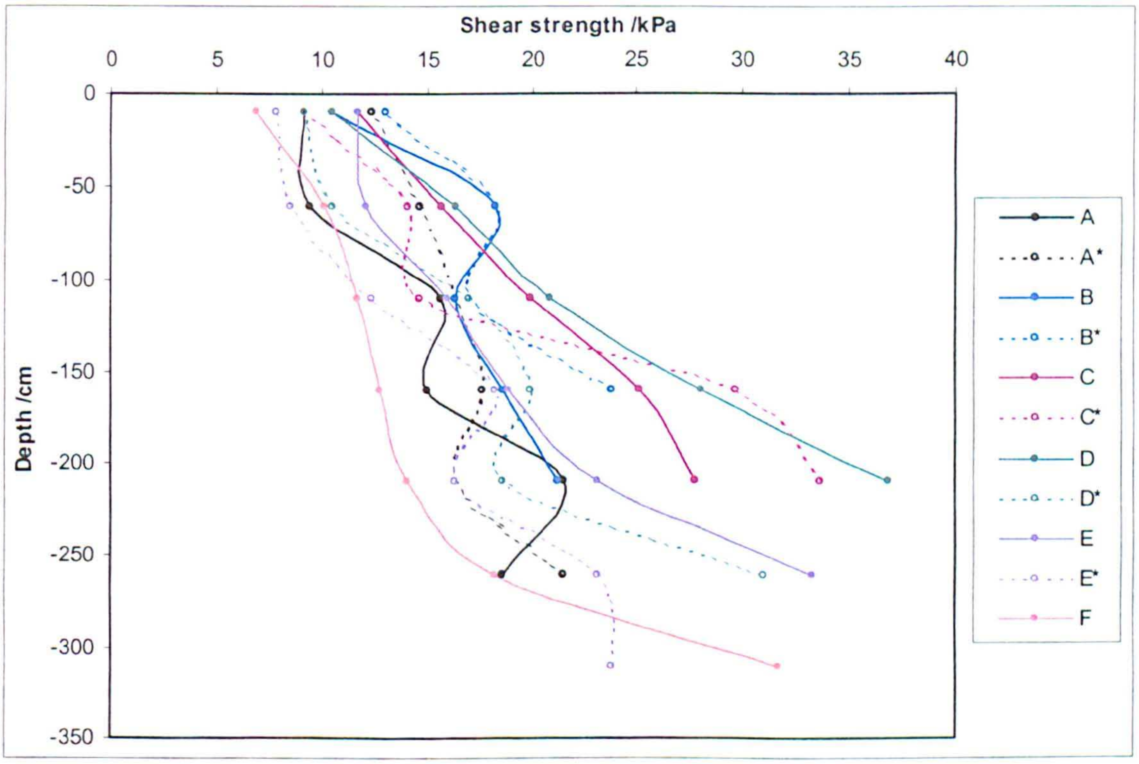


Table 3.6 Details of the vane shear strength results (kPa) for Site 1.

Depth (cm)	**A**	**A***	**B**	**B***	**C**	**C***	**D**	**D***	**E**	**E***	**F**	**Horizontal mean**
-10	9.2	12.4	10.5	13.1	11.8	9.2	10.5	9.2	11.8	7.8	6.9	**10.2**
-60	9.5	14.7	18.3	18.3	15.7	14.1	16.3	10.5	12.1	8.5	10.1	**13.5**
-110	15.7	16.3	16.3	17.0	19.9	14.7	20.9	17.0	16.0	12.4	11.8	**16.2**
-160	15.0	17.6	18.6	23.9	25.2	29.7	28.1	19.9	19.0	18.3	12.7	**20.7**
-210	21.6	16.3	21.2		27.8	33.7	36.9	18.6	23.2	16.3	14.1	**23.0**
-260	18.6	21.6						31.0	33.3	23.2	18.3	**24.3**
-310										23.9	31.7	**27.8**
VERTICAL MEAN	**14.9**	**16.5**	**17.0**	**18.0**	**20.1**	**20.3**	**22.5**	**17.7**	**19.2**	**15.8**	**15.1**	

strengths increased with depth. This strength distribution was more pronounced at sites C to D where the slope gradient was steepest and there was a shallower depth of peat.

At the top of the slope (A to B), the shear strength values remained low and ranged from 9.2 to 21.6 kPa throughout the profile with only slight increases with depth. Readings in the middle section of the slope (C to D) indicated that the peat had most variation in strength and increased with depth from 9.2 kPa to a maximum value of 36.9 kPa at the base. At the foot of the slope (E* and F), peat in the upper profile (root mat and upper acrotelm) had very little strength and ranged from 6.9 to 10.1 kPa. The strength slowly increased towards the lower catotelm, before rapidly attaining a maximum value at the base of the profile.

Table 3.6 shows that average vertical shear strength values ranged from 14.9 and 15.1 kPa at the crest and foot of the slope, to 22.5 kPa in the middle section. Hence for this pristine bog slope, shear strength values are greatest for the steepest sections of the slope where peat depth is shallowest, and diminish in the low gradient areas where peat has accumulated to form deep areas of blanket bog. This suggests that there is a relationship between *in situ* shear strength and either depth of peat or slope gradient. It is also apparent (Table 3.6) that *in situ* shear strengths increase from a minimum value in the root mat (with an average of 10.2 kPa) and upper acrotelm to attain a maximum value in the basal catotelm (27.9 kPa). Although the acrotelm peat has low apparent strength, it is considerably more fibrous in nature than the peat in the catotelm and might be expected to exhibit a higher tensile strength.

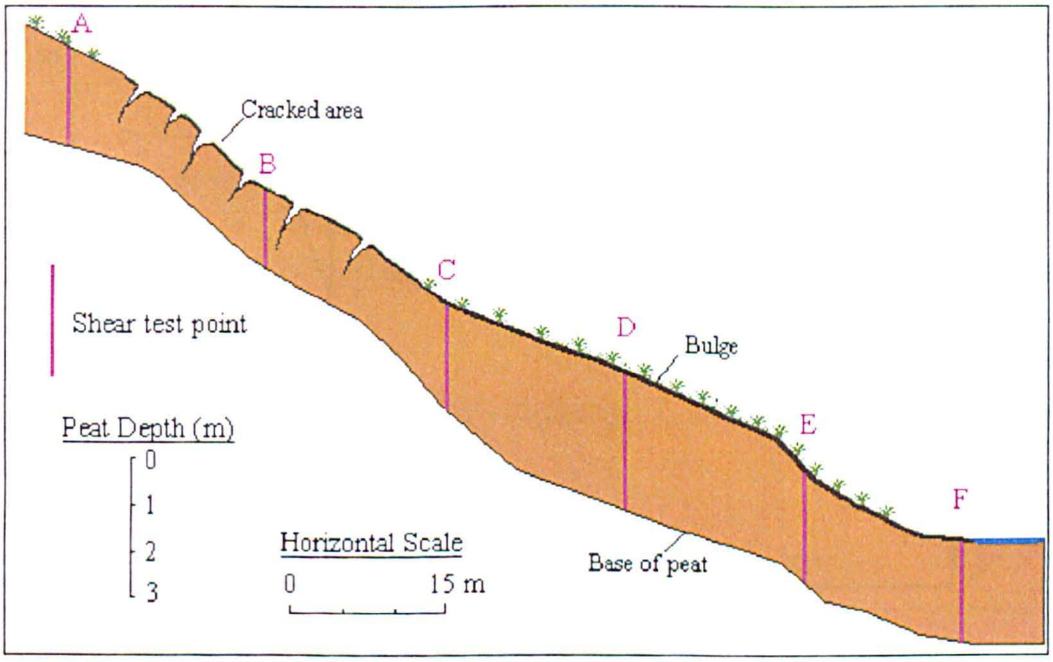
3.3.3 Site 2 - Bulging Slope on East Cuilcagh

Adjacent to two flow failure sites on East Cuilcagh (E6 and E7); a section of slope was noted to have an apparent bulge in the middle-lower section. Deep cracks had developed near the crest of the slope, some of which reached down to the base of the peat layer. The cracks and subsequent draining had caused the peat in the upper section of the slope to subside and form a semi-circular depression approximately 70m in length. A small, low energy stream and shallow pool are located at the base of the slope.

Figure 3.7 illustrates a transect measured up the centre of the slope, using a tape measure, clinometer and soil auger to determine slope angles and the depth of peat. Peat depth varied from 1.6 m on the cracked section, to 2.7 m at the centre of the bulge. It is evident that the apparent bulge noted on the surface is caused by an increase in peat depth in the middle to lower section of the slope and is not a result of the underlying substrate topography.

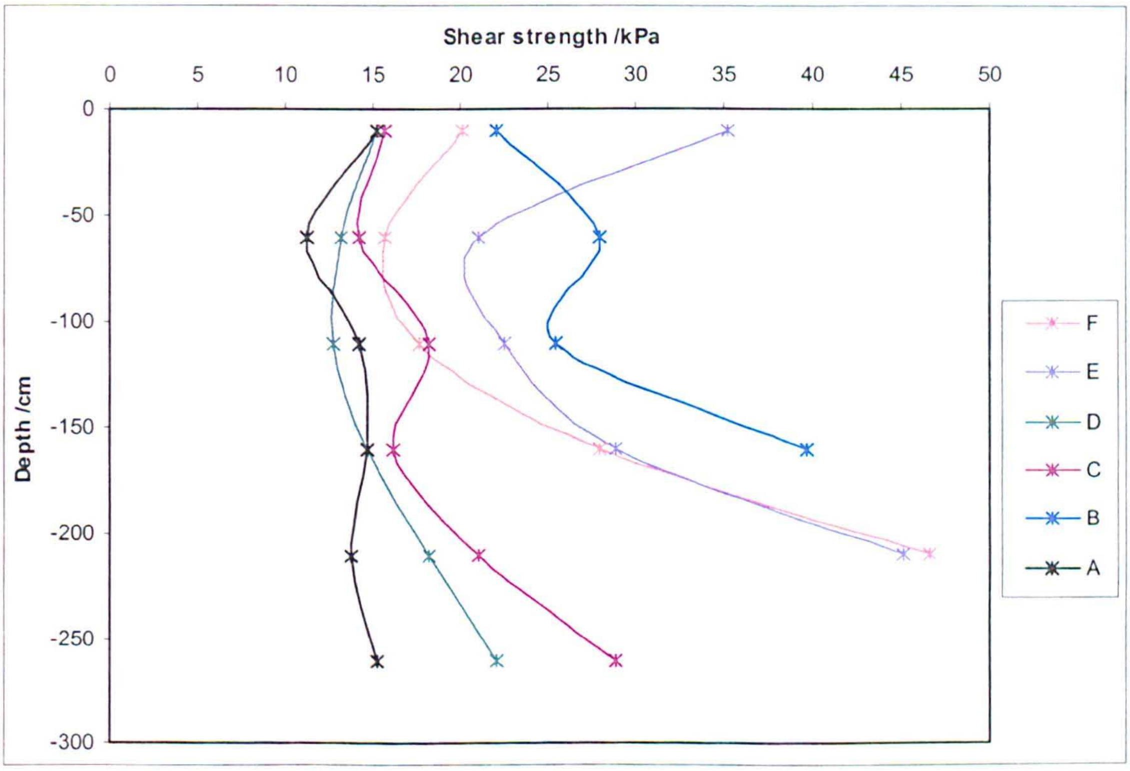
In situ shear strengths were determined for six points on the slope transect incorporating the foot, apparent bulge, cracked and subsided area and the crest of the slope (Figure 3.7). Shear strength values ranged from 11.3 kPa in the lower acrotelm, to 46.6 kPa at the base of the profile. Figure 3.8 shows that for most of the measurement points (particularly E and F situated at the foot of the slope), shear strength values were relatively high in the root mat, decreasing to a minimum in the lower acrotelm/upper catotelm and then increasing to a

Figure 3.7 Site 2, slope transect and location of shear test points.



NB Figure 3.7 is not drawn to the same horizontal scale as Figure 3.5.

Figure 3.8 Shear vane results for a bulging slope on East Cuilcagh (Site 2)



maximum at the base of the profile. This distribution is unlike that from Site 1 in which the lowest shear strengths were associated with the more fibrous upper acrotelm.

Upslope of the drained, cracked area (profile A), shear strengths were low and relatively constant throughout the profile, with an average of 14.0 kPa. This strength distribution is similar to point A at Site 1 (the crest of the pristine slope) and possibly indicates that this section of deep peat was unaffected by the slope movement and subsequent drainage which has resulted in the formation of the cracks and bulge lower down the slope. However, the highest recorded shear strengths were found within the root mat and not towards the base of the profile. Within the cracked section of the slope (B), high shear strength values were obtained throughout the shallow profile. The average strength was calculated at 28.8 kPa, with a maximum value of 39.7 kPa at the base (Table 3.7). Shear strengths in the middle of the slope, situated at the top of the bulge and downslope of the cracks (C), exhibited low values throughout the acrotelm and upper catotelm, and increased to a maximum at the base. This strength distribution was similar in the centre of the bulge, although there was a more pronounced dip in strength values in the upper catotelm and the average strength value was low (16.0 kPa). At the foot of the slope (downslope of the bulge), *in situ* shear strengths were found to be high with average values for E and F calculated as 25.5 and 25.6 kPa. Similar to the strength distribution within the bulge (D), shear strength was higher in the root mat and towards the base, than the considerably lower strength found within the upper catotelm (between 50 and 150 cm in depth).

Therefore, high *in situ* shear strength was measured throughout the shallow depth of cracked and drained peat (B). Although differences in strength may be accounted for by local variations in botanical composition, it seems likely that in this case drainage has led to increased strength, particularly with the evidence of lower strength immediately upslope and downslope of this area. Within the bulge, the catotelmic layer was noted to be of considerable thickness (over 2.0 m) and extremely low strengths were found in the upper region of this layer. This may suggest that some of the catotelm peat has moved out of the drained and cracked area (B), downslope into the middle section, to form the bulge (D). This movement of the catotelm underneath the acrotelm would account for the variability of strength in these two areas (B and D). The relatively high degree of strength that was measured within the root mat is thought to result from the presence of more heather-based vegetation. Also, high values of shear strength at the base of some of the profiles (B, E and F), particularly those towards the foot of the slope, may be the result of the influence of underlying clay. The presence of this was indicated with the use of the soil auger and is discussed later. High shear strength towards the base of profiles may also be associated with peat consolidation, which results from the greater depth of peat and the subsequent vertical load this produces.

3.3.4 Site 3 – Adjacent to the multiple peat slide scar (N4) on North Cuilcagh

To determine the strength characteristics of drained peat, a shear vane transect was completed immediately upslope of peat slide scar N4 on a northern slope of the mountain. Dipwells were also installed at this site and water level measurements are discussed in section 3.4.3. Shear vane measurements were taken at four points

Table 3.7 Details of the vane shear strength results (kPa) for Site 2.

Depth (cm)	A	B	C	D	E	F	Horizontal mean
-10	15.2	22.1	15.7	15.2	35.3	20.1	**20.6**
-60	11.3	27.9	14.2	13.2	21.1	15.7	**17.2**
-110	14.2	25.5	18.1	12.7	22.5	17.6	**18.5**
-160	14.7	39.7	16.2	14.7	28.9	27.9	**23.7**
-210	13.7		21.1	18.1	45.1	46.6	**28.9**
-260	15.2		28.9	22.1			**22.1**
VERTICAL MEAN	**14.0**	**28.8**	**19.0**	**16.0**	**25.5**	**25.6**	

on the transect, ranging from 1.0 to 8.0 metres from the failure scar. This investigation was carried out four weeks after this failure had occurred in October 1998.

Figure 3.9 illustrates the slope characteristics of Site 3 and Figure 3.10 and Table 3.8 show the *in situ* shear strength results for the transect. Shear strength values ranged from 14.2 kPa in the root mat, to 41.2 kPa at the base. Shear strength values for the surface vegetation and root mat were relatively high with an average of 18.9 kPa, particularly in comparison to Site 1 (where the average is 10.2 kPa). This is thought to be associated with the binding effects of the roots of the dominant heather vegetation, which characterise the generally steeper northern slopes of Cuilcagh Mountain. High shear strength was measured at the surface and base of the profile eight metres upslope of the failure scar. The average for this profile was 27.4 kPa, with a maximum of 41.2 kPa recorded at the base.

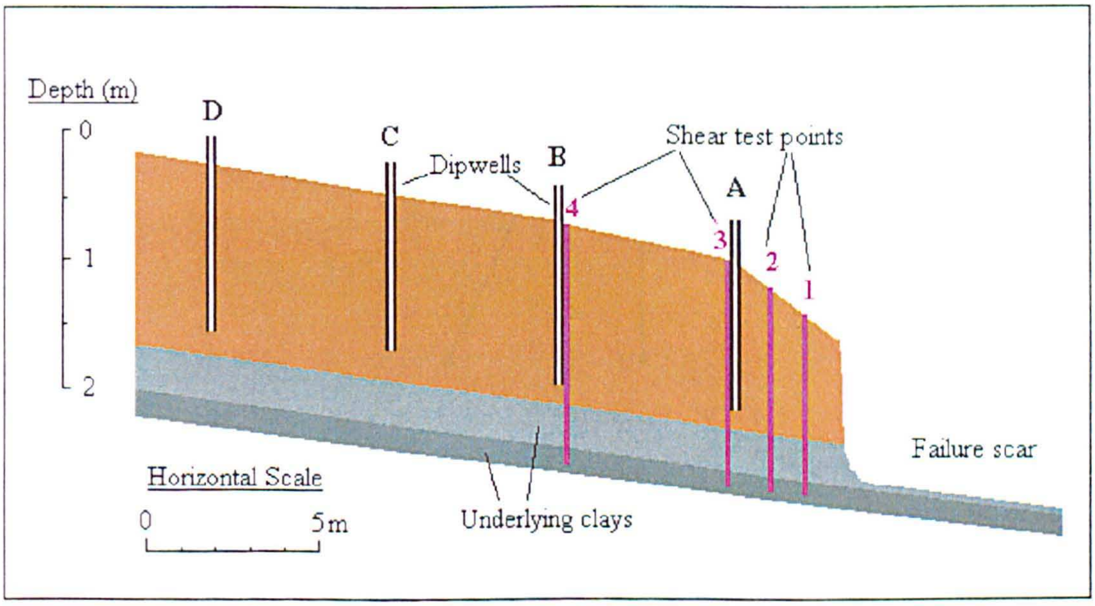
The shear strengths within the shallower depth of peat within two metres of the scar were considerably lower than those in the profile furthest from the scar (with average strengths of 15.7 and 16.7 kPa respectively). Shear strength values were at a minimum within the root mat and at a maximum approximately 60 cm below the surface. The extent to which drainage and movement of the failure event itself has altered the strength of the peat immediately upslope of the scar is difficult to establish as no measurements were taken prior to the slope failure occurring. However, it appears that drainage of the peat mass upslope of the failure might be associated with lower shear strengths. In contrast, at Site 2 the drained, cracked area of the bulging slope was characterised by higher shear strengths. In the case of Site 3, the proximity of the large-scale failure event immediately downslope may have caused disruption and alteration to the peat matrix in the form of the fibres being pulled apart, which would lead to a loss of cohesion and reduced shear strength.

3.3.5 Site 4 - Adjacent to a recent peat slide scar (NW10) on north-west Cuilcagh

To determine the strength characteristics and sensitivity of peat and the underlying clay, a shear vane transect was completed immediately upslope of a peat slide (NW10) scar on a north-west slope of the mountain. This failure event is described in section 3.1.3. Similarly to the multiple failure (N4), peat depth around the scar was around 60 to 70 cm and was underlain by a layer of pale peaty clay which appeared to rest on a surface of darker coloured sandy clay. Shear vane measurements were taken at six points on the transect, ranging from 0.5 to 5.0 metres from the failure scar (Figure 3.11). This was carried out ten days after the peat slide had occurred.

Peak shear strength for the peat ranged from 9.8 to 32.0 kPa and like the peat at sites 1 and 2, in most of the profiles shear strengths gradually increased with depth from the surface (Figure 3.12). The greater shear strengths found within the underlying clay however, increased more rapidly with depth, giving average peak strengths for 1.1 m and 1.4 m below the surface as 61.1 and 118.9 kPa respectively (Table 3.9). Residual strengths were also determined using the techniques described in Appendix 2 (Table 3.10). This was carried out to determine the *in situ* sensitivity of the peat and clay (peak strength divided by residual strength) to give an indication of the effect of remoulding on the consistency of the material. Table 3.11 shows the calculated

Figure 3.9 Site 3, location of dipwells and shear test points



NB Figure 3.9 is not drawn to the same scale as Figures 3.5 and 3.7.

Figure 3.10 Shear vane results for Site 3 on North Cuilcagh.

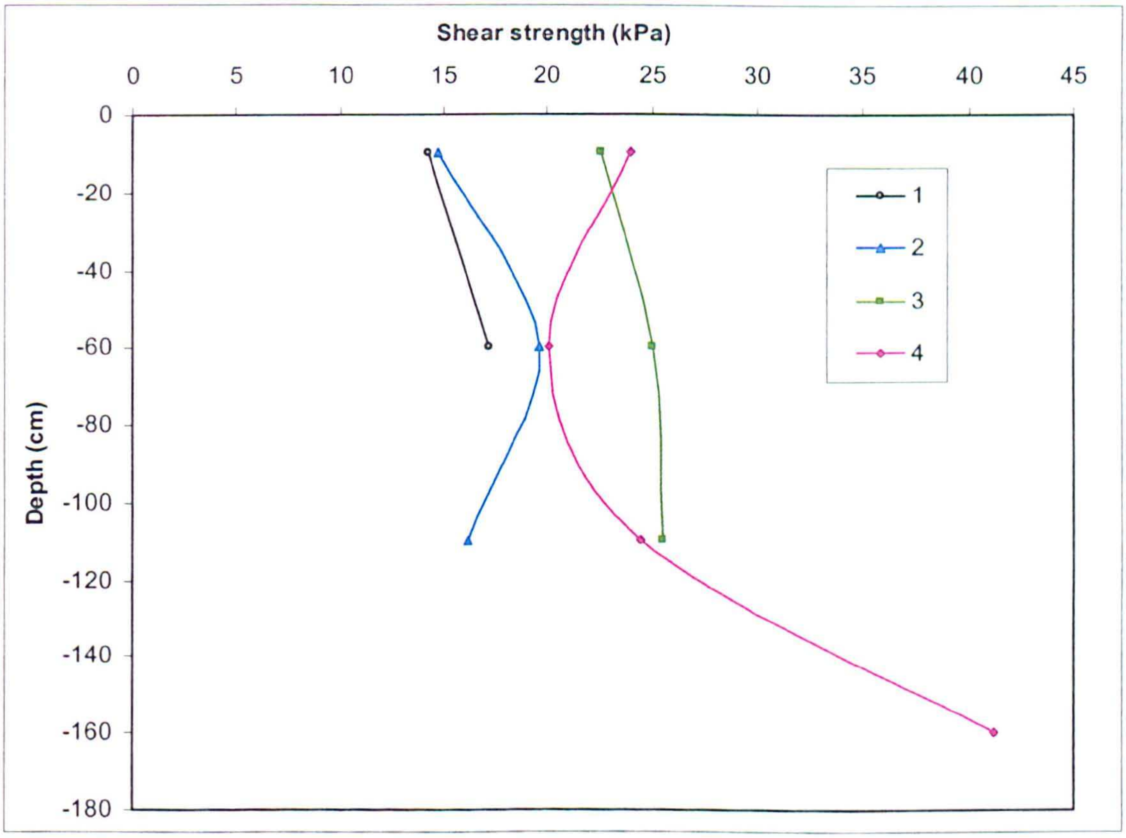
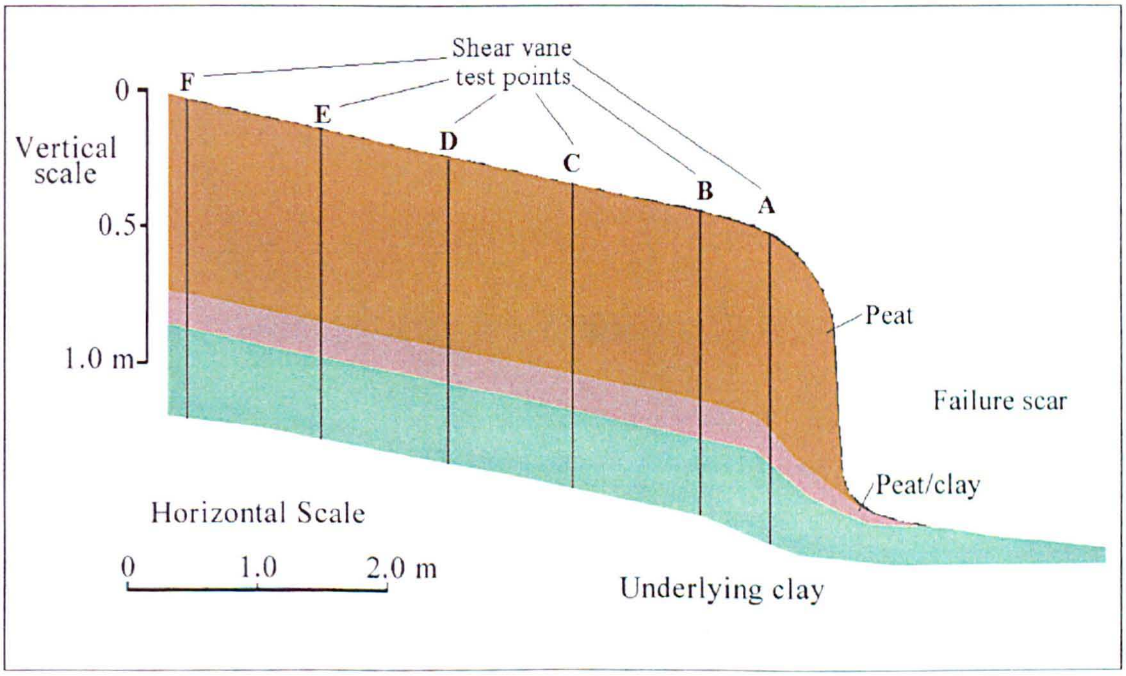


Table 3.8 Details of the vane shear strength results (kPa) for Site 3.

Depth (cm)	**1**	**2**	**3**	**4**	**Horizontal mean**
-10	14.2	14.7	22.5	24.0	**18.9**
-60	17.2	19.6	25.0	20.1	**20.5**
-110		16.2	25.5	24.5	**22.1**
-160 (clay)				41.2	**41.2**
VERTICAL MEAN	**15.7**	**16.8**	**24.3**	**27.4**	

Figure 3.11 Site 4, shear vane test points upslope of the peat slide NW10.



NB Figure 3.11 is not the same scale as Figures 3.5, 3.7 and 3.9.

Figure 3.12 Shear vane results for Site 4 on North Cuilcagh.
(Res = residual strength values)

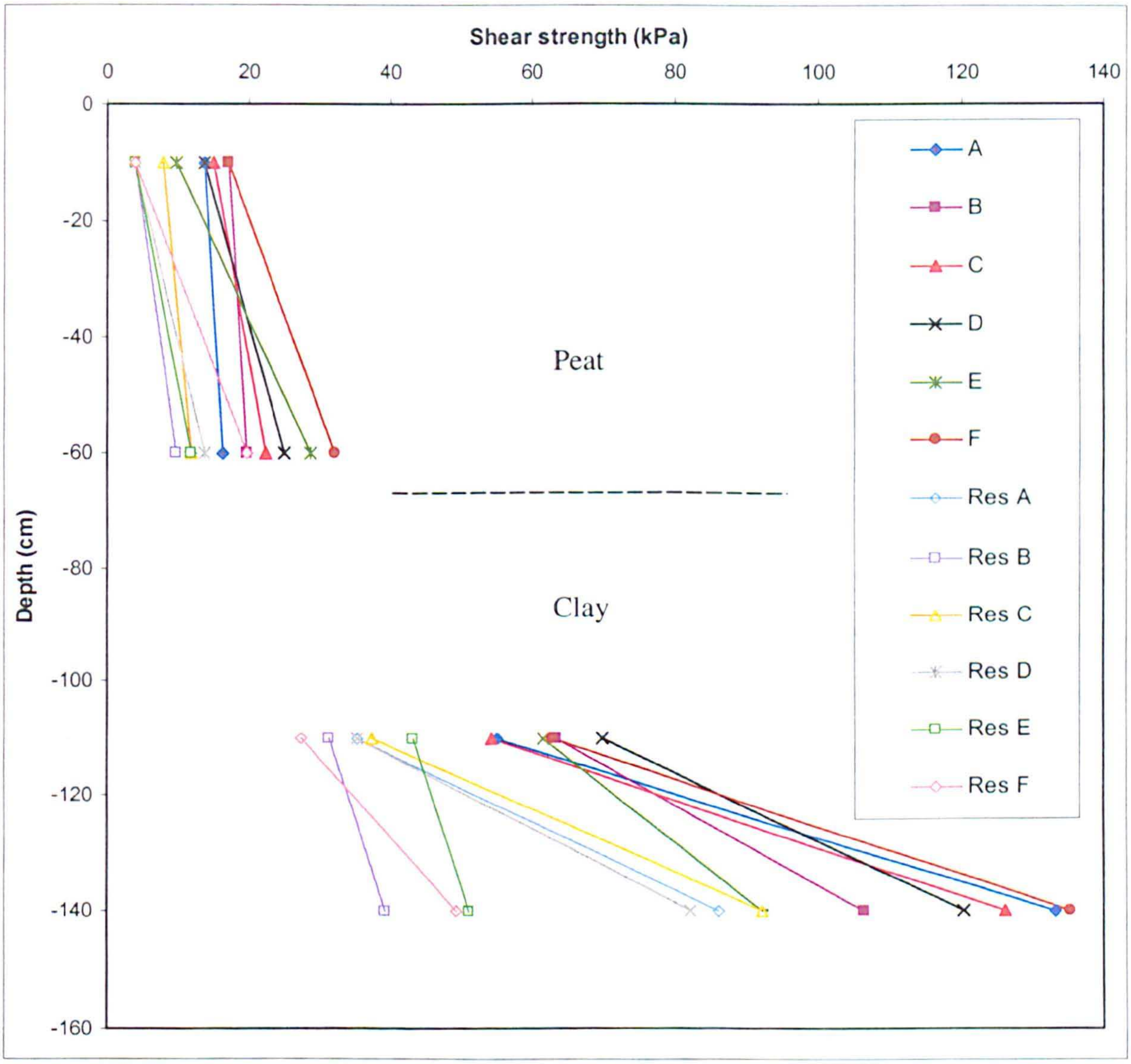


Table 3.9 Details of the vane shear strength results (kPa) for Site 4.

Depth (cm)	**A**	**B**	**C**	**D**	**E**	**F**	**Horizontal mean**
-10	13.7	17.0	15.0	13.7	9.8	17.0	**14.4**
-60	16.3	19.6	22.2	24.8	28.7	32.0	**24.0**
-110 (clay)	54.9	63.4	54.2	69.9	61.4	62.7	**61.1**
-140 (clay)	133.3	106.5	126.1	120.2	92.1	135.2	**118.9**
Vertical mean	**54.6**	**51.6**	**54.4**	**57.2**	**48.0**	**61.7**	

Table 3.10 Details of the residual shear strength results (kPa) for Site 4.

Depth (cm)	**A**	**B**	**C**	**D**	**E**	**F**	**Horizontal mean**
-10	3.9	3.9	7.8	3.9	3.9	3.9	**4.6**
-60	11.8	9.8	11.8	13.7	11.8	19.6	**13.1**
-110 (clay)	35.3	31.4	37.2	35.3	43.1	27.4	**35.0**
-140 (clay)	86.2	39.2	92.1	82.3	51.0	49.0	**66.6**
Vertical mean	**34.3**	**21.1**	**37.2**	**33.8**	**27.4**	**25.0**	

Table 3.11 Calculated sensitivity (ratio of peak strength to residual strength) of the peat and clay at site 4.

Depth (cm)	A	B	C	D	E	F	Horizontal mean
-10 (peat)	3.5	4.3	1.9	3.5	2.5	4.3	3.1
-60 (peat)	1.4	2.0	1.9	1.8	2.4	1.6	1.8
-110 (clay)	1.6	2.0	1.5	2.0	1.4	2.3	1.7
-140 (clay)	1.5	2.7	1.4	1.5	1.8	2.8	1.8
Vertical mean	1.6	2.4	1.5	1.7	1.8	2.5	

sensitivity of the peat and clay at site 4. On average, the degree of sensitivity of the peat was calculated as 2.6 and ranged from 1.4 to 4.3, whereas the average sensitivity of the clay was 1.8 and ranged from 1.4 to 2.8. A tested material is considered 'normal' with a degree of sensitivity of 2.0 to 4.0, and 'sensitive' if it lies between 4.0 and 8.0 (Terzaghi and Peck, 1967). A maximum degree of sensitivity of 4.3 was found in the fibrous acrotelm peat. Although this material has a high initial shear strength, it is more sensitive than the catotelm peat, as once the fibres have been sheared the peat strength reduces considerably. This highlights the important role of a coherent acrotelm layer in providing a natural crust to the bog.

3.4 HYDROLOGY OF THE PEAT

3.4.1 Introduction

In this section, field methods for determining different aspects of peat hydrology are described and the results discussed with relevance to site characteristics. Two hydrological parameters were measured in the field: water table levels and saturated hydraulic conductivity (k_{sat}). These are essential for the understanding of the peatland hydrological system and are critical for performing a thorough stability analysis. The main purposes of studying the water levels in the Cuilcagh peat was to get an indication of the baseline water table conditions and seasonal variations, to assess how the hydrology of the peat has been affected by the presence of a failure scar and more importantly to use the recorded water levels and the associated rainfall data to validate the hydrological model used in Chapter 5. Measurements of depth to water table also provide an indication of changes in water storage. The determinations of field k_{sat} are required for use in the hydrological model, to give an indication of the vertical variability of peat, and are also used as a comparison to laboratory determinations. Gilman (1994) has argued that the spatial variability of the hydrological parameters in peatlands (water table levels and k_{sat}) is such that they should be monitored locally. Hence, for the purposes of the present study several sites were chosen to represent the variety of peatland types encountered on Cuilcagh Mountain.

Two dipwell transects were installed in November 1998 in an area of pristine bog on East Cuilcagh (site 1) (Plate 3.12) and upslope of the peat slide N4 (site 3, as described in section 3.2.5). Each dipwell consisted of a perforated p.v.c. tube (35 mm internal diameter) inserted into the peat at depths of 50 to 170 cm from the surface. Depth to water table was measured by means of an electric contact probe.

Field measurements of saturated hydraulic conductivity (k_{sat}) were determined using nests of piezometers placed in close proximity to two failure sites, E2 on East Cuilcagh and N4 on the North Cuilcagh. Each piezometer consisted of a (non-perforated) p.v.c. tube varying from 60 cm to 250 cm in length and covered at the base with a permeable material to prevent the upwelling of peat. Each tube was inserted into the peat vertically and then lifted up ten cm to form a chamber at the base of the tube. The piezometer method has been widely used for the measurement of the hydraulic conductivity of the soil below the water table (Kirkham and Luthin, 1949; Boelter, 1965; Dai and Sparling, 1973; Chason and Siegel, 1986). This is carried out by

Plate 3.12 Reading the dipwells at site 1, East Cuilcagh. (Photo: R. Johnson, April 1999).

means of a pump test. Water is abstracted from the tube and the rate of recovery is then timed. Using a formula derived from Darcy's Law, hydraulic conductivity can then be determined. Details of the equation and the piezometers used on Cuilcagh are given in Appendix 3.

The recording of water levels in the dipwells and pump tests in the piezometers were first carried out during one week in April 1999 giving the equipment time to settle into the ground. Further water level data were collected during November 1999 and March 2000.

3.4.2 Dipwells on a Pristine Slope on East Cuilcagh (Site1)

Figure 3.5 illustrates the slope characteristics at site 1 and the position of the six dipwells. Figure 3.13 shows the recorded water levels and corresponding rainfall (collected from Marble Arch Caves) for a one week period in April 1999. Water levels were always within 13 cm of the bog surface, and two-thirds were within 5 cm. Dipwells at the top and foot of the slope (A and F) which measured the water levels in the deeper peat and at a shallower gradient, recorded the lowest water tables, fluctuating between 9 and 13 cm below the surface. On the steeper section of the slope (dipwells C and D), the water table was situated between 3.5 cm below and 2 cm above the surface. The water table levels for this slope have a range of less than 5 cm; the greatest variation (4.9 cm) was recorded at dipwell C over a three day period in which the water level was recorded above the surface vegetation. Rainfall in the days prior to the reading of the dipwells peaked on 31st March (16 mm), but decreased sharply to 1 mm the following day. Most of the recorded water levels were noted to decrease on the 3rd April. Similarly, after an increase in rainfall between 2nd and 4th April, water levels increased on the 4th and 6th April. This two day lag time was also noted after a period of lower recorded rainfall between the 6th and 8th April. The majority of the water levels had decreased by the 10th April.

It is apparent that during this week, the water table within deeper peat was at a greater depth beneath the surface than the water level in the shallow peat on a steeper gradient, but was more constant over time. It is suggested that water tables close to surface have greater potential range in values, due to precipitation falling directly into surface water storage and the higher permeability of the upper acrotelm. In theory, water held closer to the surface is also available for evapotranspiration. High water tables on steeper gradients also contain a downslope contribution from gravity drainage. However, it is difficult to establish whether this one week recorded period is representative of average conditions. Water levels recorded during Autumn 1999 and the following Spring were found to be slightly higher (approximately 2 cm) than the average water levels recorded in April 1999. Figure 3.14 shows all of the recorded water levels at site 1. No readings were obtained from dipwell F in November 1999 and March 2000 as the cover over the top of dipwell tube had been removed.

3.4.3 Dipwells on a Drained Slope on North Cuilcagh (Site 3)

At site 3, four dipwells were installed immediately upslope of a headwall of a failure scar. The first dipwell was placed three metres back from the headwall; the others were then installed at five metre intervals in a straight line (Figure 3.9).

Figure 3.13 Recorded water levels at site 1 and corresponding daily rainfall data (28/3/99 to 10/4/99).

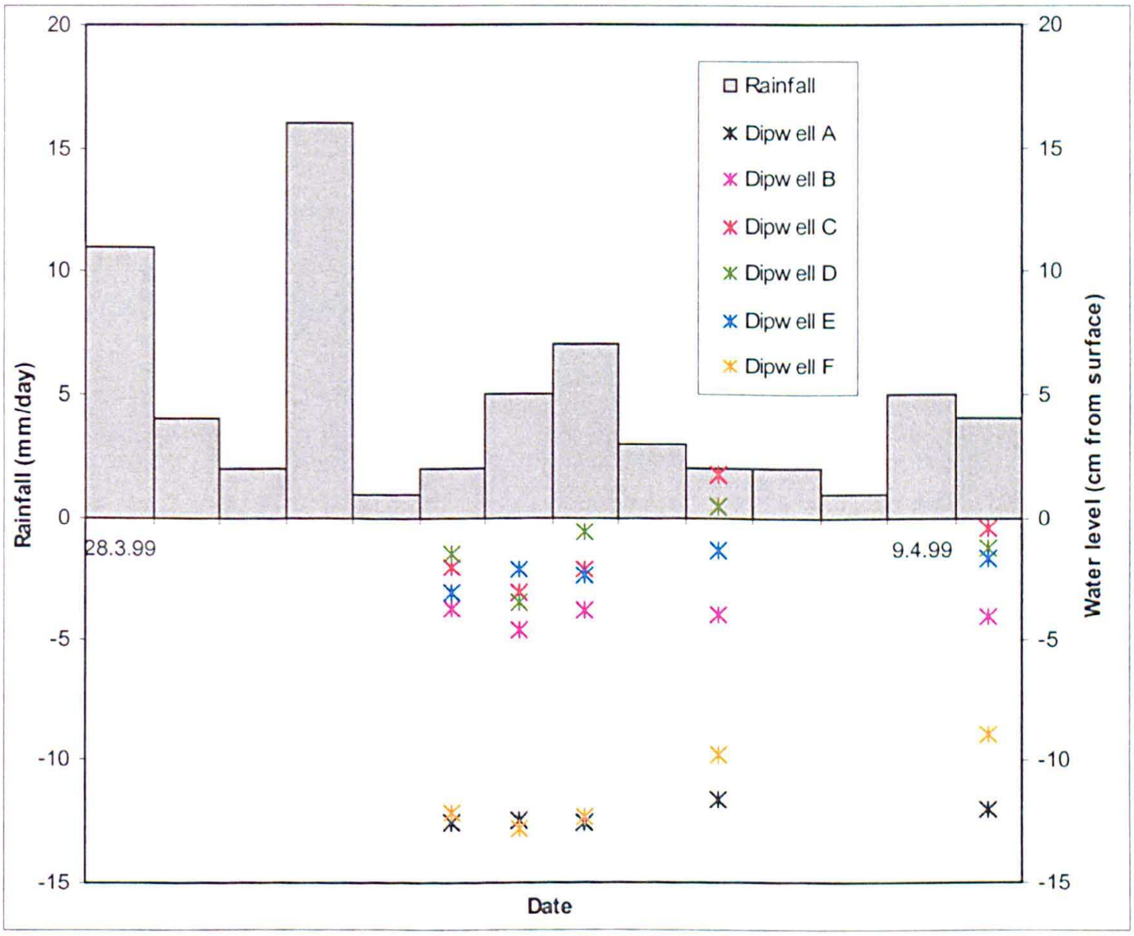


Figure 3.14 Recorded water levels at Site 1 (April and November 1999, March 2000).

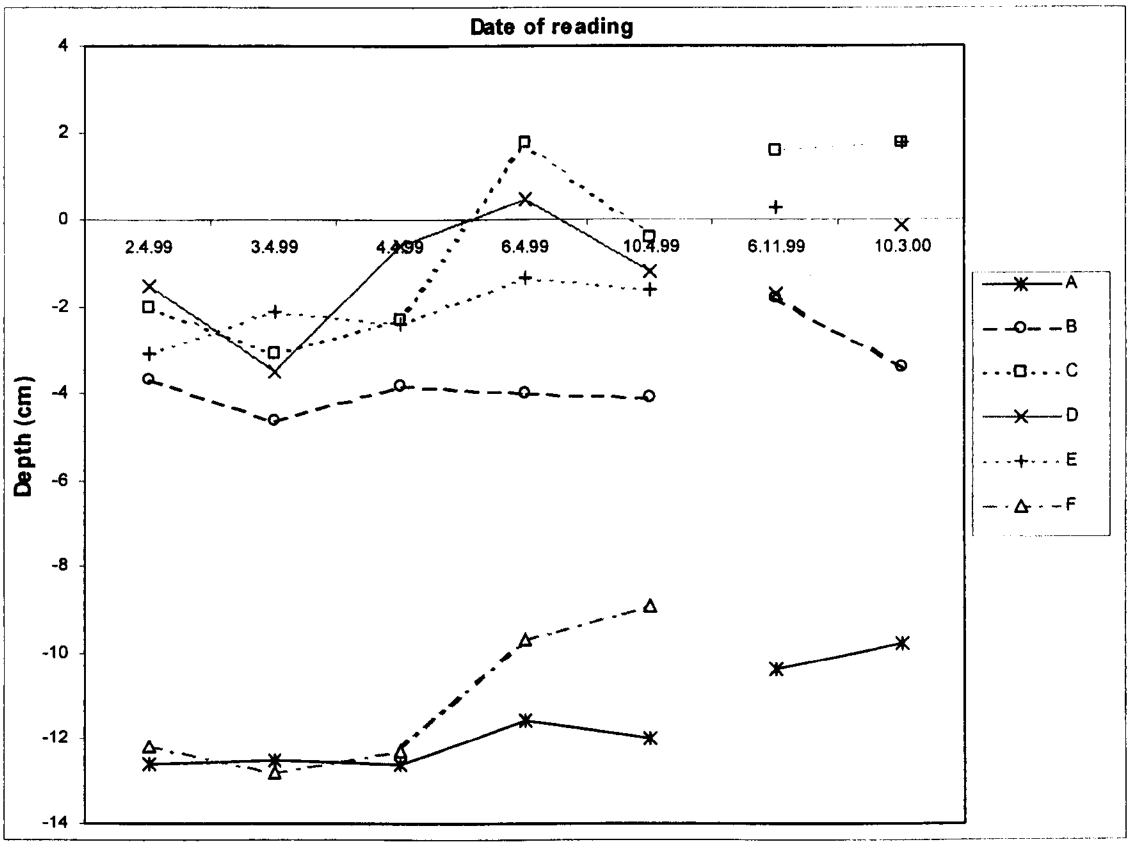


Figure 3.15 illustrates the recorded water levels at site 3. All of the water tables lay within 38 cm of the surface. The three dipwells closest to the headwall of the failure (A, B, and C) exhibited considerably lower water levels than the dipwell furthest from the scar (D), which is thought to represent undisturbed conditions. During April 1999 water levels at A, B, and C fluctuated below 20 cm from the surface. Water tables recorded at A and B remained fairly constant with a range of under 3 cm, but dipwell C (13 metres from the scar) exhibited a wider range of water levels. It is possible that dipwell C is influenced by a sub-surface (peat) pipe in the vicinity. This would allow the rapid transfer of rainwater into the peat mass, rather than the slow percolation of water through the acrotelm, giving a more flashy response to the water table. It is noted that the third reading in April 1999 (6/4/99) was taken after a period of rainfall (Figure 3.13) and is correlated with a rise in the water table of C of six cm over two days. Water tables in November 1999 were found to be an average of 7 cm higher than the average water levels recorded in the previous April. However, in March 2000 the water levels were an average of 5 cm lower than those recorded in April 1999. Without continuous monitoring, it is not possible to determine whether these are seasonal variations, or reflect differences in antecedent rainfall conditions prior to the water tables being recorded. However, as the water level at dipwell A (only 3 m upslope of the failure scar) was noted to decrease most significantly from April 1999 to March 2000, it seems reasonable to suppose that this peat is being slowly drained as a result of the proximity to the headwall of the failure scar. Unfortunately, no readings were obtained from dipwell D in November 1999 and March 2000 as the cover of the dipwell tube had been removed.

3.4.4 Piezometers on East Cuilcagh (Site 5)

Eight piezometers were installed immediately south of bog flow E2 (Figure 3.1) in two rows of four running parallel to each other (2.0 m apart). The piezometer chamber method facilitates the measurement of k_{sat} for a particular layer within the bog. For example, piezometer A1 is 170 cm in depth from the surface with a chamber of 10 cm at its base. Hence, k_{sat} can be determined for 170-180 cm from the surface. Table 3.12 shows the details of the piezometers used in sites 5 and 6. Further details, readings and k_{sat} calculations are given in Appendix 3.

Figure 3.16 shows initial water levels and recovery from the pump test for each piezometer within the peat mass and Figure 3.17 and Table 3.13 shows the calculated hydraulic conductivity. The five initial lowest water levels recorded in this nest of piezometers corresponded to the layers below one metre from the surface. Field k_{sat} at this site ranged approximately three orders of magnitude from 2×10^{-5} to 2×10^{-8} cm/s, but most of the values were around 10^{-6} to 10^{-7} cm/s. In general, the k_{sat} values decreased with depth. However, there was considerable variability over the metre depth of peat tested. For example, k_{sat} at piezometer B3 (90-100 cm) was relatively high (2×10^{-5}), whereas only 10 to 20 cm below this (B2), the k_{sat} was extremely low (2×10^{-8}). The rapid rate of recovery from the pump test at B3 may indicate the presence of a fibrous undecomposed layer, or the close proximity of a peat pipe that would allow a higher transfer rate of water. At the other extreme, the low initial water level and calculated k_{sat} at B2 may have been associated with a more impermeable layer (resulting from a variation in botanical composition or degree of decomposition), a gas pocket, or possibly a block in the piezometer tube.

Figure 3.15 Recorded water levels at Site 3

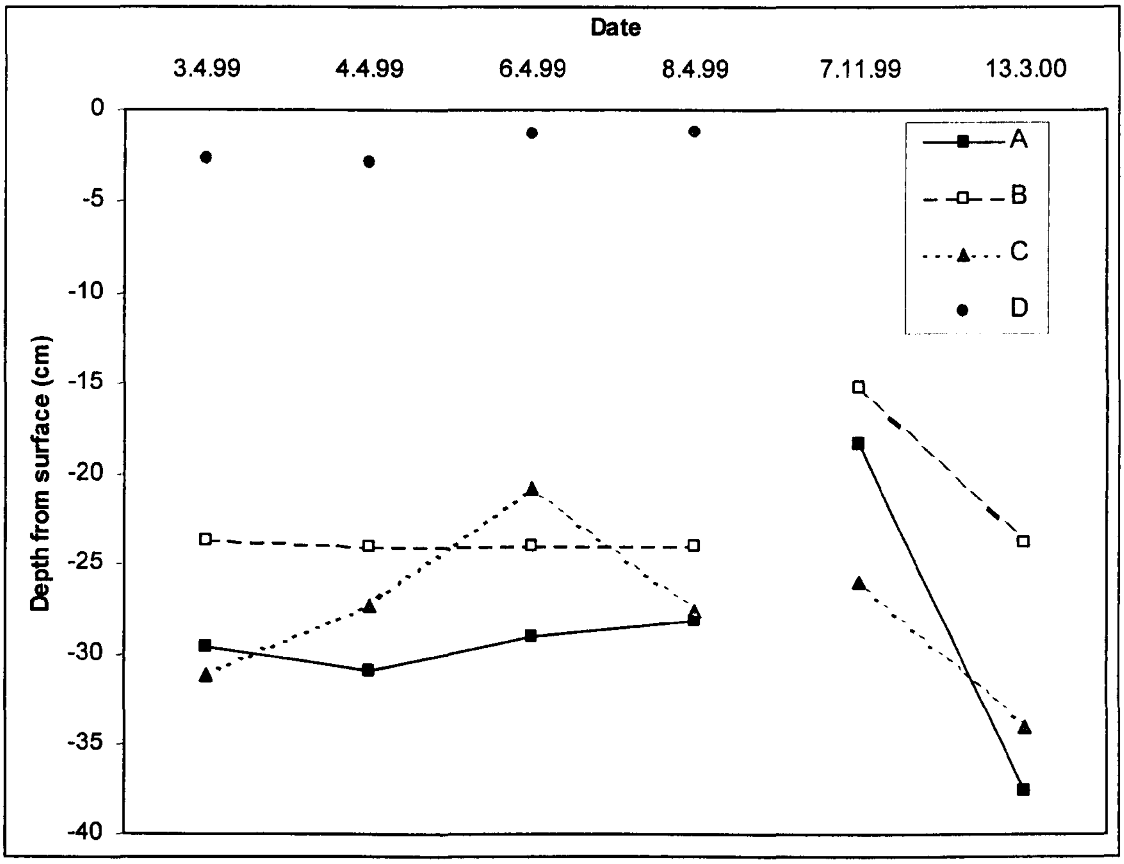


Table 3.12 Details of the piezometers used at sites 5 and 6.

Site	Piezometer Number	Piezometer depth (cm) (without chamber)	Piezometer chamber depth (cm)	Depth of peat (cm)
Pristine slope (Site 5)	A1	170	10	199
	A2	120	10	189
	A3	100	10	179
	A4	75	10	157
	B1	138	10	200
	B2	110	10	188
	B3	90	10	179
	B4	55	10	169
Adjacent to failure N4 (Site 6)	C1	145	10	211
	C2	100	10	152
	C3	90	10	144
	C4	30	10	139
	D1	120	10	211
	D2	85	10	197
	D3	60	10	169
	D4	40	10	130

Figure 3.16 Pump test on piezometers at Site 5, East Cuilcagh (2/4/99-10/4/99).

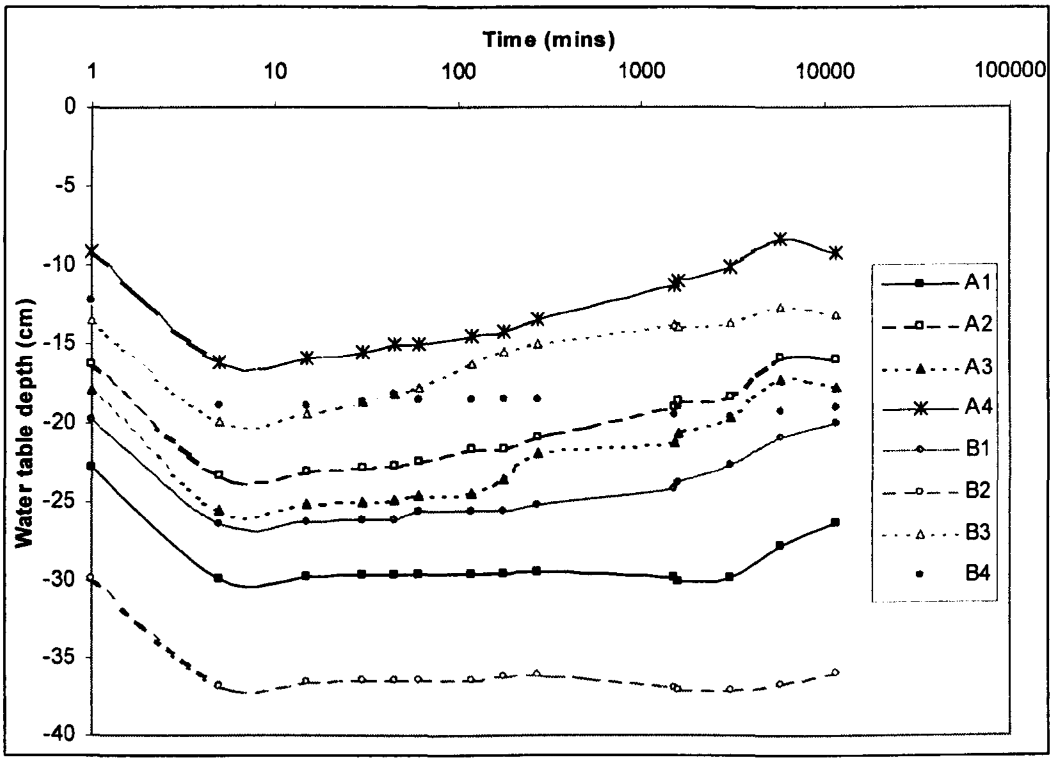


Figure 3.17 Calculated field hydraulic conductivity using piezometers at sites 5 and 6.

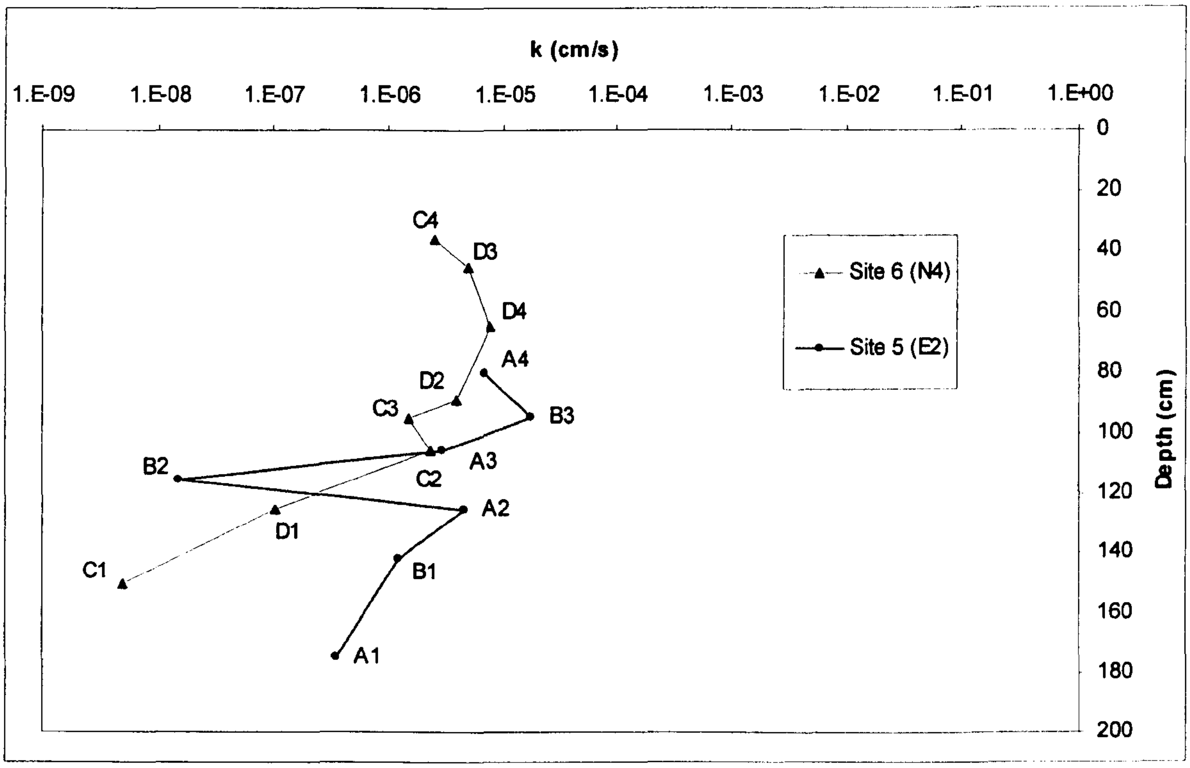


Table 3.13 Values of k_{sat} determined using piezometers on Cuilcagh Mountain.

Site	Piezometer	Depth (cm)	Field k (cm/s)
East Cuilcagh (Site 5)	**A1**	170-180	3.5×10^{-7}
	A2	120-130	4.6×10^{-6}
	A3	100-110	2.9×10^{-6}
	A4	75-85	6.8×10^{-6}
	B1	138-148	1.2×10^{-6}
	B2	110-120	1.5×10^{-8}
	B3	90-100	1.7×10^{-5}
	B4	55-65	-
North Cuilcagh (Site 6)	**C1**	145-155	5.1×10^{-9}
	C2	100-110	2.3×10^{-6}
	C3	90-100	1.5×10^{-6}
	C4	30-40	2.5×10^{-6}
	D1	120-130	1.0×10^{-7}
	D2	85-95	3.9×10^{-6}
	D3	60-70	7.7×10^{-6}
	D4	40-50	5.0×10^{-6}

Piezometer B4 at 55 to 65 cm in depth below the surface initially exhibited a very slow rate of recovery (i.e. an increase in water level) from the pump test, but then the water level slowly decreased within the piezometer. It is possible that this variability was influenced by the natural fluctuations of the water table within the lower acrotelm and upper catotelm. As a consequence, this result was disregarded. Therefore, in general, the piezometers measuring the deeper layers within the peat mass exhibited a lower initial water level and lower k_{sat} in comparison to the peat tested in the upper profile.

3.4.5 Piezometers on North Cuilcagh (Site 6)

Eight piezometers were installed to the west of peat slide N4 on North Cuilcagh in the same ground pattern as site 4. This incorporated a range in depths from 30 to 155 cm from the bog surface (Table 3.12). Figure 3.18 shows initial water levels and recovery from the pump test and Figure 3.17 illustrates the calculated k_{sat}.

Field k_{sat} at this site ranged approximately three orders of magnitude from 8×10^{-6} (at 40 to 50 cm) to 5×10^{-9} cm/s (145 to 155 cm). The k_{sat} measured in the upper and middle profile (from 30 to 100 cm) were all between 2 and 8×10^{-6} cm/s and also had higher initial water levels. The two piezometers C1 and D1 with the deepest chambers (below 1.2 m) illustrated the lowest water levels and slowest rates of recovery from the pump test, e.g. k was lower than 5×10^{-9} cm/s for the peat at 145 to 155 cm below the surface. In general, water levels were found to be nearer the surface in the shallower piezometers, and lowest in the piezometers measuring the deeper peat. In comparison to site 5, values of k_{sat} were slightly lower in the middle section of the peat (80 to 100 cm) and (with the exception of B2) were considerably lower at the base of the profile.

Hydraulic conductivity is related to the structure and porosity of the material (Boelter, 1965; Heathwaite *et al.*, 1993), but more precisely to specific yield and pore size distribution. Specific yield is the volume of water that can be drained from the saturated material by gravity per unit saturated bulk volume (Boelter, 1965). Values of specific yield for peat in different stages of decomposition are given in Table 3.14. Peat pores differ in size and shape and are dependent on plant residues and degree of decomposition. As decomposition increases, specific yield decreases, resulting in smaller pore spaces and changes in the type of water held within the peat matrix. This makes it less susceptible to movement of water. The less decomposed peat within the acrotelm contains larger pore spaces, particularly with the presence of macropores, such as root channels. Therefore, water can drain relatively easily through these layers. The peat making up the catotelm is more decomposed, compacted and water is retained in small pores, and so k_{sat} is much lower than in the acrotelm where the structure is looser. The presence of gases given off during the process of humification has also been reported to decrease permeability within the catotelm (Baird *et al.*, 1997). Field determinations of k_{sat} and will be discussed further in Chapter 4 with the results of the laboratory analysis. The debate as to whether k in more humified peat obeys Darcy's Law (as mentioned in Chapter 1) will also be considered (Section 4.2.2).

Figure 3.18 Pump test on piezometers at Site 6, North Cuilcagh (3/4/99-8/4/99).

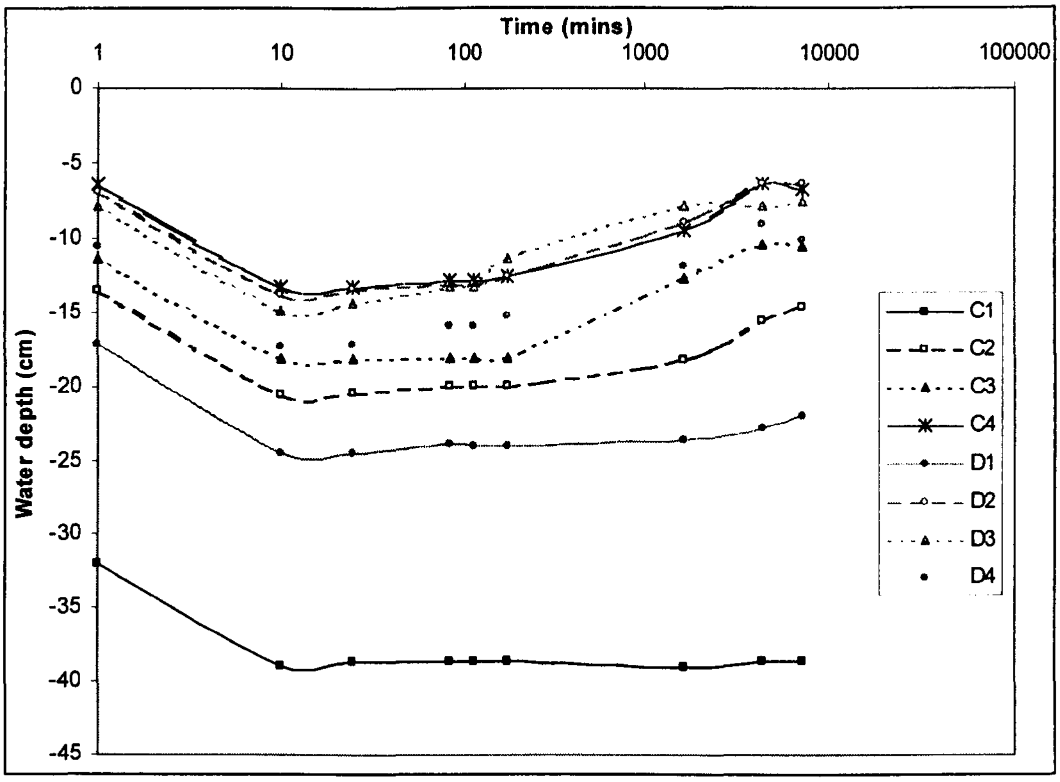


Table 3.14 Specific yield and hydraulic conductivity of various peat horizons (Boelter, 1965)

Depth (cm)	**Peat Type**	**Specific Yield (cc/cc)**	**Hydraulic Conductivity (cm/s)**
0-10	Live *Sphagnum* moss	0.79	-
15-25	Undecomposed moss peat	0.52	10^{-4}
45-55	Undecomposed moss peat	0.33	10^{-5}
50-60	Well decomposed moss peat	0.10	10^{-7}

3.5 SUMMARY

1. On Cuilcagh Mountain, different areas of the blanket bog appear to be prone to two different types of slope failure. All failures on East Cuilcagh are bog flows situated around the 350 m contour line, whereas peat slides are more prevalent on the northern and southern slopes close to the 450 m contour line.
2. Various topographic features are associated with the different types of failure found on Cuilcagh Mountain. Typically, large proportions of areas affected by bog flows are made up of subsided and cracked bog at the margins of the failure scars. Long crescent-shaped rafts are often transported a considerable distance from the source area with large amounts of peat slurry to form well defined flow tracks and levees. Peat slides generally consist of a bare clay scar and an area of deposited large rafts towards the foot of the slope, confined to a relatively small distance from the source area.
3. A total of 47 individual bog failures has been identified on Cuilcagh Mountain blanket bog. It has been estimated that these events involved the removal of over 300,000 m^3 of peat from a total area of 200,000 m^2. Since 1981, 23 bog failures have occurred, the majority of which were peat slides thought to be associated with periods of increased sheep stocking and uncontrolled burning in the 1980's.
4. The magnitudes of bog failures on Cuilcagh Mountain are highly variable. On average, areas disrupted by bog flows tend to be considerably larger than those affected by peat slides.
5. *In situ* shear strengths were determined at four sites on Cuilcagh Mountain. In general, the lowest shear strengths were found in an area of 'pristine' bog on East Cuilcagh while some of the highest were found on a drained and cracked section of bog associated with the bulging slope. Although determined shear strengths were variable throughout the profiles, higher shear strengths were mainly associated with the basal catotelm peat, whereas the lowest were found in the acrotelm and upper catotelm.
6. On the pristine slope the water table was always within the upper 13 cm of bog. The lowest and most constant water tables were found within the deeper peat at a shallow gradient. Water levels in the peat upslope of a failure scar seemed to be more variable. Average water levels within three metres of the scar were recorded at 27 cm from the surface, whereas 18 m from the scar water levels were found to be within 3 cm of the surface.
7. Field hydraulic conductivity (k) was determined for a range of depths at two sites in the proximity of failure scars and was found to vary over three orders of magnitude. Calculated k_{sat} within the upper 90 cm of peat was approximately 10^{-6} cm/s, and with the exception of one anomalous reading, in the lower catotelm k_{sat} decreased steadily to 10^{-9} cm/s.

CHAPTER 4

PEAT PROPERTIES: LABORATORY METHODS AND RESULTS

4.0 INTRODUCTION

The great diversity that exists in peat and the complex nature of continuing decomposition make it essential to carry out a detailed investigation into the physical properties of the peat and their variation with depth. This is particularly important as comparisons in literature are complicated by the sensitivity of the ecosystem and the peatlands development within a specific climatic regime. The importance of studying the changes in the physical, hydrological and geotechnical properties with depth through the peat column are highlighted in Chapter 2.

There is a general lack of data concerning the physical, geotechnical and hydrological properties of blanket bog peat, particularly in the catotelm, as this is relatively inaccessible. Therefore, in this study it has been necessary to use data from ombrotrophic raised bogs for comparison with the Cuilcagh peat. It is recognised however, that although ombrogeneous peat is essentially the same type of material, peat from raised and blanket bogs can be substantially different as a result of the different environmental conditions and topography of the areas in which they have accumulated.

Published relationships between property variables usually refer to the degree of humification, as opposed to depth from the surface, to illustrate the changing properties of peat within a bog. Presumably one of the main reasons for this is to enable comparisons between different types of peat, for example the comparison of a relatively thin depth of blanket bog peat with a much greater depth of raised bog peat. The importance of the degree of decomposition is recognised with respect to the physical properties of the peat; however, the von Post test is purely subjective, relying on the experience of the tester. To ascertain the characteristics and changing properties of the acrotelm and catotelm, sampled depth profiles have been used here.

To determine the characteristics of the Cuilcagh peat, to assess the changing properties with depth and to ascertain any differences between the slopes prone to bog flows and peat slides, samples were collected from sites on East Cuilcagh and the northern slopes of the mountain. Details of the selection of sites are given in Chapter 3. The physical properties of the peat tested in this study comprised degree of humification, dry bulk density, organic content and field moisture content and have been used to give an indication of the state, condition and variability of the peat. Various geotechnical and hydrological properties were determined to give an indication of the strength of the peat at different levels of decomposition and comprised saturated hydraulic conductivity, Atterberg tests (liquid and plastic limits), consolidation and shear strength determinations.

As discussed in Chapter 2, all physical properties of peat are affected by the plant species forming the peat as well as the processes of decomposition. Variability of the peat resulting from differences in botanical composition occurs during deposition and also from stress applications. This structural diversity is further complicated by variations in the intensity of the humification process, as certain parts of the plants are more resistant to breakdown than others, making peat both horizontally and vertically heterogeneous. The botanical composition and degree of decomposition of the peat also affects the ability of the material to retain water (Landva and Pheeney, 1980). Differences in the structure and distribution of water held within the peat are reported to have a particularly important influence on the geotechnical properties of peat (e.g. Hanrahan, 1954; Hanrahan *et al.*, 1972; Landva and Pheeney, 1980; Hobbs, 1986).

4.1 PHYSICAL PROPERTIES OF THE CUILCAGH PEAT

4.1.1 Introduction

Standard methods of physical analyses were used to determine the following properties of the peat samples: degree of humification (Hobbs, 1986); dry bulk density (Galvin, 1976); ash content (Landva *et al.*, 1983; Jarratt, 1983); and field moisture content (Rycroft *et al.*, 1975; Galvin, 1976). These determinations were carried out to provide an indication of the general characteristics and changing state of the peat with depth in the profile.

4.1.2 Degree of Humification

An investigation of the degree of decomposition of peat is of vital importance in the study of the peat's material properties, as it gives rise to the great diversity observed in peat structure and also affects its geotechnical characteristics. The rate of humification is affected by many factors such as temperature, water supply and oxygen supply, all of which can be correlated with depth (Hobbs, 1986). This results in temporal variability of peat within a bog as degree of humification changes through space and time.

The humification classification system of von Post (explained in section 2.1.3 and in Table 2.2) was used to describe the structure of the mainly *Sphagnum*-based Cuilcagh peat in semi-quantitative terms. The peat was graded on a scale of 1 to 10 (with 1 representing no decomposition and 10 being completely humified) and designated H_1 to H_{10}. Other tests can be used to determine the humic or fibre content of organic samples. However, these tend to be time consuming and result in variable success. For example, Malterer *et al.* (1992) reviewed and evaluated methods to measure degree of decomposition and fibre content and found the von Post humification method more successful at separating more classes of peat with greater precision than the fibre content methods. Therefore, in the present study, the von Post field classification system (together with laboratory-based bulk density and organic content determinations) has been used to indicate the degree of humification of the Cuilcagh peat.

There are very few studies of changing humification with depth in blanket bogs. This is remarkable given that differences in decomposition give peat its inherent variability. It is considered that one of the main reasons for this is the difficulty of sampling bogs at depth. Indeed, often entire peat masses are characterised by the properties of the tested upper acrotelm as it is more easily accessible (for example Päivänan, 1973; Clymo, 1984a, 1991). Humification is usually used to characterise other properties of the peat (as explained earlier) as it is closely related to botanical composition, but it is equally important to assess the changing nature of the material with depth. This gives an indication of the dynamics of the overall peat system.

Figure 4.1 illustrates the changes in degree of humification with depth of a *Sphagnum* dominated raised bog in Canada (Landva and Pheeney, 1980). It is noted that most of the peat in the profile lies between H_2 and H_5. The peat in the upper profile (acrotelm) was designated $H_{2\text{-}3}$ and sharply increased to form an upper peak at a depth of one metre. This was followed by an equally sharp decrease and illustrates the variable nature of the peat in the uppermost two metres of bog. Below this depth, the degree of humification was noted to increase steadily. At closer inspection using a SEM, Landva and Pheeney (1980) noted that the material at the base of the bog designated as H_8 actually consisted of alternating layers of $H_{3\text{-}6}$ and H_{10} material and that this was not uncommon in bogs.

Figure 4.2 illustrates the changes in humification with depth (average of 3–4 determinations) for sampled profiles on eight sites on Cuilcagh Mountain. Although there is an overall trend of increasing humification with depth, there is a notable degree of spread due to the variety of vegetation forming the peat and differences in the intensity of the decomposition process which, due to varying environmental conditions, are site specific (Lüttig, 1986). Figure 4.3 illustrates all humification determinations for profiles on two failure sites. Although humification seems more variable at greater depths, Table 4.1 shows that the standard deviation is at a minimum at the base of the profiles, particularly for N4. This indicates that at each site, the degree of humification increases with depth in relation to its own particular profile. Immediately below the surface of living vegetation, the remains of the flora display small degrees of decomposition of between H_2 and H_3. Humification increases with depth in most of the sampled sites; however, at 45 cm depth in some of the profiles on the north side of the mountain, a layer of less decomposed fibres and woody remains of heather (*Calluna vulgaris*) were noted to be present on some profiles. This layer indicates different environmental conditions during vegetation growth and peat transformation, possibly due to the effect of a period of burning or overgrazing and subsequent growth of drier-based vegetation. Humification attains a maximum towards the base of the bog, noted in both areas of deep peat adjacent to bog flows and thinner peat at the margins of the peat slides. However, at the very base of the profiles, particularly those from the northern slopes, the peat is amorphous, pasty and relatively sticky in nature. It is thought that the influence of the underlying clay (discussed later) has the effect of producing an apparent reduction in the degree of humification to between H_7 to H_8.

It was noted that, disregarding total depth of peat, one of the main differences between bog flow and peat slide sites was the absence of basal peat slurry on slide sites. Although most of this material had drained from the bog immediately surrounding the older scar areas on East Cuilcagh, basal peat slurry (as described in section 3.1.4) was found on and around the fresh failure scar of E6 and was extracted by the soil auger on the pristine slope (site 1) and the bulging slope (site 2). This basal peat was amorphous with no identifiable plant structure and upon squeezing all the peat passed between the fingers, indicating it was completely humified (H_{10}).

4.1.3 Bulk density

Bulk density is recognised as being an important physical parameter of soil analysis, and for organic soils can be used to indicate degree of humification (Boelter, 1969; Päivänan, 1969). It is also considered important in studies of peat accumulation rates (Clymo, 1983). In comparison with mineral soils, the dry bulk density of peat

Figure 4.1 Degree of humification for a *Sphagnum* dominated bog (Landva & Pheeney, 1980).

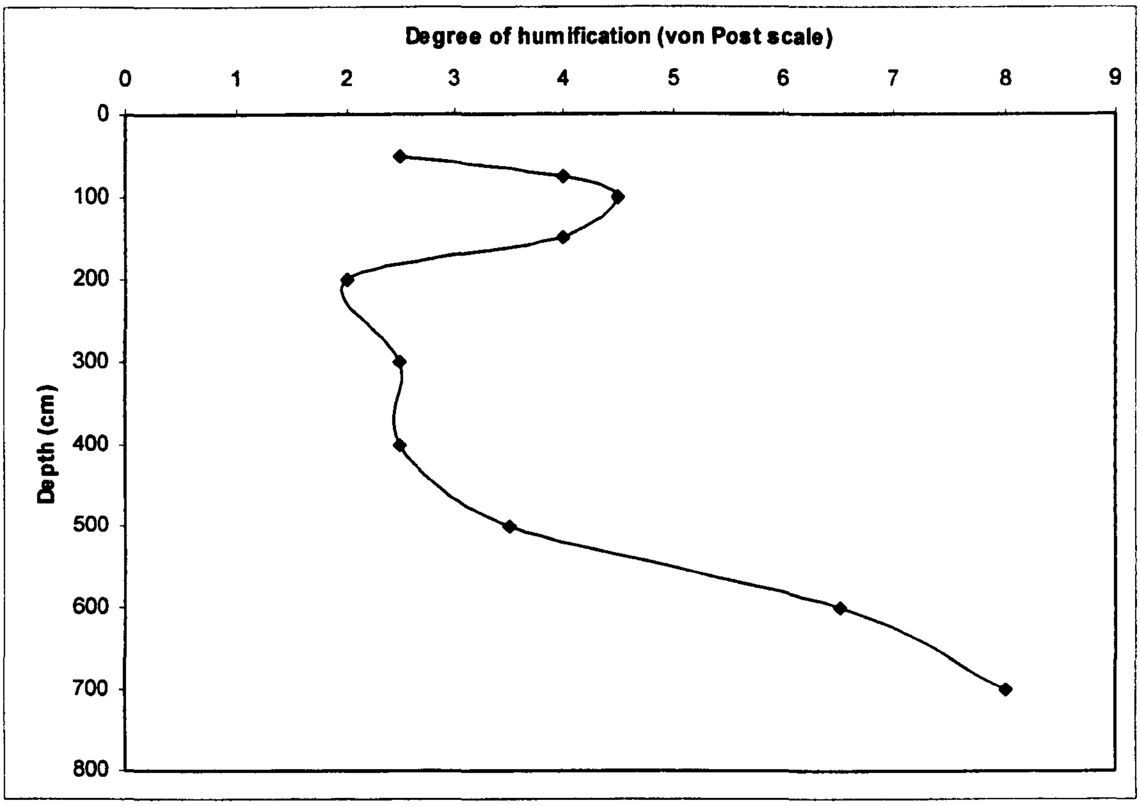


Figure 4.2 Mean degree of humification values for all failure sites on Cuilcagh Mountain.

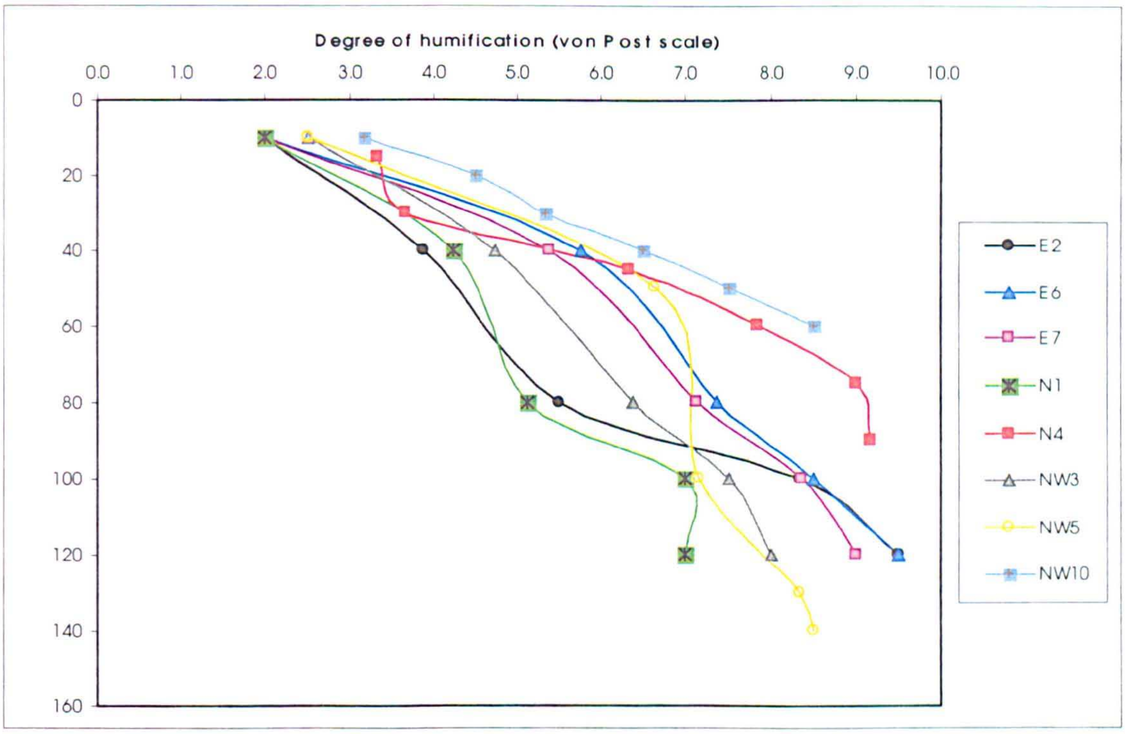


Figure 4.3 Range of degree of humification for two sites on Cuilcagh Mountain.

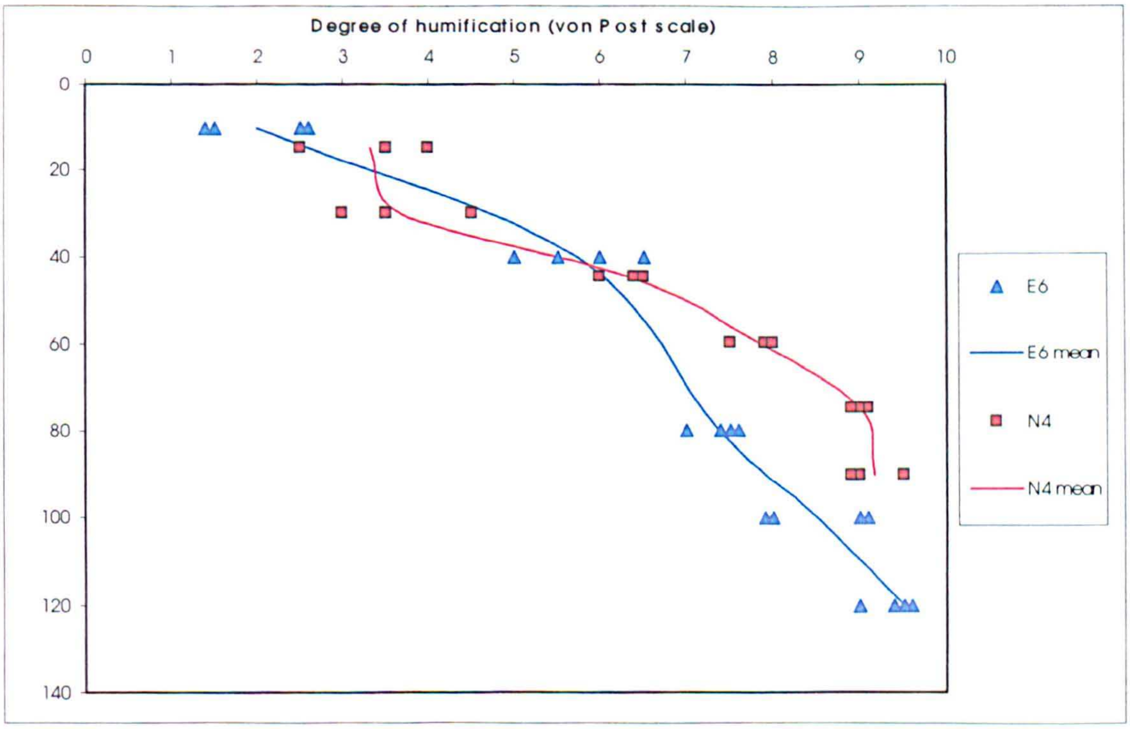


Table 4.1 Summary of degree of humification data for two failure sites on Cuilcagh Mountain (corresponding to figure 4.3)

DEPTH (cm)	NUMBER OF SAMPLES	SAMPLE MEAN	STANDARD DEVIATION	RANGE
E6				
10	4	2	0.58	1.5 - 2.5
40	4	5.8	0.65	5.0 - 6.5
80	4	7.5	0.25	7.0 - 7.5
100	4	8.5	0.58	8.0 - 9.0
120	4	9.5	0.25	9.0 - 9.5
N4				
15	3	3.3	0.76	2.5 - 4.0
30	3	3.7	0.76	3.0 - 4.5
45	3	6.3	0.29	6.0 - 6.5
60	3	7.8	0.29	7.5 - 8.0
75	3	9.0	0.00	All 9.0
90	3	9.2	0.29	9.0 - 9.5

is low and variable and is related to the organic content, moisture content, degree of saturation and void ratio (Hobbs, 1986).

A typical profile as reported by Clymo (1983) for a *Sphagnum* dominated bog shows relatively high dry bulk density at the surface of the bog (0.07 g/cm³), falling rapidly to approximately 0.02 to 0.04 g/cm³ in the underlying tightly packed mosses. Dry bulk density then gradually increases to a point where the load can no longer be supported by the weakened moss structure (typically 10 to 30 cm) where it increases rapidly to 0.1 g/cm³ (Clymo, 1983). Further increases in dry bulk density are noted with depth and increased humification. Herbaceous peat results in slightly higher bulk densities, such as 0.12 to 0.15 g/cm³ (Tallis and Switsur, 1973). Figure 4.4 illustrates some published values showing the close relationship between bulk density and decomposition. Field bulk density is also considered to be important for indicating the general state of peat (Hobbs, 1986). Hobbs states that for bog peat at low moisture contents (0-500%), field bulk densities are variable and range between 1.0 and 1.3 g/cm³, whereas at higher moisture contents exceeding 500% the bulk density remains fairly constant between 0.9 and 1.0 g/cm³.

The dry bulk density of the Cuilcagh peat was determined using standard techniques which involved drying samples of known field volume at 80-90°C for 48 hours (Galvin, 1976). The bulk density could then be calculated by dividing the dry mass by the volume of the sample as collected from the field.

Figure 4.5 illustrates the range of dry bulk density values for all of the sites on Cuilcagh. Each value represents the mean of at least four results. All of the values lie between 0.08 and 0.2 g/cm³, and show a maximum at, or towards the base of the profile. However, there is no general pattern to describe all of the sites. The profiles from three sites (E2, E7 and N4) have relatively high bulk densities for the surface layer, which decrease until approximately 40 cm, before gradually increasing towards the base of the profile. The profiles of three other sites (N1, NW3 and NW5) illustrate a distinctly different pattern with lower bulk densities at the surface increasing at different levels to attain maximum at the base. Figure 4.6 illustrates all of the results of dry bulk density for two failure sites (E2 and N4). Although E2 is a bog flow in deep peat and N4 is a peat slide site in a shallow depth of peat, they both show a similar relationship between bulk density and depth. The highest bulk densities within the profile are located in the root mat (upper acrotelm) and the basal peat (lower catotelm). The middle of the profile consisting of the transition zone and upper catotelm (at 40-70 cm) has lower bulk densities. Undecomposed peat is characterised by variable bulk densities due to differences in surface vegetation and void spaces, but it tends to have higher bulk densities due to the accumulation of fresh vegetation which can be tightly packed into layers. Peat in the transition zone has been broken down by humification but still remains relatively uncompressed, at least in comparison with the base of the peat mass where the normal load exerted by the weight of the accumulated peat results in an increased bulk density. The basal peat also contains fewer void spaces as the fabric of the peat has been broken down into an amorphous granular structure as decomposition is at a maximum. A summary of the data for E2 and N4 sites is given in Table 4.2. The variability of bulk density values is noted to be greatest at the surface and base of the profiles. Although caution was taken during extraction of samples to minimise disturbance, it is possible that compression of the peat may have occurred, particularly with samples from the fibrous upper acrotelm. Variability of the basal peat may have been the result

Figure 4.4 Some published values of changes in dry bulk density with degree of humification.

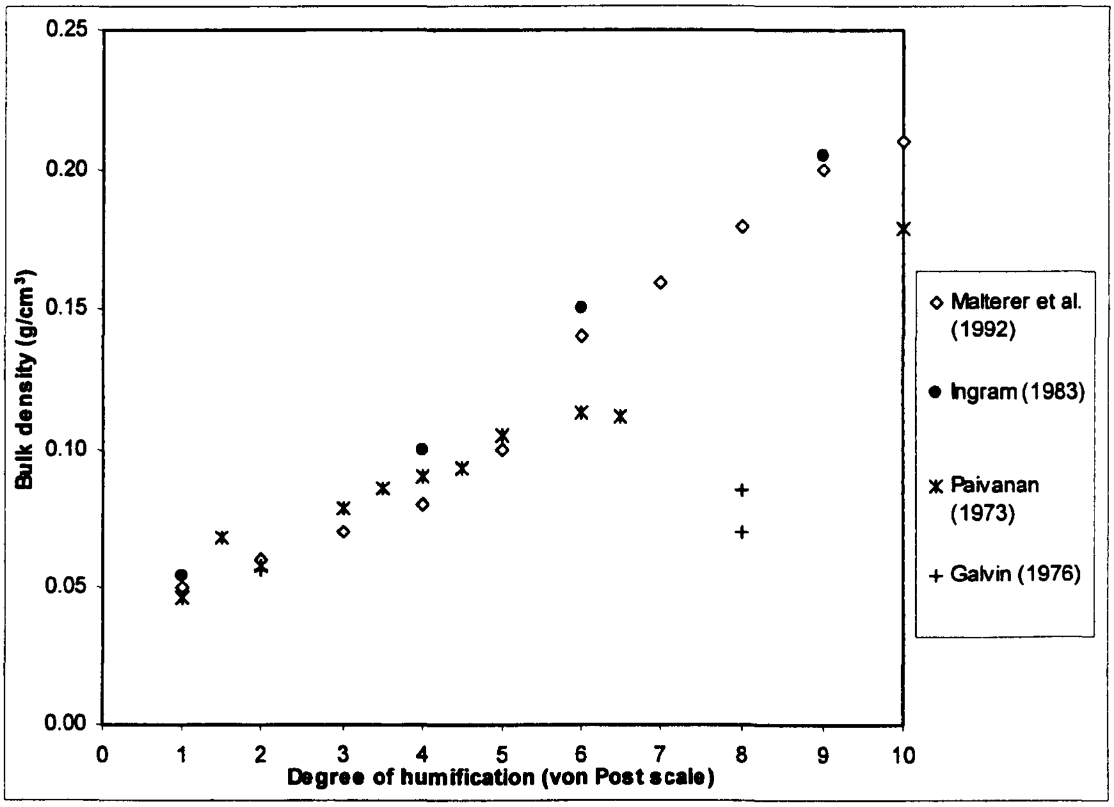


Figure 4.5 The range of mean dry bulk density values calculated for all failure sites on Cuilcagh Mountain.

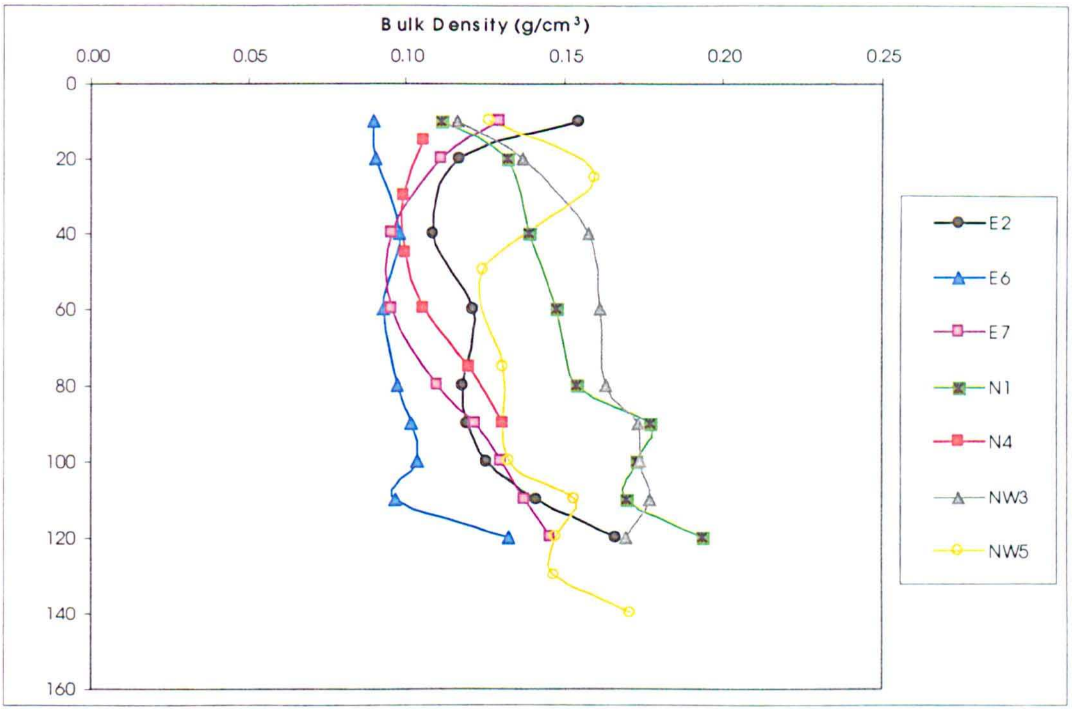


Figure 4.6 All dry bulk density results for two failure sites on Cuilcagh Mountain.

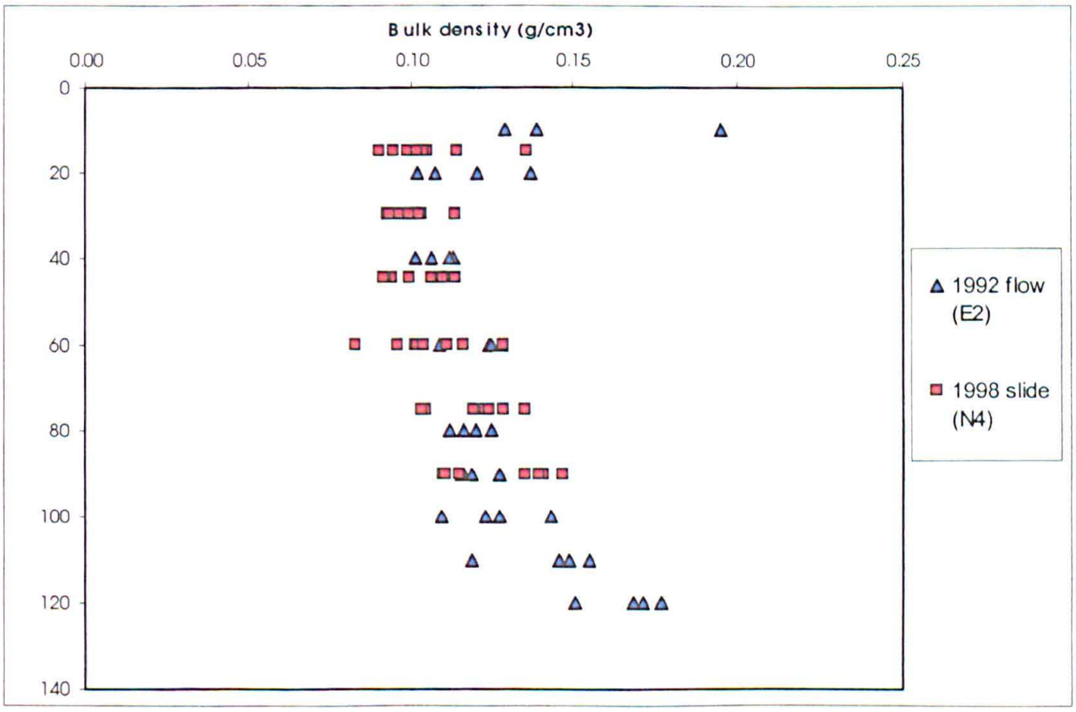


Table 4.2 Summary of the dry bulk density data for two failure sites on Cuilcagh Mountain.

Site	Depth (cm)	Number of samples	Sample mean (g/cm^3)	Standard deviation	Range of values (g/cm^3)
E2	10	3	0.154	0.036	0.129 - 0.195
	20	4	0.117	0.016	0.102 - 0.137
	40	4	0.108	0.005	0.102 - 0.113
	60	4	0.121	0.009	0.109 - 0.128
	80	4	0.118	0.005	0.112 - 0.125
	90	4	0.119	0.005	0.115 - 0.127
	100	4	0.126	0.014	0.110 - 0.143
	110	4	0.142	0.016	0.119 - 0.155
	120	4	0.167	0.012	0.150 - 0.177
N4	15	8	0.106	0.014	0.090 - 0.136
	30	8	0.099	0.007	0.093 - 0.114
	45	8	0.100	0.009	0.091 - 0.114
	60	8	0.105	0.014	0.083 - 0.129
	75	8	0.120	0.011	0.103 - 0.135
	90	8	0.131	0.016	0.110 - 0.147

of the presence of mineral matter within the samples, which would increase the bulk density. Evidence of this is discussed in the following section.

4.1.4 Organic Content

Measurements of organic content are based on the assumption that organic matter is generally combustible, as opposed to the mineral constituent, which can be part of the plant growth or extraneous matter and is incombustible and ash forming (Landva *et al.*, 1983). As a soil property, organic content has been used as a means of classifying peat and organic soils (for example, Landva *et al.*, 1983). Pure *Sphagnum* peat consists of 99% organic matter, and most peat contains less than 20% inorganic matter (Clymo, 1983). Herbaceous peat is denser than moss peat and results in higher ash contents (Clymo, 1983). Small amounts of inorganic constituents of peat may result from concentration in precipitation of elements (such as sodium, magnesium and chloride) which originate from sea spray, dry deposition resulting from soil dust and industrial and domestic gases (Clymo, 1983). It is also noted that inorganic matter from dry deposition and precipitation varies with place and fluctuates with season and with agricultural practice (Boatman *et al.*, 1975). For example, accumulations of minerals are likely to be present on a bog surface which has been subjected to periods of grazing and burning (Pearsall, 1950). The amount of organic material is an important geotechnical property as it affects the water holding capacity of the soil (Hobbs, 1986).

The organic content has been measured using the loss on ignition method, which requires determination of the loss in mass of an oven dried sample after ignition in a furnace (Gale and Hoare, 1991). The samples were first oven dried at 80-90 °C for 48 hours, and then pulverised and mixed before being placed into a furnace to ignite at 450 °C for 24 hours (Jarratt, 1983; Hobbs, 1986).

Figure 4.7 illustrates the changes in organic content with depth for a *Sphagnum* dominated raised bog in Canada (Landva and Pheeney, 1980). Most of the peat (0-600 cm) contains more than 97% organic matter, which rapidly declines towards the base of the bog (600-700 cm), as a result of increased mineral matter (inorganic matter). No information on the changing organic content of blanket bog peat with depth was found, although Päivänan (1973) provides an apparent relationship between organic content and humification in a *Sphagnum*-dominated bog. However, the results of Päivänan's work are irrelevant in this study as all of the samples were taken from the upper 10 to 15 cm of bog.

Figure 4.8 illustrates the range in organic contents for all of the sampled sites on Cuilcagh. Each value is the mean of 3 to 8 results. Overall, mean organic contents on Cuilcagh range between 80 and 99%. However, the organic contents at the bog flow sites on East Cuilcagh (E2, E6 and E7) range between 93 and 99%, whereas at sampled peat slide sites (N4 and NW10), values range from 80 to 97%. As a general pattern, all of the profiles attain a maximum in the middle of the profiles at a variety of depths. Also, with the exception of E7, the minimum values are associated with either the surface or the base of the profiles. To further investigate the differences between bog flow and peat slide sites Figure 4.9 shows all of the organic content results for three sites (E2, E6 and N4). Table 4.3 shows a summary of the corresponding data. The two bog flow sites (E2 and E6) are characterised by very high organic contents (> 93%) and a relatively small degree of scatter with

Figure 4.7 Published values of organic content for a *Sphagnum* dominated raised bog (Landva & Pheeney, 1980).

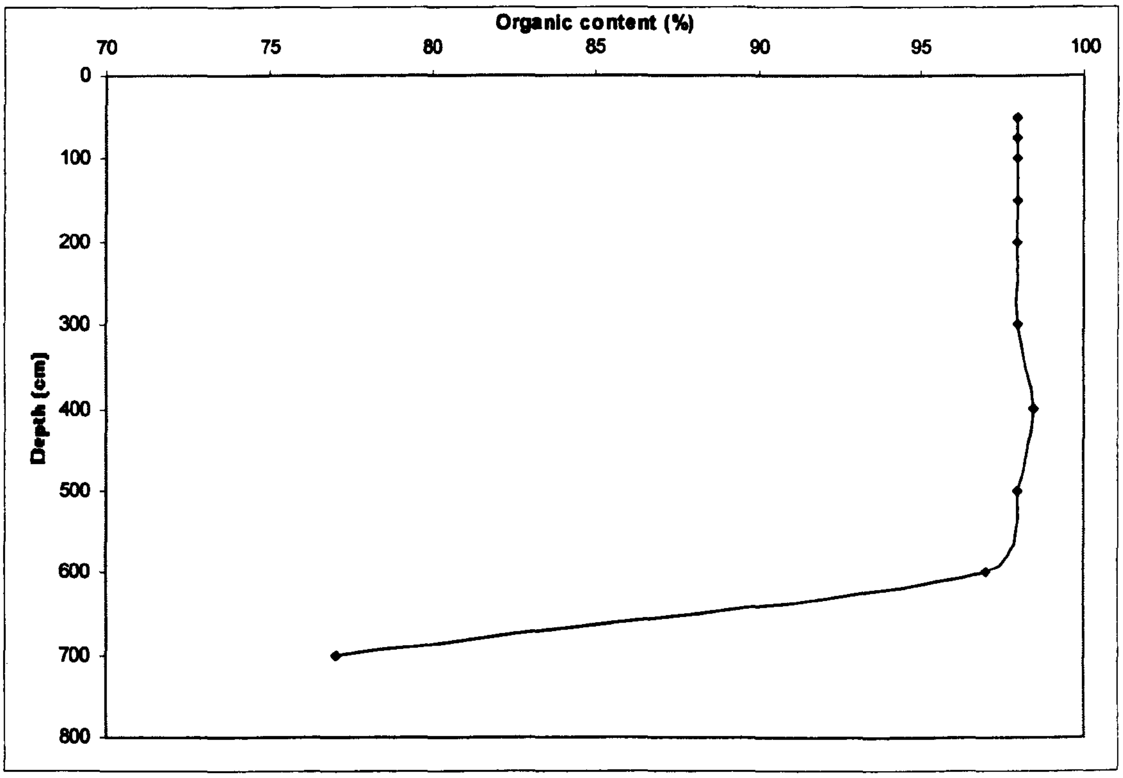


Figure 4.8 The range of mean organic content values calculated for all failure sites on Cuilcagh Mountain.

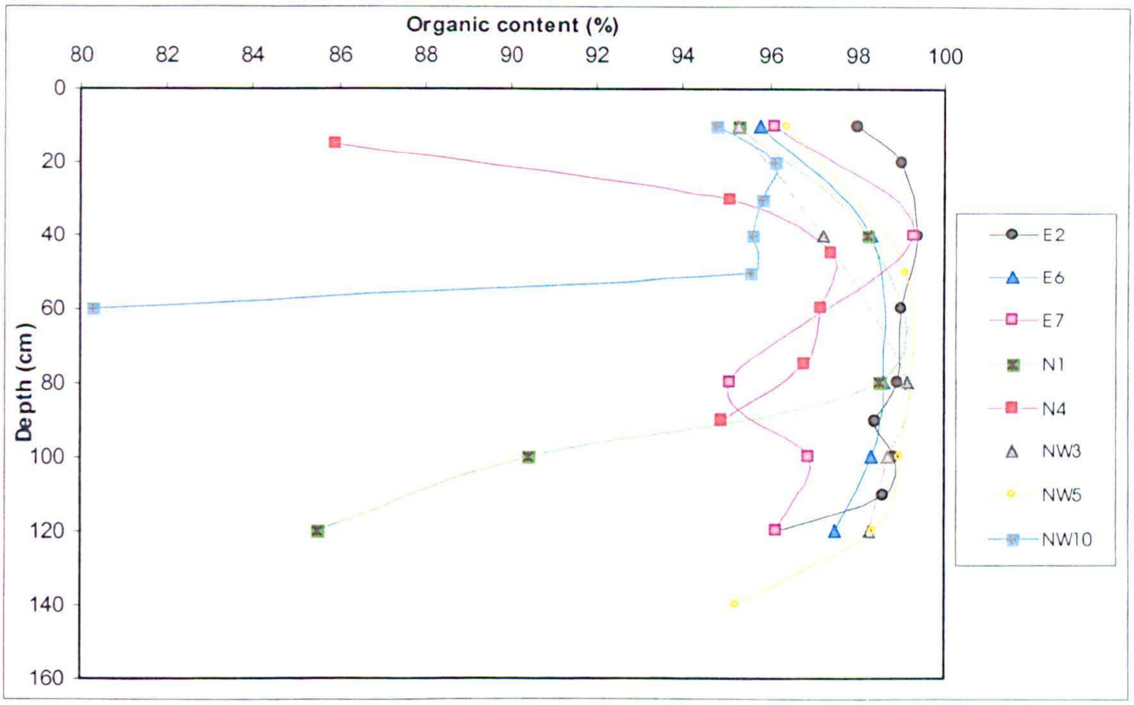


Figure 4.9 All organic content results for three failure sites on Cuilcagh Mountain.

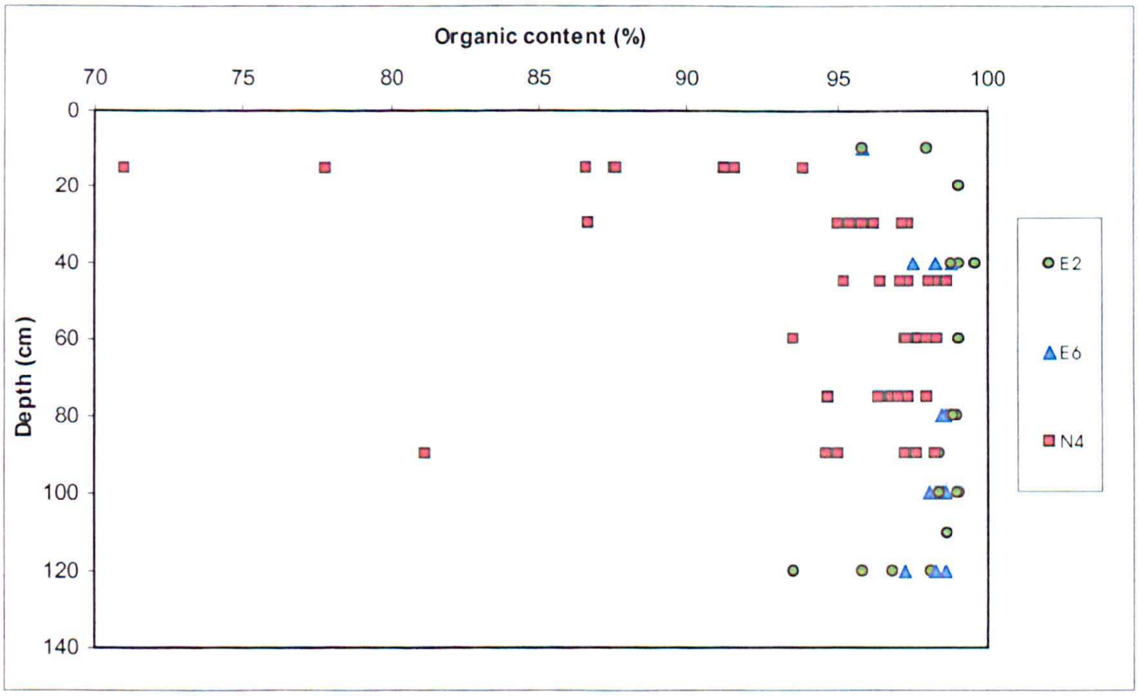


Table 4.3 Summary of organic content data for three failure sites on Cuilcagh Mountain.

Site	Depth (cm)	Number of samples	Sample mean (%)	Standard deviation	Range of values (%)
E2	10	1	98.00	-	-
	20	1	99.04	-	-
	40	3	99.42	0.34	99.03 - 99.61
	60	1	99.03	-	-
	80	3	98.93	0.12	98.79 - 99.01
	90	1	98.41	-	-
	100	3	98.85	0.63	98.50 - 99.04
	110	1	98.63	-	-
	120	3	96.17	2.34	93.56 - 98.09
E7	10	2	95.80	0.00	-
	40	4	98.34	0.60	97.51 - 98.80
	80	4	98.61	0.18	98.43 - 97.86
	100	4	98.33	0.23	98.04 - 98.60
	120	4	97.48	1.25	95.80 - 98.60
N4	15	8	85.92	7.73	71.04 - 93.89
	30	8	95.11	3.53	86.65 - 97.40
	45	8	97.42	1.15	96.43 - 98.68
	60	8	97.17	1.52	93.54 - 98.35
	75	8	96.78	0.97	94.70 - 98.00
	90	8	94.89	5.71	81.15 - 98.26

standard deviations not exceeding 0.7 until the very base of the peat. In comparison, values at the peat slide site (N4) are more variable, particularly at the surface and the base giving standard deviations of 7.7 and 5.7 respectively. This increased variability of the peat at the surface on northern slopes compared to eastern slopes may be the result of a number of factors. Firstly, vegetation cover on north Cuilcagh consists of mainly of heather and grasses compared to the more gentle slopes on East Cuilcagh where the bog is mainly dominated by *Sphagnum* mosses. Secondly, the northern slopes of the mountain are more heavily grazed. Both of these factors give rise to increased proportions of inorganic matter. Variability of organic contents at the base of the bog results from the influence of the underlying clay and soil that also increases the mineral content. This was noted to be the case for all sampled sites.

4.1.5 Field Moisture Content

As stated in Chapter 2, the moisture content of peat is variable both horizontally and vertically, can range from 200 to 2000% of dry weight and usually decreases with humification (Hobbs, 1986). It has also been suggested that the range of moisture contents from different climatic regions can be compared successfully (Hobbs, 1986). Gravimetric field moisture content was determined by the standard technique (Galvin, 1976) which involved drying samples at 80-90°C for 48 hours. Gravimetric rather than volumetric moisture content is usually the preferred parameter for describing organic soils as it is sensitive to small changes in the weight of solids (Landva and Pheeney, 1980; Hobbs, 1986).

Figure 4.10 illustrates the range of moisture content values with depth in a *Sphagnum* dominated bog in Canada (Landva and Pheeney, 1980). Although this is classed as a raised bog, Hobbs (1986) suggests that morphologically it would be described as a blanket bog in the UK. The limits of field moisture content in the upper and middle sections of the bog are most variable, ranging from a minimum of 800% at 50 cm, to a maximum of 1900% at 250 cm. Moisture contents decline with decreasing variability as depth increases. At the very base of the bog (700 cm), the moisture content ranges between 400 and 800%. Although the hydrology and related physical properties of bogs differ with morphology, surface topography, and a suite of environmental conditions, Hobbs (1986, p. 30) states that this range of moisture contents is comparable to values obtained from a Welsh blanket bog and states that, "as a general rule the range of water content found in peats in the UK is very similar to that from other parts of the world."

Figure 4.11 illustrates the range of mean field moisture contents for all sampled sites (average of at least three determinations). With the exception of sites N4 and NW10, these samples were collected over a one week period in May 1998. Sites N4 and NW10 were sampled within a few weeks of the failure events occurring. The mean field moisture contents range between 430 and 950% (dry weight), and are therefore lower than the values quoted for various other bogs (Galvin, 1976; Landva and Pheeney, 1980; Hobbs, 1986). There is no general pattern that fits all of the sampled profiles, although it is noted that all moisture contents decrease within the middle section to reach a minimum value at the base. Figure 4.12 shows all field moisture content values for four sites (E7, N1, N4 and NW3) and Table 4.4 shows a summary of these data. The two profiles for E7 and N4 have a similar pattern to that described by Landva and Pheeney (1980) in Figure 4.10. Two other profiles (N1 and NW3) show a distinctly different relationship of moisture content with depth as moisture content decreases

Figure 4.10 Published values of field moisture content of a *Sphagnum* dominated raised bog in Canada (Landva & Pheeney, 1980).

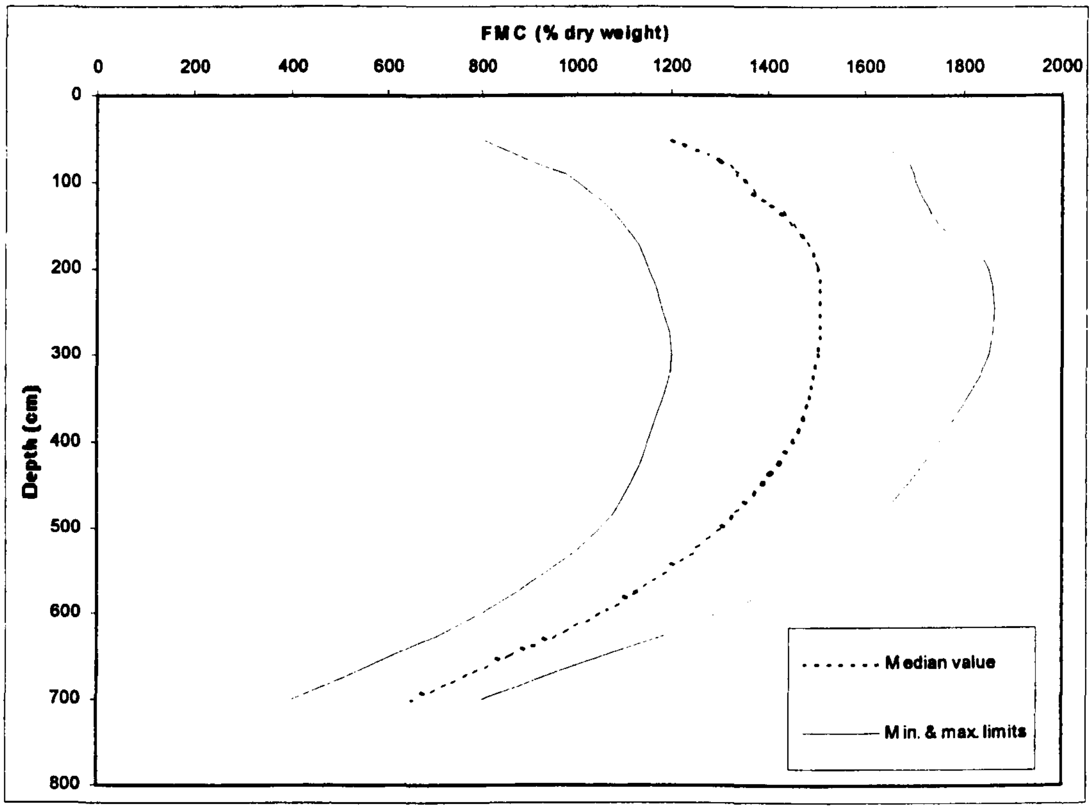


Figure 4.11 The range of mean field moisture contents (% dry weight) at all failure sites on Cuilcagh Mountain.

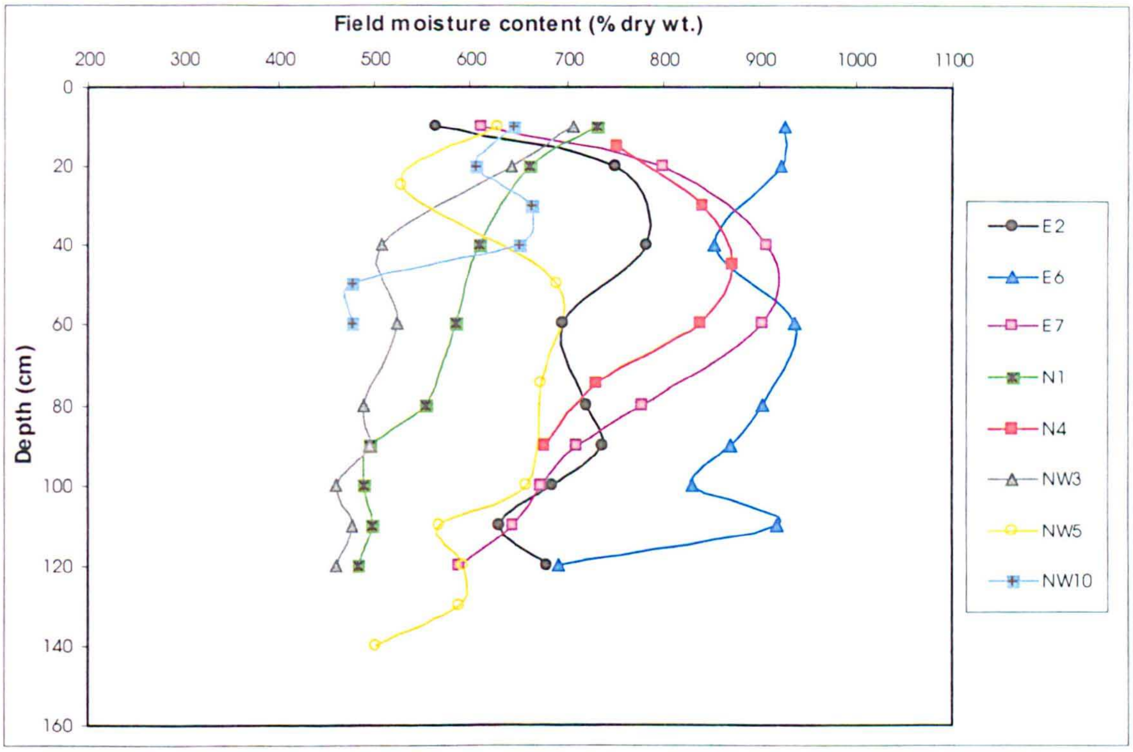


Figure 4.12 Field moisture content (% dry weight) at four failure sites on Cuilcagh Mountain.

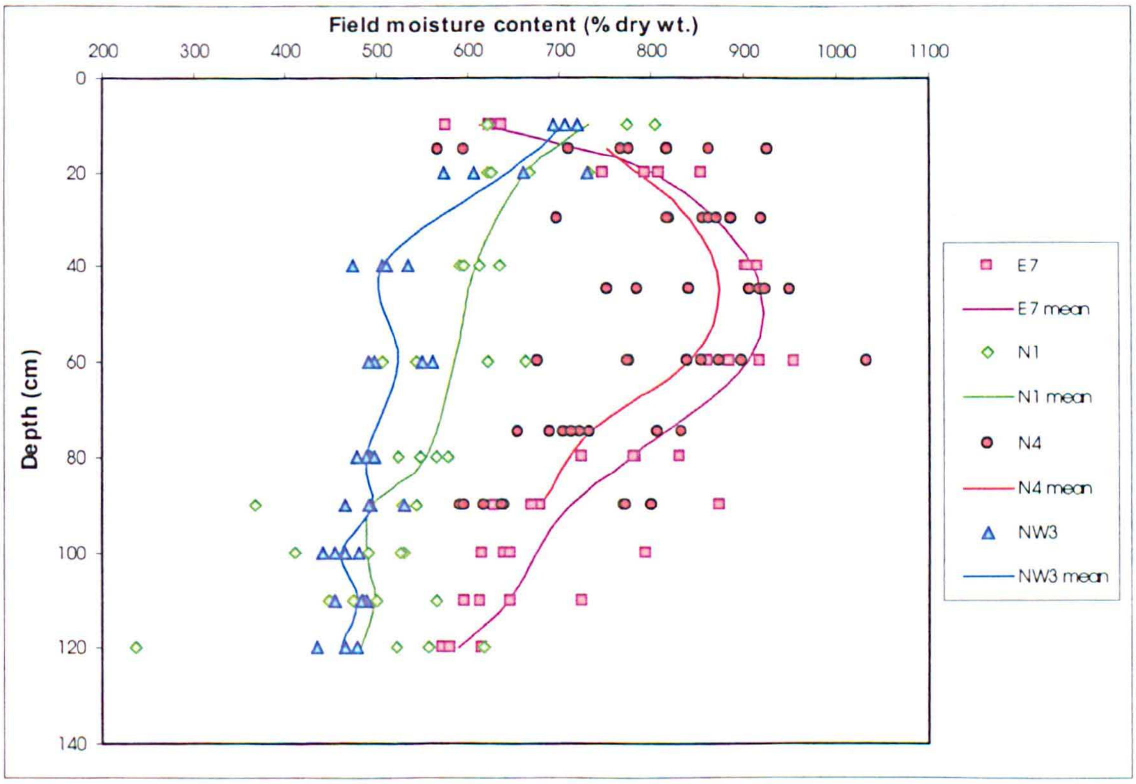


Table 4.4 Summary of field moisture content data for four failures on Cuilcagh Mountain (corresponding to Figure 4.12).

SITE	DEPTH (cm)	NUMBER OF SAMPLES	MEAN MOISTURE CONTENT (% dry wt.)	STANDARD DEVIATION	RANGE
E7	10	3	612	31	577 - 636
	20	4	801	44	748 - 855
	40	4	908	5	902 - 914
	60	4	904	40	861 - 953
	80	4	779	43	724 - 830
	90	4	712	110	628 - 873
	100	4	674	80	616 - 793
	110	4	644	56	595 - 723
	120	3	589	23	571 - 615
N1	10	3	733	98	621 - 803
	20	4	662	51	621 - 732
	40	4	609	20	591 - 635
	60	4	584	72	507 - 664
	80	4	554	23	524 - 577
	90	4	496	86	367 - 544
	100	4	490	55	411 - 530
	110	4	497	50	448 - 566
	120	4	483	169	236 - 618
N4	15	8	753	124	568 - 926
	30	8	841	67	697- 919
	45	8	874	73	751 - 950
	60	8	840	105	675 - 1033
	75	8	732	59	655 - 832
	90	8	678	87	590 - 799
NW3	10	3	707	13	694 - 720
	20	4	643	69	573 - 731
	40	4	507	25	474 - 536
	60	4	525	35	491 - 560
	80	4	489	9	478 - 497
	90	4	495	26	465 - 529
	100	4	460	17	440 - 479
	110	4	477	15	455 - 488
	120	4	461	18	435 - 477

only slightly, but directly from the surface to reach a basal minimum. Fibrous peat in the upper section of the profiles generally contains more water than more humified granular amorphous peat (Hobbs, 1986). This ability to retain water results from the structure and distribution of water held within the peat, which is directly related to botanical composition and degree of humification (Landva and Pheeney, 1980). Intracellular water (free water) held within the internal cells usually dominates in relatively undecomposed peat, whereas interparticle water held by capillary forces and adsorbed water dominate in more humified peat where the cellular structure has been broken down (Hobbs, 1986). At sites E7 and NW3, the variability of moisture contents is low, whereas for sites N1 and N4, standard deviations are generally much higher indicating a higher degree of variability of the data, particularly at the surface and base of the profiles. This may result from the variable botanical composition and intensive areas of grazing on the northern slopes leading to a higher inorganic content at the surface (as described in section 4.1.4), and thereby reducing the water holding capacity of the peat. The presence of clay at the base of the peat also results in reduced moisture contents. Field moisture content in the surface acrotelm is also dependent on the position of the transition zone and water table at the time of sampling. For example, the water table at site E7 was approximately 20-30 cm below the ground surface at the time of sampling, whereas at NW3, the water table was at the surface.

4.2 HYDROLOGICAL AND GEOTECHNICAL PROPERTIES OF THE CUILCAGH PEAT

4.2.1 Introduction

The various hydrological and geotechnical properties of the Cuilcagh peat are studied to give an indication of the strength of the peat and its variability with depth below the surface. This hydrological and geotechnical information, together with other hydrological data collected from Cuilcagh forms the basis for the investigation on the controls of stability in blanket bog peatlands. The properties under examination comprise hydraulic conductivity, Atterberg limits, and consolidation and shear strength characteristics. As discussed in Chapter 3, site selection focused on the examination of the different failure types identified as being present on Cuilcagh Mountain. These sites, and the samples obtained from them, are detailed in section 3.2.3.

4.2.2 Saturated Hydraulic Conductivity

The hydraulic conductivity of peat is considered to be the most important geotechnical property as it controls the rate of consolidation and therefore strength under loads, such as embankments and fill sites (Hobbs, 1986). Unfortunately, it is notoriously difficult to determine in peat. Under natural loads, a few experiments have been carried out on peat of low humification (H_2-H_4) within the acrotelm, the permeability of which is reported to be high (10^{-1} to 10^{-3} cm/s) and follows Darcy's Law quite closely (Ingram *et al.*, 1974; Rycroft *et al.*, 1975; Clymo, 1983). The hydraulic conductivity of decomposed peat however, is much lower (approximately 10^{-6} cm/s according to Clymo, 1983) and there is much debate as to whether it obeys Darcy's Law. Indeed Ingram *et al.* (1974) states that the very concept of hydraulic conductivity does not apply to humified *Sphagnum* peat due to its perceived anisotropic nature. Other authors, such as Egglesmann and Mäkelä (1964) (cited in Päivänen, 1973) found Darcy's Law to be obeyed in such circumstances. The movement of water within a soil depends on the range in pore sizes and how the water is held within the material. For peat, differences in botanical composition and levels of decomposition affect the amount and distribution of water within the microstructure.

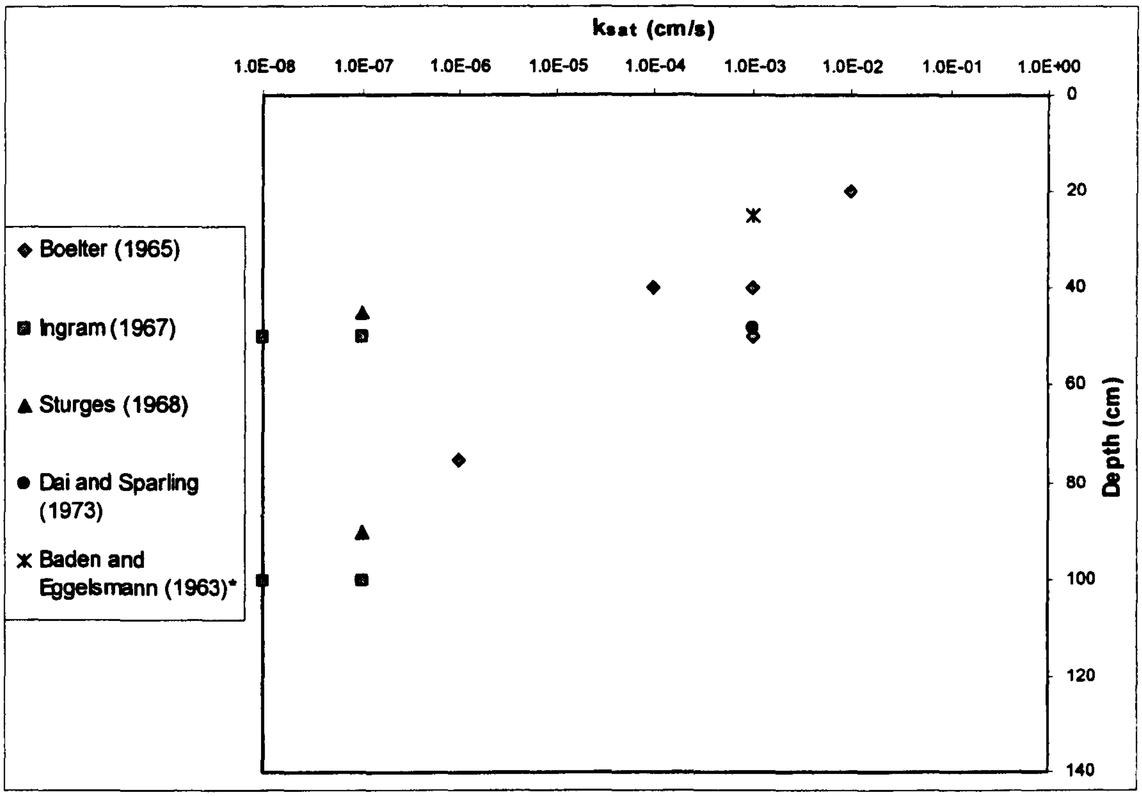
Most of the water in undecomposed peat is held within internal cells (intraparticle) or by capillary forces (interparticle), whereas water in more decomposed peat is bonded by stronger chemical forces (Clymo, 1983). Within the catotelm, higher bulk densities and increased loading of the peat mass results in further decreases in permeability.

The saturated hydraulic conductivity (k_{sat}) of the Cuilcagh peat was determined using constant-head apparatus. The samples were saturated in distilled water (as described by Galvin, 1976), then mounted on a fine mesh sieve with a collecting tray beneath. A constant head of water was maintained above the sample with the use of a sealed connector pipe and overflow tube. The rate of flow was measured by stopwatch and graduated cylinder. This method was generally effective although in an occasional sample the water bypassed the peat along the cylinder wall. In these instances the throughflow was considerably more rapid, and the peat around the outside of the sample had turned from brown to black due to oxidation. Consequently, these samples were disregarded. Galvin (1976) reports similar difficulty in reproducing some results particularly on those samples with either a larger wood content or a lower humification.

Published values of saturated hydraulic conductivity (k_{sat}) in peat are focused either exclusively on the permeability of the more accessible acrotelm, or on the measurement of the two extremes–undecomposed fibrous peat and highly humified amorphous peat. Very little field data is available on permeability at depth in the catotelm and there has been no study of the variability of hydraulic conductivity within an entire profile. However, Figure 4.13 has been compiled from a number of sources and illustrates the range of k_{sat} values for mainly *Sphagnum* peat with depth. Values of k_{sat} range several orders of magnitude, from 10^{-2} cm/s at the surface (20 cm) to 10^{-8} cm/s at 100 cm in depth and generally decrease with depth from the surface. This pattern is complicated by the inherent variability of k_{sat}, particularly in the middle section (40-50 cm) which may have resulted from comparing peat from different origins and geographic locations. Figure 4.14 illustrates the hyperbolic relationship between hydraulic conductivity and degree of humification for different types of peat (Rycroft *et al.*, 1975). It is noted that *Sphagnum* peat has lower k_{sat} than the herbaceous plant species and the range in k_{sat} values for all types is large for undecomposed peat (H_2-H_5) and decreases steadily towards 10^{-4} cm/s as humification continues.

An investigation of field k_{sat} using the Piezometer method is described in Chapter 3. Figure 4.15 illustrates the range in laboratory measurements of the rates of water movement in the Cuilcagh peat. Details of laboratory k_{sat} formulation and the data used are given in Appendix 4. The permeability of the root mat immediately below the live vegetation layer is relatively high with k_{sat} values situated mainly around 10^{-2} cm/s as the fibrous, undecomposed structure of the root mat and mosses can facilitate the rapid passage of water. As humification increases rapidly through the aerobic zone (i.e. above the level of the fluctuating water table), the permeability of the lower acrotelm and upper catotelm (35-45 cm) decreases to around 10^{-3} to 10^{-5} cm/s. Further decreases in permeability with depth are associated with the smaller proportion of available intracellular water and larger pore spaces, as more tightly bound adsorbed water dominates and bulk densities increase. Hobbs (1986) suggests that peat is hydraulically anisotropic, with horizontal permeability exceeding the vertical, given the nature of peat accumulation. He also suggests that this ratio (k_{horiz} to k_{vert}) is greater in the acrotelm and that humified peat is

Figure 4.13 The range of published values of hydraulic conductivity of peat.



* = Cited by Päivänen (1973)

Figure 4.14 The hyperbolic relationship between hydraulic conductivity and degree of humification for different types of peat (Rycroft *et al.*, 1975).

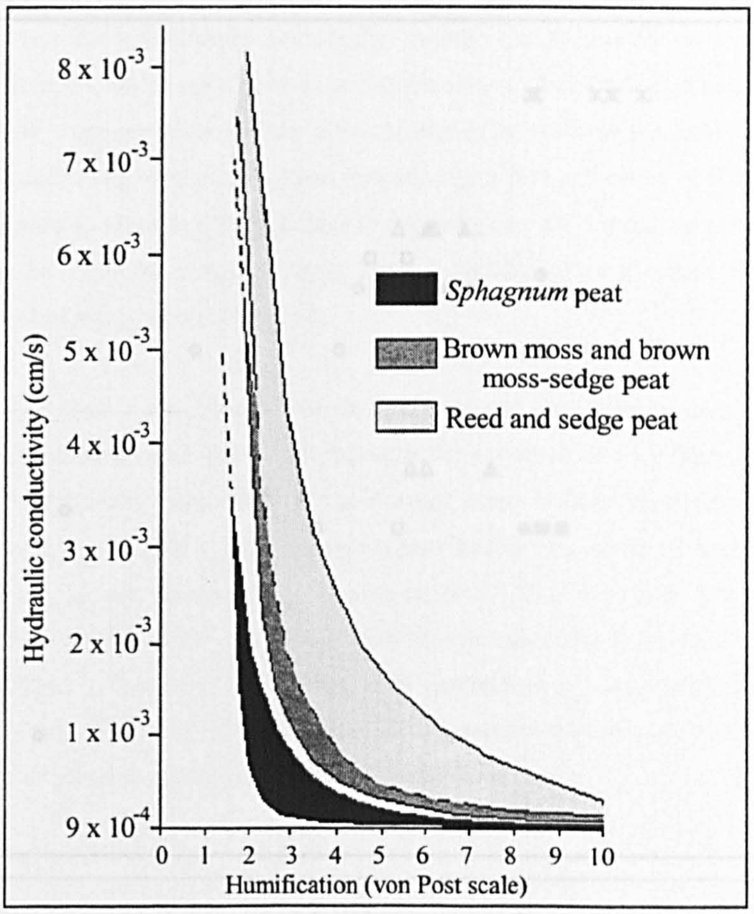
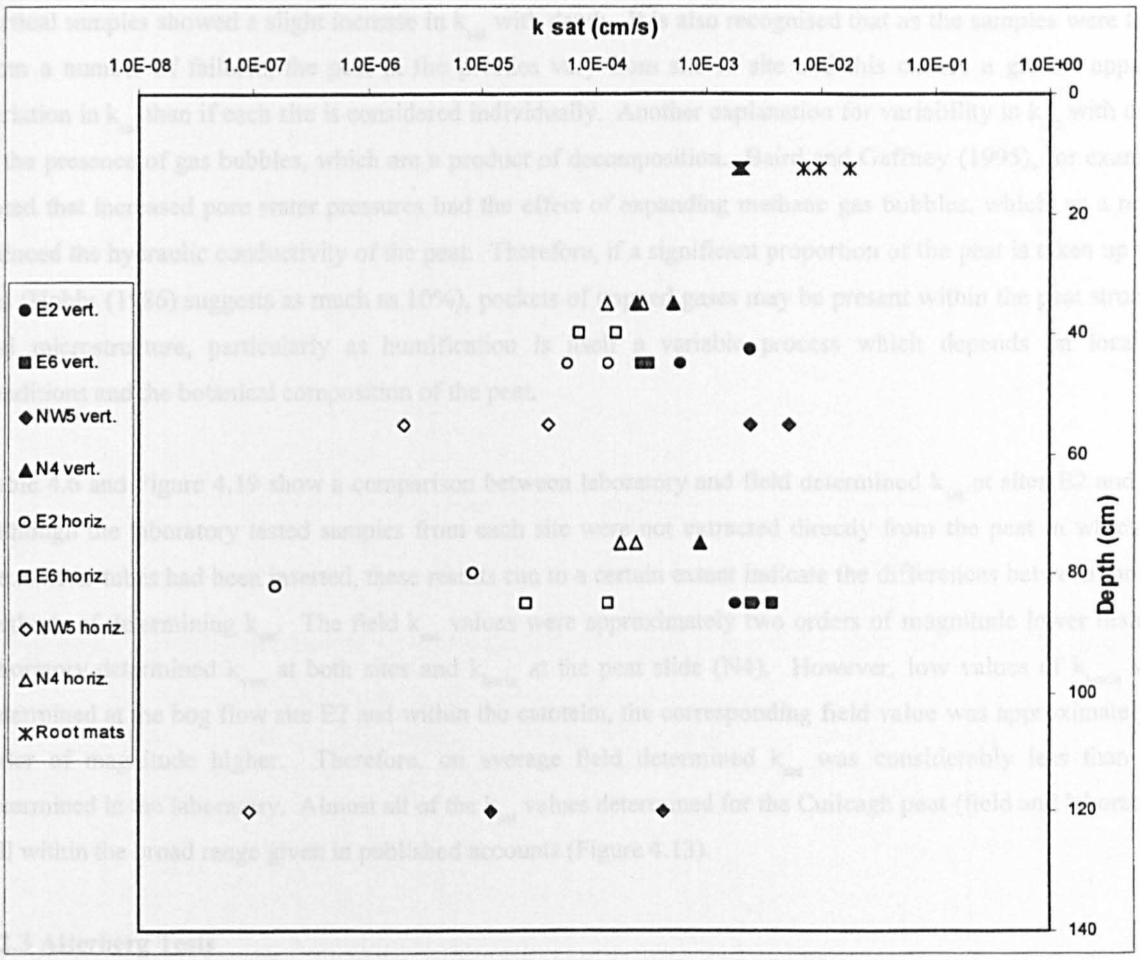


Figure 4.15 Laboratory determined saturated hydraulic conductivity (k_{sat}) for sites on Cuilcagh Mountain.



expected to be fairly uniform. However, values of laboratory determined vertical k_{sat} for peat on Cuilcagh Mountain exceeds the horizontal values at all depths. This is illustrated in Figure 4.16 and 4.17, which show values of k_{vert} and k_{horiz} respectively. Table 4.5 shows a summary of the data. The vertical range in permeability is from 10^{-2} to 10^{-5} cm/s and horizontally, k_{sat} ranges from 10^{-3} to 10^{-8} cm/s (excluding the root mat). Most variability is found within the root mat and acrotelm and diminishes through the catotelm. Although k_{sat} in the catotelm is noted to vary over two orders of magnitude, this is relatively unimportant as the values tend towards zero (Figure 4.18). The majority of horizontal samples showed decreasing k_{sat} with depth possibly due to the breakdown of the plant structure by decomposition and compaction of the peat mass. However, most of the vertical samples showed a slight increase in k_{sat} with depth. It is also recognised that as the samples were taken from a number of failures, the peat in the profiles vary from site to site and this causes a greater apparent variation in k_{sat} than if each site is considered individually. Another explanation for variability in k_{sat} with depth is the presence of gas bubbles, which are a product of decomposition. Baird and Gaffney (1995), for example, noted that increased pore water pressures had the effect of expanding methane gas bubbles, which, as a result, reduced the hydraulic conductivity of the peat. Therefore, if a significant proportion of the peat is taken up with gas (Hobbs (1986) suggests as much as 10%), pockets of trapped gases may be present within the peat structure and microstructure, particularly as humification is itself a variable process which depends on localised conditions and the botanical composition of the peat.

Table 4.6 and Figure 4.19 show a comparison between laboratory and field determined k_{sat} at sites E2 and N4. Although the laboratory tested samples from each site were not extracted directly from the peat in which the piezometer tubes had been inserted, these results can to a certain extent indicate the differences between the two methods of determining k_{sat}. The field k_{sat} values were approximately two orders of magnitude lower than the laboratory determined k_{vert} at both sites and k_{horiz} at the peat slide (N4). However, low values of k_{horiz} were determined at the bog flow site E2 and within the catotelm, the corresponding field value was approximately an order of magnitude higher. Therefore, on average field determined k_{sat} was considerably less than that determined in the laboratory. Almost all of the k_{sat} values determined for the Cuilcagh peat (field and laboratory) fall within the broad range given in published accounts (Figure 4.13).

4.2.3 Atterberg Tests

Atterberg limits are used very extensively in geotechnical engineering not only for identification, description, and classification of soils, but also as a basis for preliminary assessment of their mechanical properties (Mitchell, 1993). The results of the liquid and plastic limit tests depend entirely on the same factors that determine the resistance and permeability of soils (Terzaghi and Peck, 1967). In peat, the liquid limit is reported to fall from 800% for low humification, to about 300% for higher humification (Hobbs, 1986) and is used to give an indication of the structure and Cation Exchange Ability (CEA) of a particular material. The liquid limit of peat depends on three main properties: botanical composition, the degree of humification and the proportion of clay present in the sample (Hobbs, 1986). Very little has been published on the plasticity of peat due to the reported difficulties and usefulness of carrying out the test (Hobbs, 1986).

Figure 4.16 Vertical saturated hydraulic conductivity values at four failure sites on Cuilcagh Mountain.

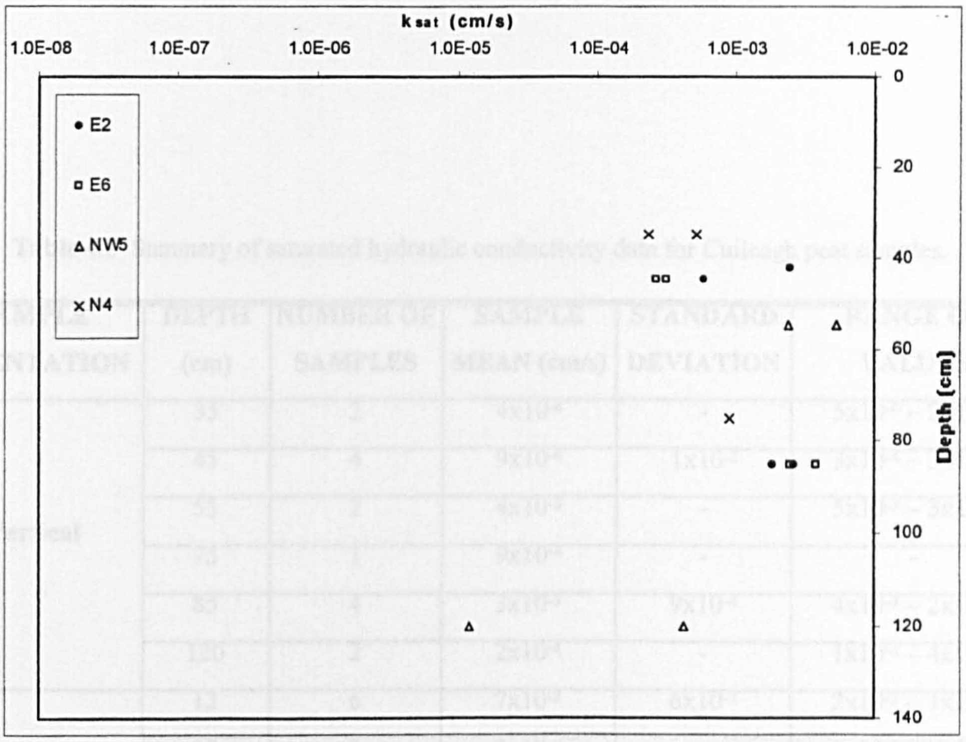


Figure 4.17 Horizontal saturated hydraulic conductivity values at four failure sites on Cuilcagh Mountain.

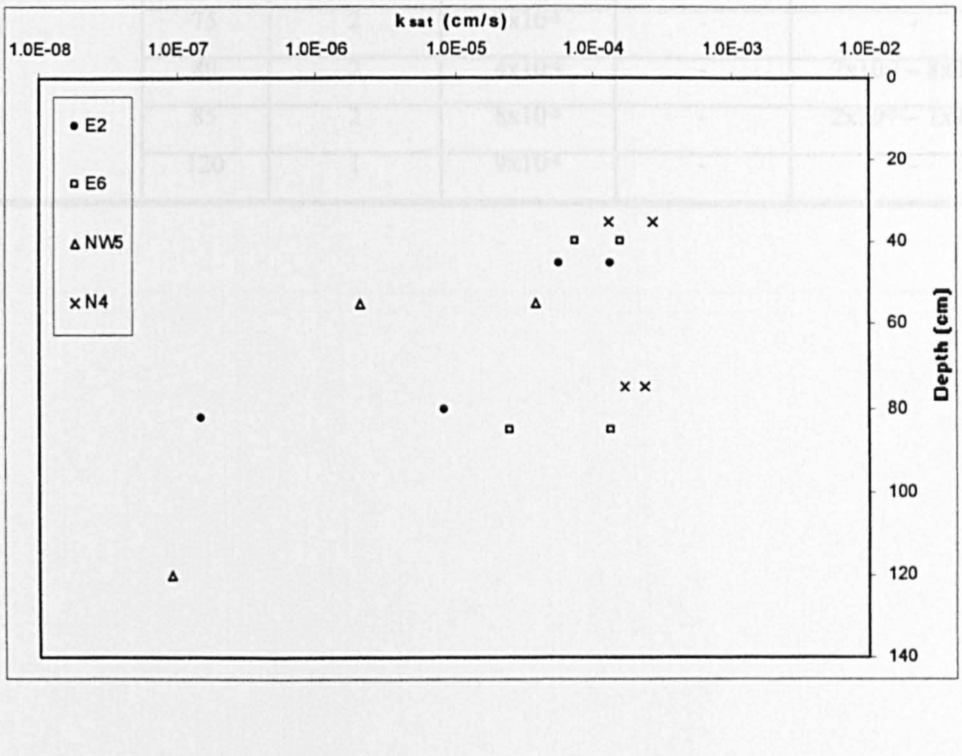


Table 4.5 Summary of saturated hydraulic conductivity data for Cuilcagh peat samples.

SAMPLE ORIENTATION	DEPTH (cm)	NUMBER OF SAMPLES	SAMPLE MEAN (cm/s)	STANDARD DEVIATION	RANGE OF VALUES
Vertical	35	2	4×10^{-4}	-	$5 \times 10^{-4} - 2 \times 10^{-4}$
	45	4	9×10^{-4}	1×10^{-3}	$3 \times 10^{-4} - 3 \times 10^{-3}$
	55	2	4×10^{-3}	-	$5 \times 10^{-3} - 3 \times 10^{-3}$
	75	1	9×10^{-4}	-	-
	85	4	3×10^{-3}	9×10^{-4}	$4 \times 10^{-3} - 2 \times 10^{-3}$
	120	2	2×10^{-4}	-	$1 \times 10^{-5} - 4 \times 10^{-4}$
Horizontal	12	6	7×10^{-3}	6×10^{-3}	$2 \times 10^{-3} - 1 \times 10^{-2}$
	35	2	2×10^{-4}	-	$3 \times 10^{-4} - 1 \times 10^{-4}$
	40	2	1×10^{-4}	-	$7 \times 10^{-5} - 2 \times 10^{-4}$
	45	2	1×10^{-4}	-	$6 \times 10^{-5} - 1 \times 10^{-4}$
	55	2	2×10^{-5}	-	$2 \times 10^{-6} - 4 \times 10^{-5}$
	75	2	2×10^{-4}	-	-
	80	2	4×10^{-6}	-	$2 \times 10^{-7} - 8 \times 10^{-6}$
	85	2	8×10^{-5}	-	$2 \times 10^{-5} - 1 \times 10^{-4}$
	120	1	9×10^{-8}	-	-

Figure 4.18 Saturated hydraulic conductivity (k_{sat}) for Cuilcagh peat (absolute values)

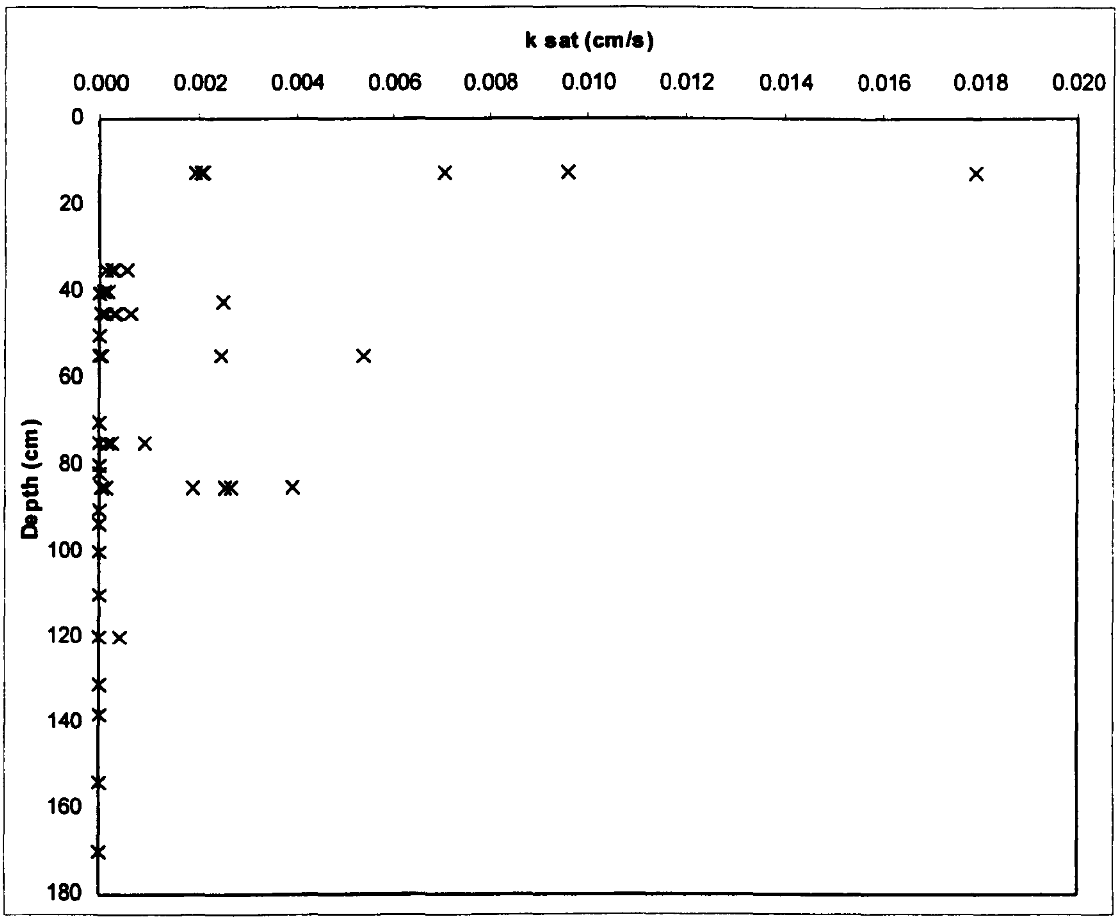
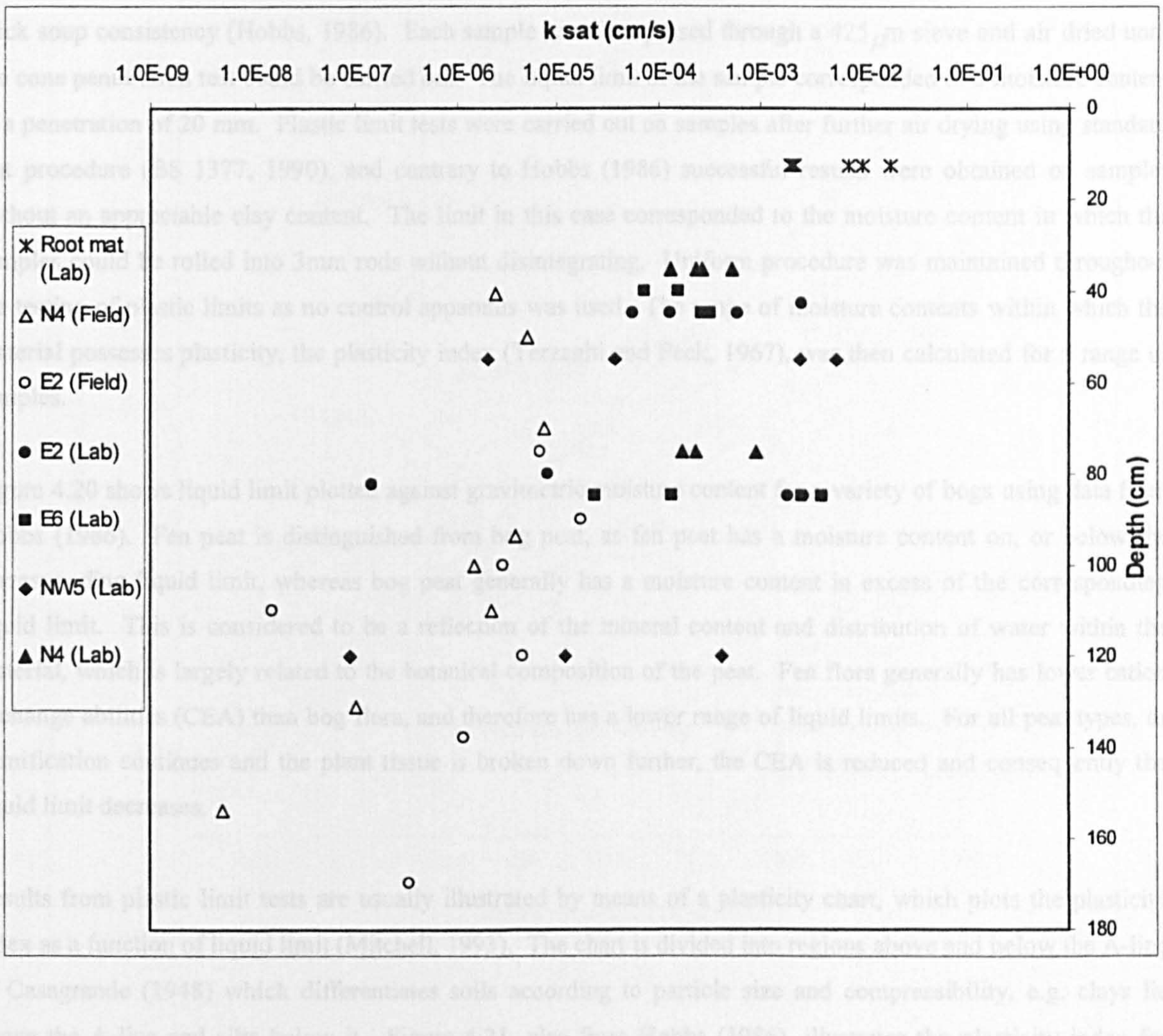


Table 4.6 Comparison between laboratory and field determined saturated hydraulic conductivity (k_{sat}) at two sites on Cuilcagh Mountain.

Site	Depth (cm)	Laboratory determined vertical k_{sat} (cm/s)*	Laboratory determined horizontal k_{sat} (cm/s)*	Field determined k_{sat} (cm/s)
E2	45	1.55×10^{-3}	9.61×10^{-5}	-
	85	2.26×10^{-3}	4.24×10^{-6}	1.2×10^{-5}
N4	35	3.77×10^{-4}	1.99×10^{-4}	2.5×10^{-6}
	75	9.16×10^{-4}	2.04×10^{-4}	7.7×10^{-6}

* Average of two values

Figure 4.19 Field and laboratory determined saturated hydraulic conductivity (k_{sat}) for sites on Cuilcagh Mountain.



It is important to understand that in order to carry out liquid and plastic limit tests, the entire structure of the peat has to be altered. The larger fibres and wood fragments are removed and those remaining are broken down into fine particles. As highlighted by Hobbs (1986), the resulting material tested bears little relation to the material sampled. This is particularly true for the fibrous peat within the acrotelm. However, the amorphous nature of the more humified peat at the base of the profile is such that this material is little altered by the test preparation.

To determine the liquid limit of the Cuilcagh peat, the standard test was performed using the cone penetrometer method (BS 1377, 1990) once the peat was transformed into an acceptable condition. The samples were prepared by firstly removing large fibres and wood fragments with tweezers, adding a small quantity of distilled water (pH 4.5, equal to bog water on Cuilcagh), and processing in a domestic liquidiser until broken down into a thick soup consistency (Hobbs, 1986). Each sample was then passed through a $425\mu m$ sieve and air dried until the cone penetration test could be carried out. The liquid limit of the sample corresponded to a moisture content at a penetration of 20 mm. Plastic limit tests were carried out on samples after further air drying using standard test procedure (BS 1377, 1990), and contrary to Hobbs (1986) successful results were obtained on samples without an appreciable clay content. The limit in this case corresponded to the moisture content in which the samples could be rolled into 3mm rods without disintegrating. Uniform procedure was maintained throughout the testing of plastic limits as no control apparatus was used. The range of moisture contents within which the material possesses plasticity, the plasticity index (Terzaghi and Peck, 1967), was then calculated for a range of samples.

Figure 4.20 shows liquid limit plotted against gravimetric moisture content for a variety of bogs using data from Hobbs (1986). Fen peat is distinguished from bog peat, as fen peat has a moisture content on, or below the corresponding liquid limit, whereas bog peat generally has a moisture content in excess of the corresponding liquid limit. This is considered to be a reflection of the mineral content and distribution of water within the material, which is largely related to the botanical composition of the peat. Fen flora generally has lower cation exchange abilities (CEA) than bog flora, and therefore has a lower range of liquid limits. For all peat types, as humification continues and the plant tissue is broken down further, the CEA is reduced and consequently the liquid limit decreases.

Results from plastic limit tests are usually illustrated by means of a plasticity chart, which plots the plasticity index as a function of liquid limit (Mitchell, 1993). The chart is divided into regions above and below the A-line of Casagrande (1948) which differentiates soils according to particle size and compressibility, e.g. clays lie above the A-line and silts below it. Figure 4.21, also from Hobbs (1986), illustrates the plasticity index for British peat. The results from different types of peat illustrate a considerable scatter below the A-line. Fen and transition peat is located around the lower trend line with results showing an increasing divergence from the A-line with increasing liquid limits. Hobbs (1986, p 41) states that this indicates that, "while organic matter has a great water holding capacity, its highly frictional nature requires a disproportionate increase in plastic limit compared with liquid limit to maintain plasticity." He concludes that the results give little information on the nature of the material.

Figure 4.20 Liquid limits for a variety of bog types (Hobbs, 1986).

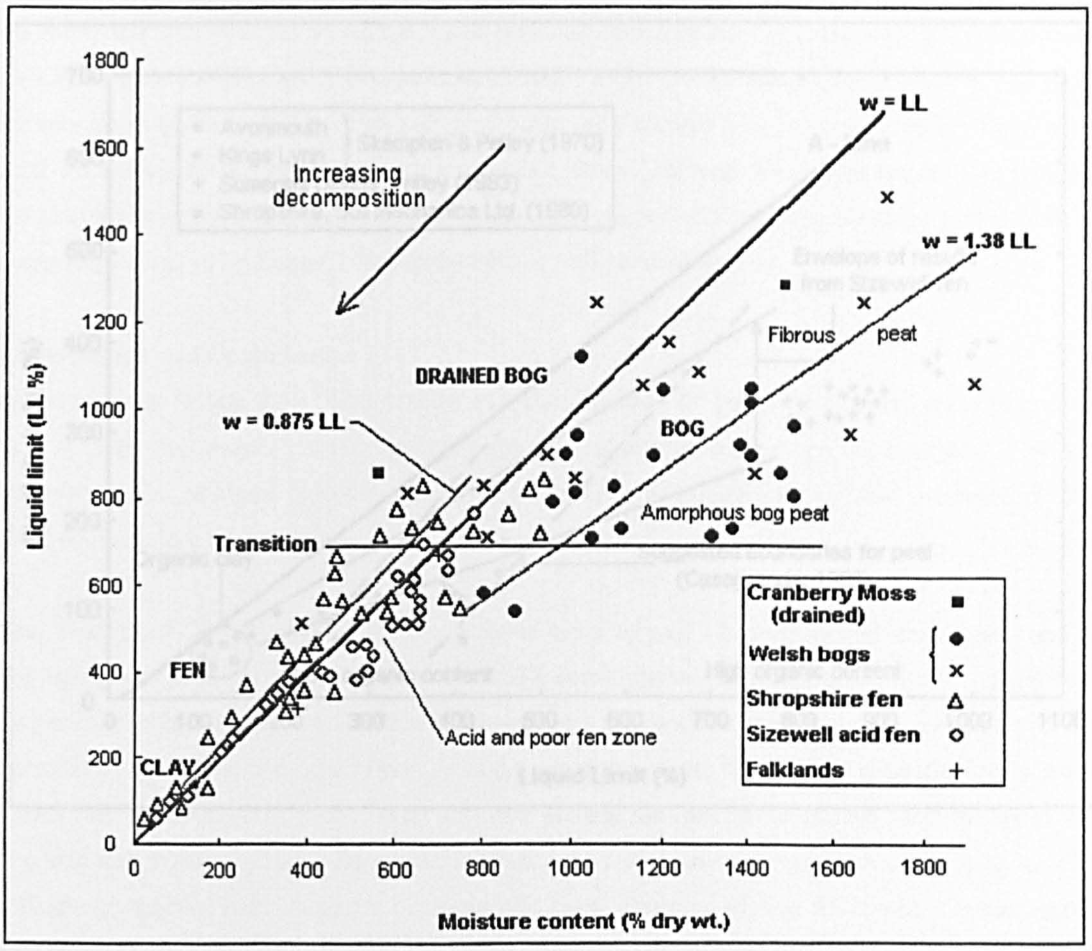


Figure 4.21 Published plasticity index (PI) and liquid limits (LL) for some British peat (from Hobbs, 1986).
A-Line: PI = 0.73(LL-20)

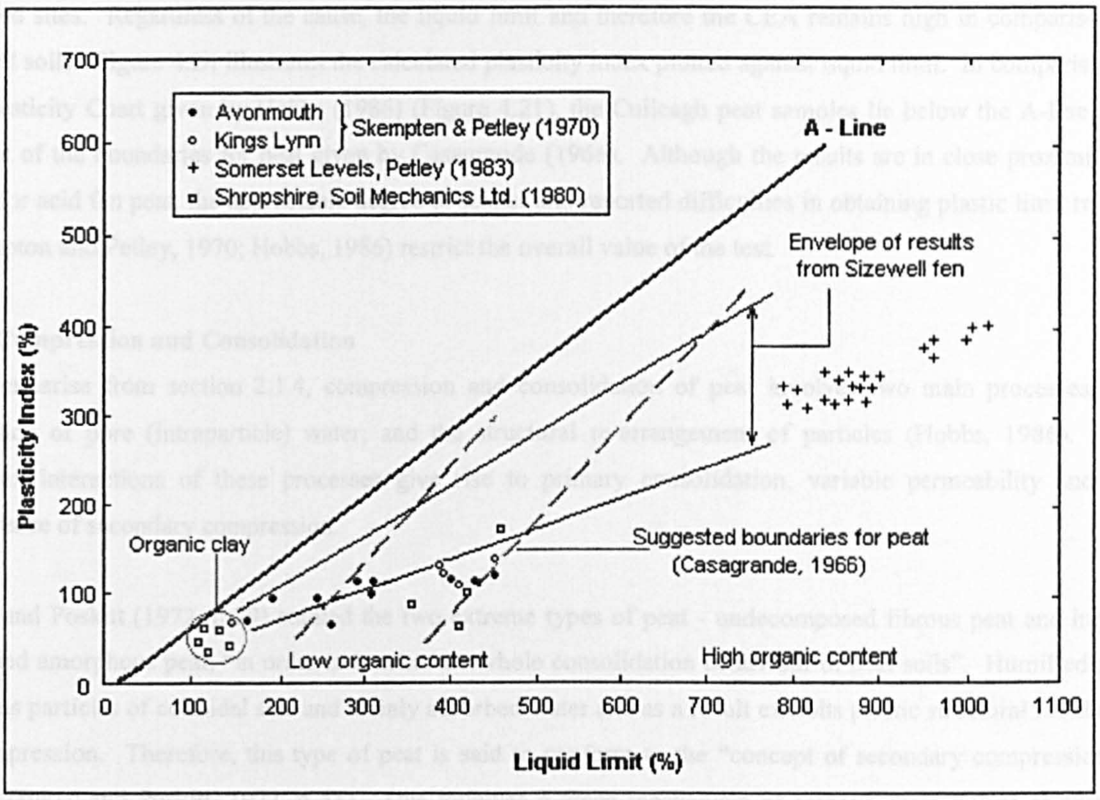


Figure 4.22 illustrates the changes in liquid and plastic limits with depth at two sites on Cuilcagh. Both sampled profiles show a strong positive correlation between liquid and plastic limit and depth (displayed in the high R^2 values). The peat at site N4 has lower liquid and plastic limits than site E2. In comparison with Figure 4.20 from Hobbs (1986), Figure 4.23 shows that the Cuilcagh peat values lie in the proximity of the transition zone between fen and bog peat. At site N4, a considerable amount of fibres had to be removed from the peat within this profile prior to the test being carried out. The liquid limits of the remainder of the peat are found close to their field moisture contents, suggesting that the fibres act as a support to the more decomposed peat matrix. At site E2, all of the calculated liquid limits exceed the field moisture content. The Cuilcagh peat values are situated at the lower end of the range for bog peat given in Figure 4.20. This may indicate a lower CEA than the suggested values for bog peat, or may simply be the result of the lower field moisture contents for the two sampled sites. Regardless of the cause, the liquid limit and therefore the CEA remains high in comparison to mineral soils. Figure 4.24 illustrates the calculated plasticity index plotted against liquid limit. In comparison to the Plasticity Chart given by Hobbs (1986) (Figure 4.21), the Cuilcagh peat samples lie below the A-line, and outside of the boundaries for peat given by Casagrande (1966). Although the results are in close proximity to those for acid fen peat, the appreciable degree of scatter and reported difficulties in obtaining plastic limit results (Skempton and Petley, 1970; Hobbs, 1986) restrict the overall value of the test.

4.2.4 Compression and Consolidation

To summarise from section 2.1.4, compression and consolidation of peat involves two main processes: the expulsion of pore (intraparticle) water; and the structural re-arrangement of particles (Hobbs, 1986). The complex interactions of these processes give rise to primary consolidation, variable permeability and the occurrence of secondary compression.

Berry and Poskitt (1972, p 29) studied the two extreme types of peat - undecomposed fibrous peat and highly humified amorphous peat, "in order to bracket the whole consolidation behaviour of peat soils". Humified peat contains particles of colloidal size and mainly adsorbed water and as a result exhibits plastic structural resistance to compression. Therefore, this type of peat is said to conform to the "concept of secondary compression of clays" (Berry and Poskitt, 1972, p 51). This involves a creep mechanism of viscous shear failure at particle contact points into a more stable configuration following the initial rupture of the structure during the primary stage. However, fibrous peat comprises an essentially open structure of fine fibres and a larger amount of intraparticle (free) and interparticle (capillary) water. Primary consolidation of this type of peat involves the drainage of intraparticle water (Barden, 1968), whereas secondary compression is the slow drainage of interparticle water into the larger pore network.

Hanrahan (1954) noted that the consolidation of bog peat with a high moisture content was highly variable as a result of its anisotropic nature. Although final settlement was not observed in normally consolidated peat, at normal pressures of 36 and 55 kPa, total consolidation after 17 hours on samples approximately 19 mm thick were given as 4.3 to 7.6 and 5.6 to 10.2 mm respectively. The magnitude of consolidation depended on the sample thickness and was noted to be proportional to the logarithm of time (Hanrahan, 1954; Berry and Poskitt, 1972; Clymo, 1978). A decrease in permeability during and after consolidation was affected by the magnitude

Figure 4.22 Changes in liquid and plastic limits with depth at two bog failure sites on Cuilcagh Mountain.

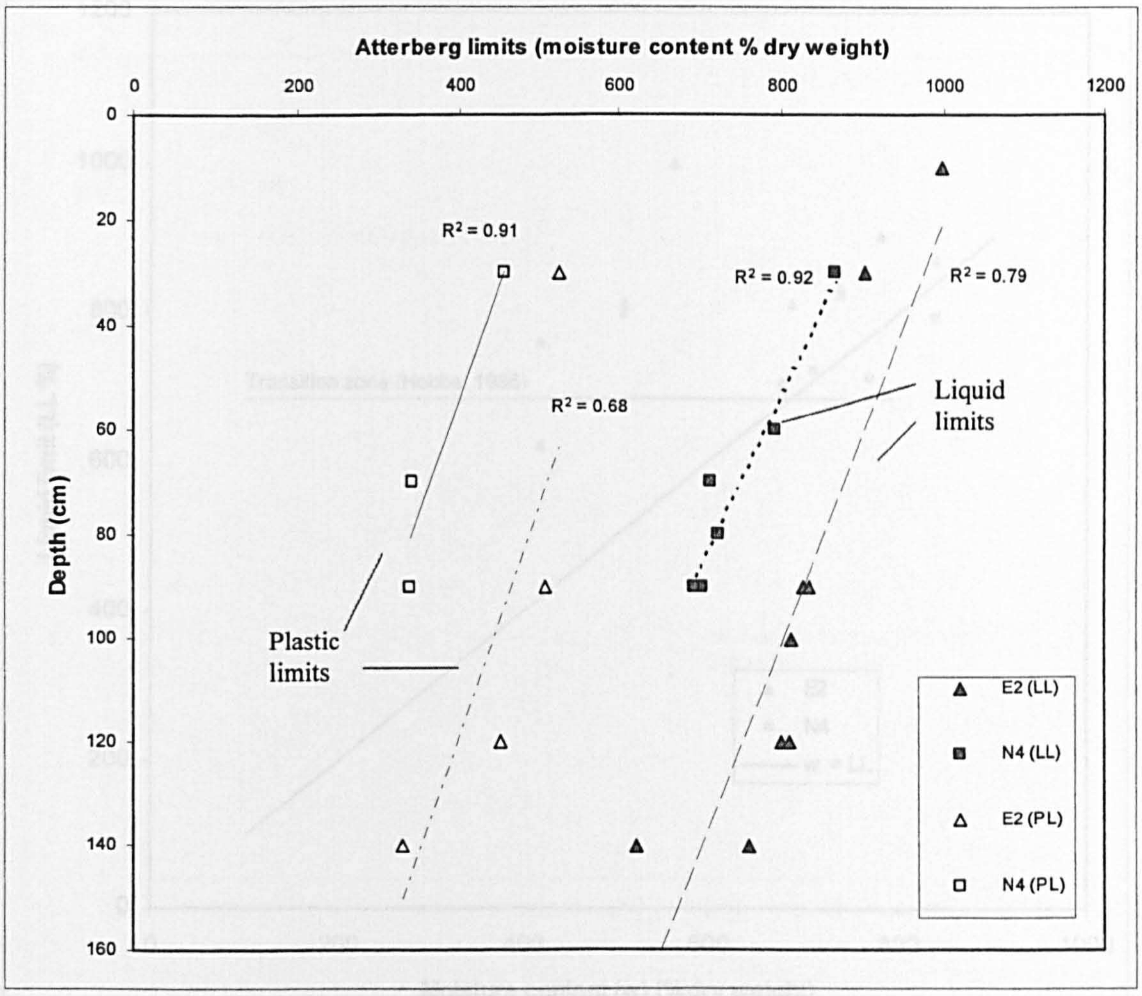


Figure 4.23 Liquid limits plotted against moisture content for two sites on Cuilcagh Mountain.

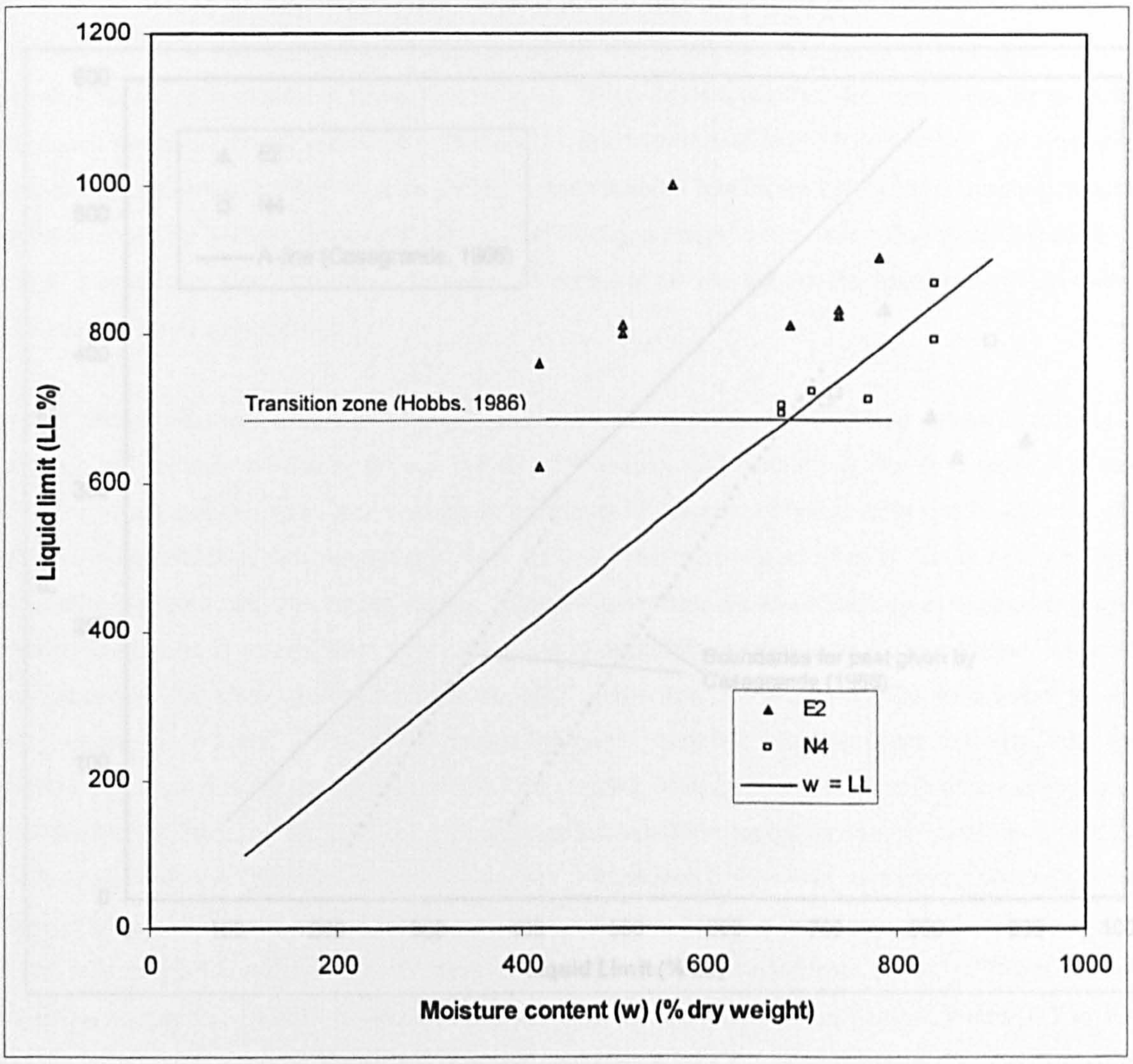
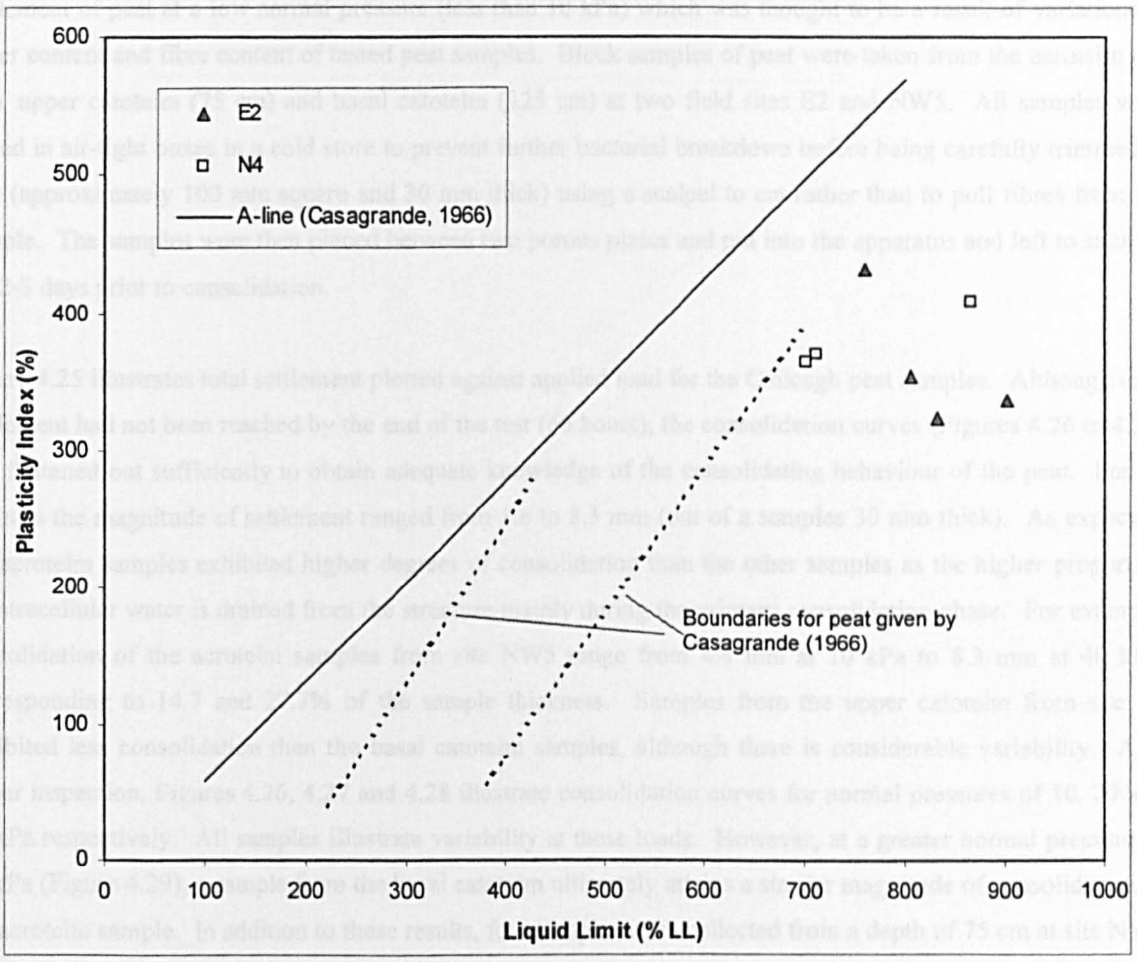


Figure 4.24 Plasticity Chart for two failures on Cuilcagh Mountain.



and duration of loading and was attributed to a reduced void ratio and lateral contraction of the peat structure.

For the present study, one dimensional consolidation tests were carried out on undisturbed, trimmed samples using laboratory consolidation and shear box apparatus. Peat depth near failure sites on Cuilcagh Mountain range between approximately 0.7 m on the northern slopes to over 3.0 m on East Cuilcagh. Average field bulk density of the Cuilcagh peat has been calculated as 1.01 g/cm^3. This equates to normal pressures in the field ranging from 6.9 to 29.7 kPa at the base of the peat. Therefore, normal pressures of 10, 20, 30 and 40 kPa were applied to the samples. Lower normal pressures would not be expected to yield reliable results for the type and size of apparatus used (Dykes, 1995). Also, Landva and La Rochelle (1983) reported difficulties in determining settlement of peat at a low normal pressure (less than 10 kPa) which was thought to be a result of variations in water content and fibre content of tested peat samples. Block samples of peat were taken from the acrotelm (30 cm), upper catotelm (75 cm) and basal catotelm (125 cm) at two field sites E2 and NW5. All samples were stored in air-tight boxes in a cold store to prevent further bacterial breakdown before being carefully trimmed to size (approximately 100 mm square and 30 mm thick) using a scalpel to cut rather than to pull fibres from the sample. The samples were then placed between two porous plates and put into the apparatus and left to saturate for 2-3 days prior to consolidation.

Figure 4.25 illustrates total settlement plotted against applied load for the Cuilcagh peat samples. Although total settlement had not been reached by the end of the test (66 hours), the consolidation curves (Figures 4.26 to 4.29) had flattened out sufficiently to obtain adequate knowledge of the consolidating behaviour of the peat. For all samples the magnitude of settlement ranged from 1.6 to 8.3 mm (out of a samples 30 mm thick). As expected, the acrotelm samples exhibited higher degrees of consolidation than the other samples as the higher proportion of intracellular water is drained from the structure mainly during the primary consolidation phase. For example, consolidation of the acrotelm samples from site NW5 range from 4.4 mm at 10 kPa to 8.3 mm at 40 kPa, corresponding to 14.7 and 27.7% of the sample thickness. Samples from the upper catotelm from site E2 exhibited less consolidation than the basal catotelm samples, although there is considerable variability. At a closer inspection, Figures 4.26, 4.27 and 4.28 illustrate consolidation curves for normal pressures of 10, 20 and 30 kPa respectively. All samples illustrate variability at these loads. However, at a greater normal pressure of 40 kPa (Figure 4.29), a sample from the basal catotelm ultimately attains a similar magnitude of consolidation as the acrotelm sample. In addition to these results, four samples were collected from a depth of 75 cm at site NW5 and all consolidated at 10 kPa. Total settlement of these samples ranged from 2.0 to 3.9 mm (6.7 to 13.0%), giving a mean of 3.0 mm (10.0%) and standard deviation of 0.87. This indicates the variable nature of apparently uniform peat, which results from variations in pore spaces, the proportion of the different distribution of water within the material and possible structural alignment of the peat fabric (Landva and Pheeney, 1980).

4.2.5 Shear Strength

The geotechnical parameters of cohesion and angle of internal friction are required to perform a stability analysis. The strength of organic material varies considerably according to decomposition and structural characteristics. For example, fibres in undecomposed peat act as a reinforcement to increase the overall strength

Figure 4.25 Total settlement plotted against applied load for Cuilcagh peat samples.

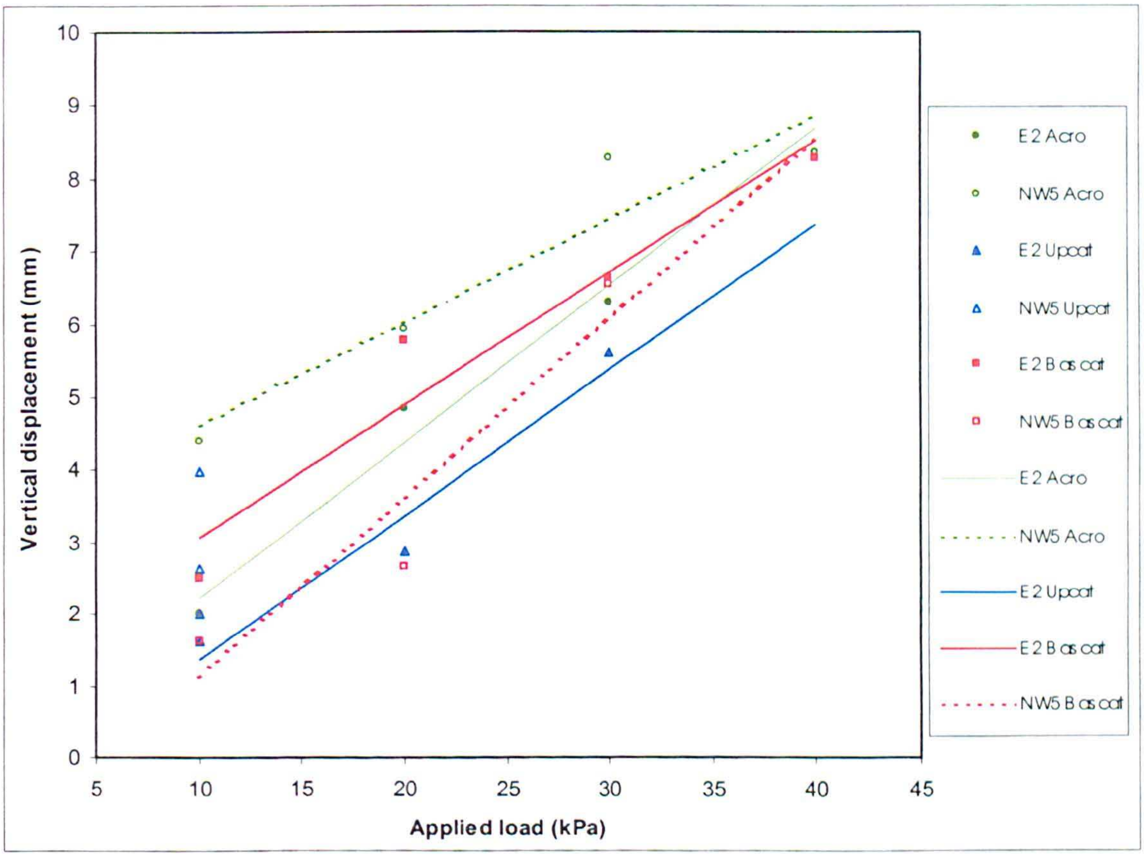


Figure 4.26 Consolidation curve for samples at 10 kPa.

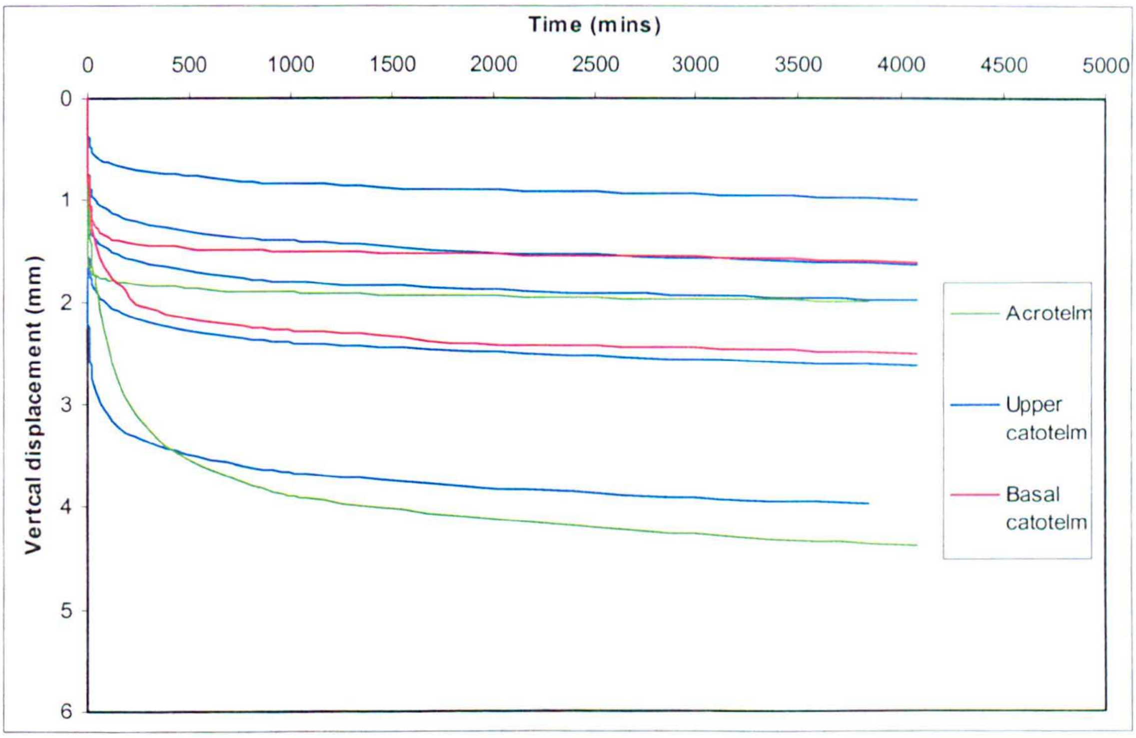


Figure 4.27 Consolidation curve for samples at 20 kPa.

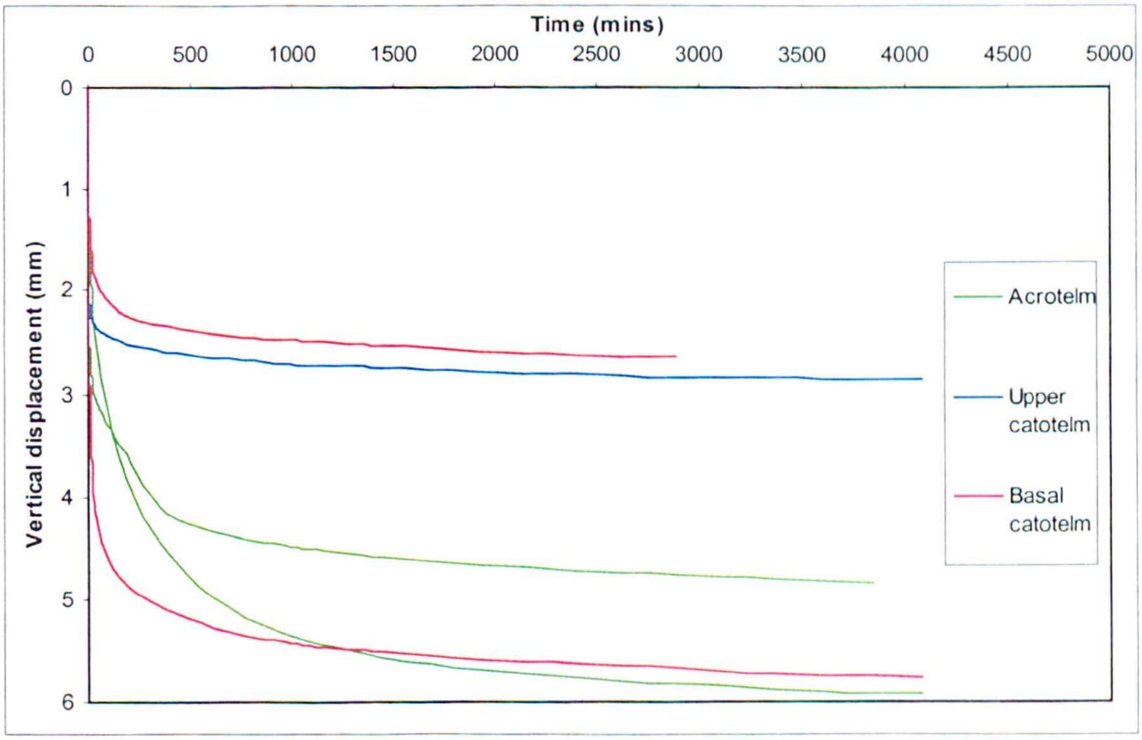


Figure 4.28 Consolidation curve for samples at 30 kPa.

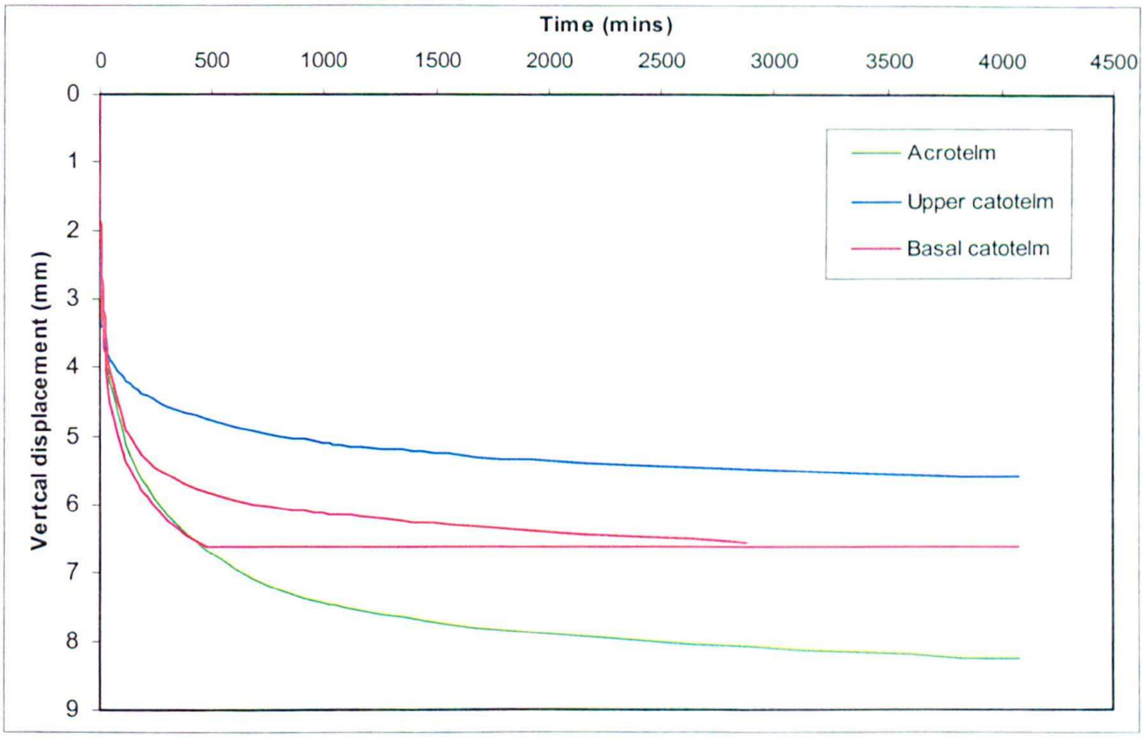
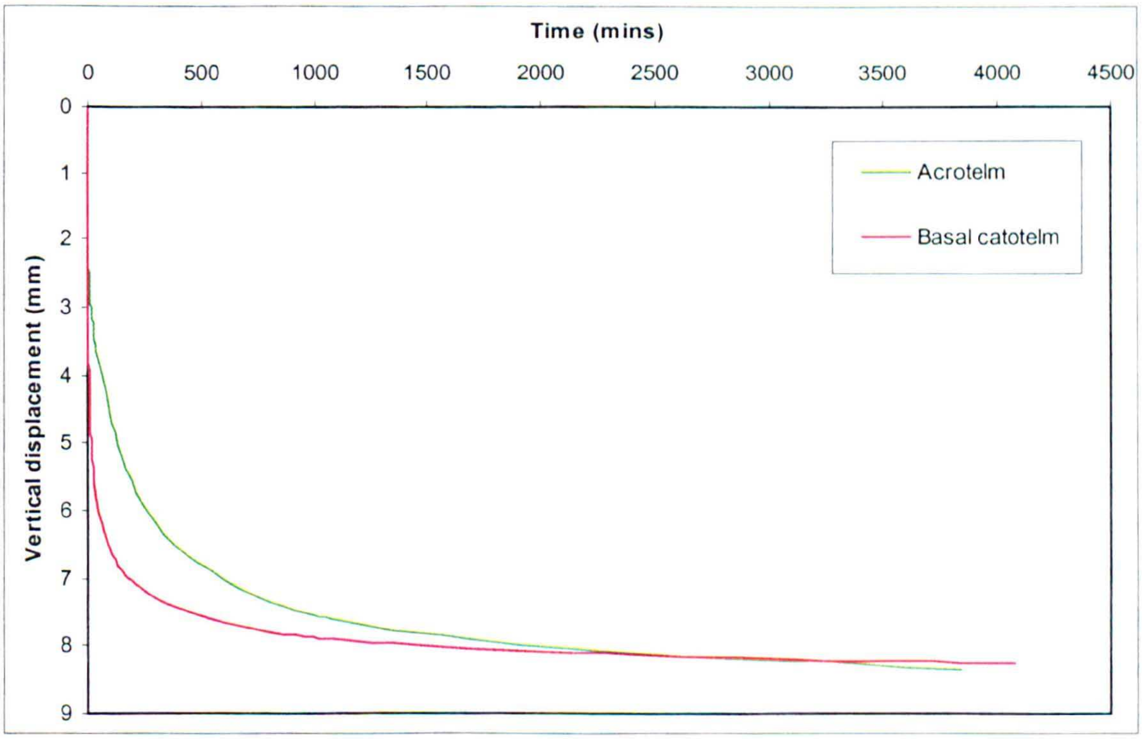


Figure 4.29 Consolidation curve for samples at 40 kPa.



of the material, whereas in highly humified peat the strongly adsorbed water modifies the strength properties but undrained strength is reduced as a result of high moisture contents and plasticity (Mitchell, 1993).

There are relatively few studies of shear strength characteristics of peat, as most geotechnical investigations concentrate on compression under high loads for engineering purposes. The studies that have been carried out tend to give substantially different results. This is perhaps unsurprising given the variable nature of the material and the likelihood that different types of peat possess different strength characteristics. Further differences result from the different testing methods used. Table 4.7 shows some published values of cohesion and angle of internal friction. Hanrahan (1954) concluded that peat with high moisture content is exclusively cohesive in character, and Adams (1965) stated that peat with low moisture contents is essentially frictional. The most comprehensive study of the shear strength of peat is given by Landva and La Rochelle (1983). Figure 4.30 illustrates some of their shear strength results on *Sphagnum* peat. The failure envelope of all normally consolidated samples range between c = 2.4 kPa, ϕ = 27.1°, and c = 4.7 kPa, ϕ = 35.4°, whereas without the residual shearing data, the failure envelope lies between c = 2.4 kPa, ϕ = 27.1° and c = 2.4 kPa, ϕ = 32.5°. At normal loads of less than 13 kPa, it was noted that apparent cohesion increases and friction decreases to correspond to a strength of 5-6 kPa at zero normal pressure. The increase in apparent cohesion was attributed to fibre entanglement.

Even fewer data are available on shear characteristics of humified peat. Landva and La Rochelle (1983) tested only one sample of well decomposed peat (H_8) and found it to fall within the failure envelope for more fibrous peat at H_3-H_4. They therefore assumed that humified peat possessed the same strength characteristics as the fibrous peat.

Most of the Cuilcagh peat samples from this study were subjected to consolidated, drained shear tests using direct shear apparatus (described in chapter 2). A data logger automatically recorded vertical and horizontal displacement (and therefore volume change) and shearing resistance by means of pressure transducers. The shear rates used were dependent on the depth at which the sample was extracted, which relates to estimated permeability. This allowed time for the dissipation of pore pressures within the sample during the test. Therefore, samples from the acrotelm were sheared over approximately 4 hours and 30 minutes (at 0.04 mm/min), whereas samples from the upper and basal catotelm were sheared over 68 hours (at 0.004 mm/min).

Drained shear tests on the peat were terminated at maximum horizontal displacement of the shearbox (11 mm) without a peak strength being reached. This was also noted to occur on drained tests of peat by Hollingshead and Raymond (1972). However, as with the consolidation tests, the shear strength/horizontal displacement curves in most cases had sufficiently flattened out for upper limit strength values to be estimated (see Appendix 5). Figure 4.31 illustrates the shear strength results of 35 peat and organic-rich clay samples from Cuilcagh Mountain. The majority of the peat results fall within the ranges set for peat by Landva and La Rochelle (1983) in Figure 4.30. The main failure envelope for pre-consolidated peat ranges from c = 2.7 kPa, ϕ = 30.4° and c = 8.2 kPa, ϕ = 26.3° with the majority of samples having cohesion values around 3.0 to 4.6 kPa, and frictional values of approximately 30°. Table 4.8 shows the values of cohesion and angle of internal friction for the

Table 4.7 The range of published values for the shear strength of peat.

Author(s)	**Peat Type/ Characteristics**	**Cohesion (c)**	**Angle of internal friction (ϕ)**
Hanrahan (1954)	*Sphagnum* peat with high moisture contents	High	5°
Adams (1965)	Peat at low moisture contents	Extremely low	48°
Hanrahan *et al.* (1967)	Remoulded and undisturbed *Sphagnum* peat	5.5 – 6.1 kPa	36.6 – 43.5°
Hollingshead & Raymond (1972)*		4.0 kPa	34°
Landva and La Rochelle (1983)	*Sphagnum* peat (mainly fibrous)	2.4 – 4.7 kPa	27.1 – 35.4°
Marachi *et al.* (1983)	Fibrous delta peat with low moisture contents	18.0 kPa	28°

* as cited by Landva and La Rochelle (1983)

Figure 4.30 Shear strength results on *Sphagnum* peat (Landva & La Rochelle, 1983)

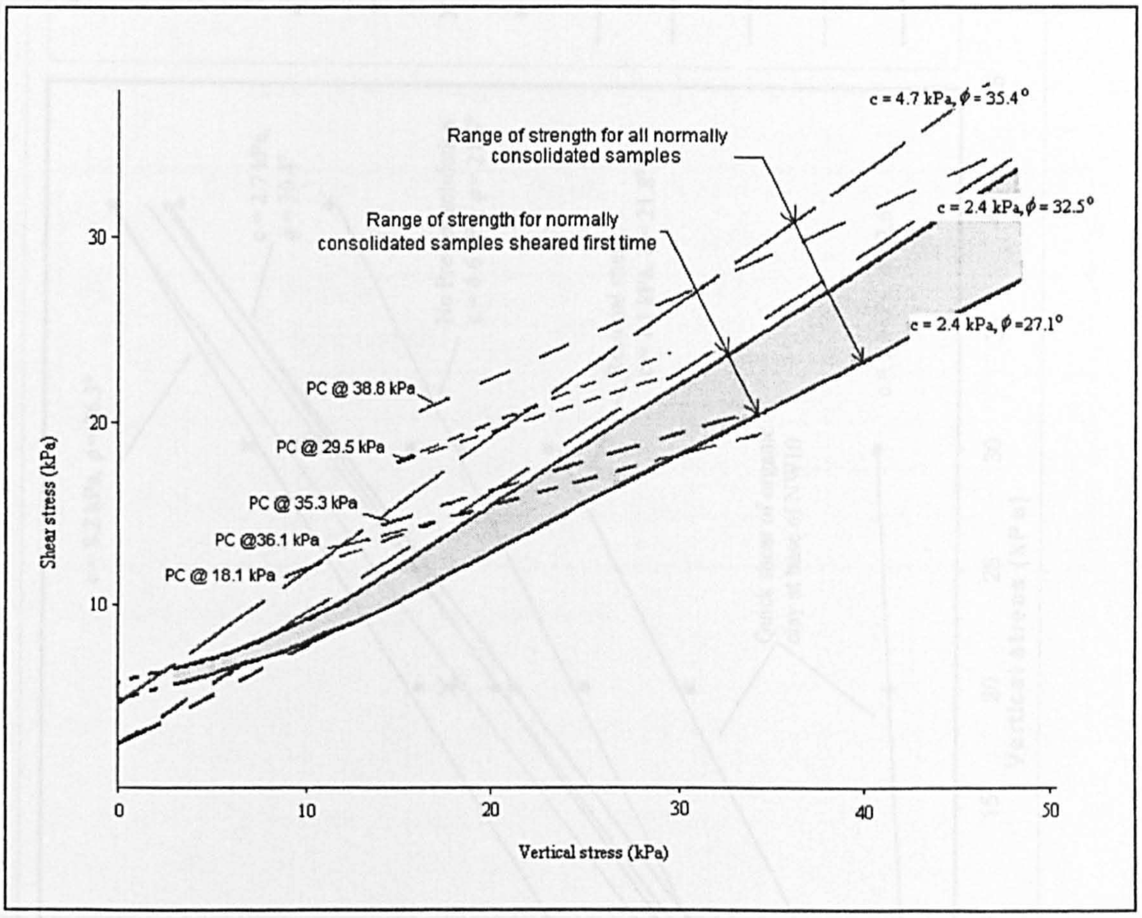


Figure 4.31 Results of 35 shear strength tests on Cuilcagh peat and organic-rich clay samples.

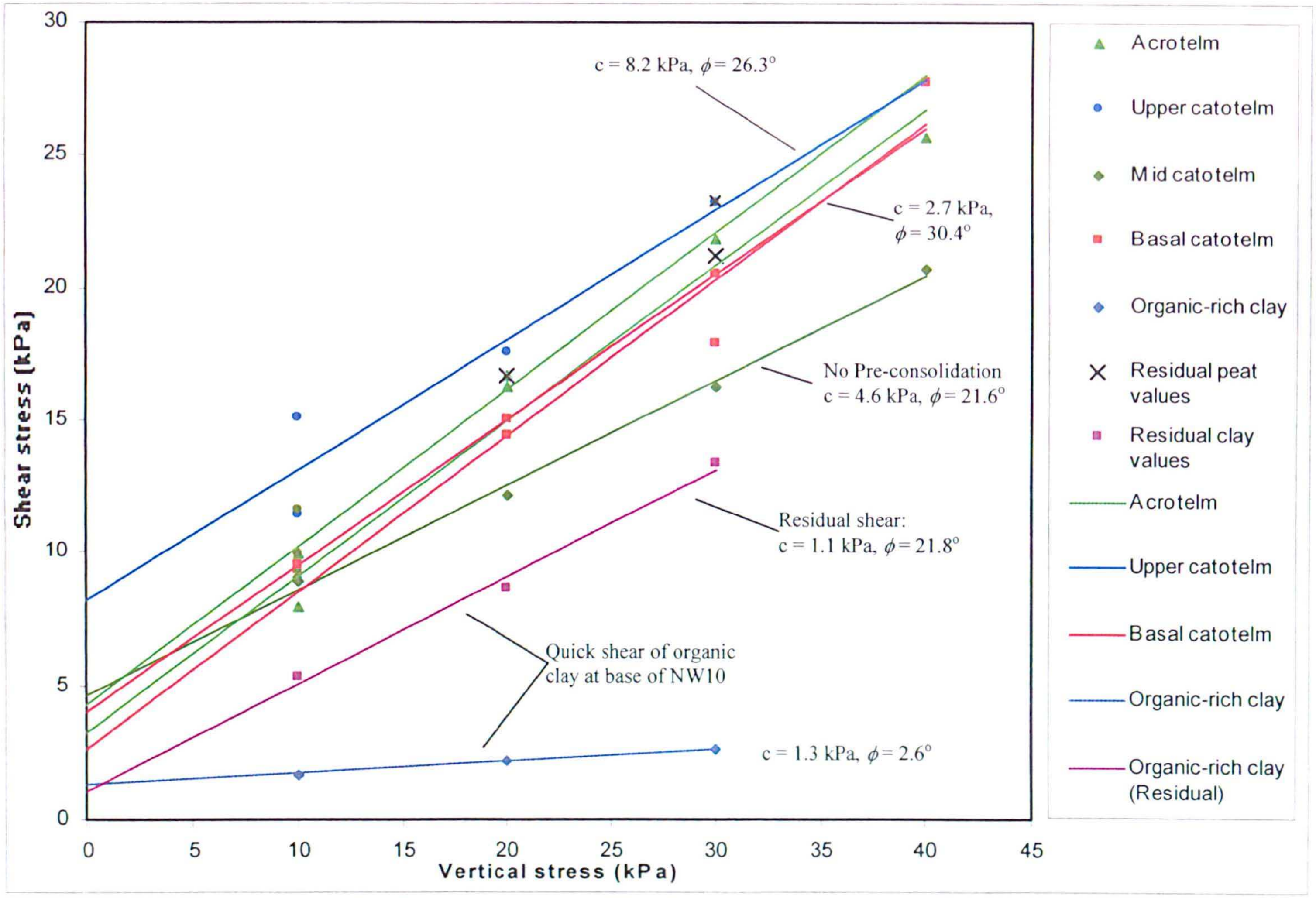


Table 4.8 Shear strength results for the Cuilcagh peat samples.

Site/Sample		Depth (cm)	Cohesion (kPa)	Angle of Internal Friction (°)
E2	Acrotelm	35	4.2	30.8
	Upper catotelm	75	8.2	26.1
	Basal catotelm	125	2.6	30.4
NW5	Acrotelm	35	3.2	30.4
	Middle catotelm*	100	4.6	21.6
	Basal catotelm	125	4.0	28.8

* Samples quick sheared with no pre-consolidation

samples of peat collected from failure sites E2 and NW5 and Tables 4.9 and 4.10 show a summary of the results. Overall, there is only small degree of scatter for inherently different types of material, e.g. fibrous acrotelm samples display similar strength behaviour to the decomposed amorphous peat from the basal catotelm, but generally, the basal catotelm samples exhibit slightly lower cohesion values than for upper catotelm and acrotelm samples. Samples of peat from the upper catotelm give a surprisingly higher value of cohesion in comparison to the other peat samples. In addition to these samples, four peat samples from site NW5 were extracted at the same depth (100 cm), consolidated at 10 kPa and sheared at 0.04 mm/min for the purpose of examining the natural variability of the material. The peak shear strength of the samples ranged from 9.3 to 11.6 kPa, with a mean of 10.0 kPa and standard deviation of 1.2. This indicates that the peat has considerable natural variability over a small horizontal distance.

Several peat samples illustrated an initial peak in strength followed by a rapid decrease and further slow increases until attaining a maximum shear stress at the maximum horizontal displacement of the shearbox. This behaviour was noted on some of the more fibrous samples and surprisingly was not restricted to the acrotelm. Figure 4.32 shows the horizontal displacement/shear stress curves for one acrotelm and two basal catotelm samples. It is thought that this behaviour was associated with fibres within the matrix acting as a reinforcement and then either being pulled to their limit or sheared. Landva and Pheeney (1980) state that the internal resistance of fibres is the result of friction and their tensile strength. In the less humified acrotelm sample, an initial peak in strength occurred at 3.8 mm, whereas in the well decomposed peat, it occurred between 0.4 and 1.1 mm. This reflects the structure of the material, which results mainly from its degree of decomposition. Fibres in the fresh peat have not been broken down and are longer than those that remain in the more decomposed peat. This behaviour highlights the importance of fibres within the peat matrix in affecting the strength of the material.

As a result of consolidating the samples, the peat was noted to differ considerably from the peat slurry present at recent bog flow sites and the peat at the margins of failure scars. Therefore, some samples were sheared with no pre-consolidation. Also, an increased rate of shear was used to investigate the behaviour of the material under simulated undrained conditions with excess pore water pressures. Samples sheared at 0.4 mm/min with no pre-consolidation (from the mid-catotelm at NW5) were noted to give a low value of friction (21.6°), whereas the value of cohesion lies within range set by pre-consolidated samples. The lower frictional values are thought to result from less frictional contact between constituent particle/fibres in the early stages of the test with no pre-consolidation and increased pore water pressure within the sample.

In addition to the samples of pure peat, shear strength results were also obtained from samples of organic-rich clay from the peat slide NW10. The extracted material had an average moisture content of 190%, with an organic content of 23% and a slurry-like consistency. As a result of this, the material was in a remoulded state when placed into the shearbox apparatus. These samples were quick sheared at 0.4 mm/min with no pre-consolidation. Initial shear strength tests of this material yielded extremely low values of cohesion (1.3 kPa) and particularly friction (2.6°), as illustrated in Figure 4.31. Residual strength tests gave a similar cohesion value but an increased the angle of friction of 21.8°. This large difference in frictional strength is thought to be the result

Table 4.9 Summary of shear strength results for the Cuilcagh peat samples following consolidation.

Parameter	Maximum value	Minimum value	Mean value	Standard deviation
Cohesion (c)	8.2 kPa (Upper catotelm)	2.7 kPa (Basal catotelm)	4.4 kPa	2.18
Angle of internal friction (ϕ)	30.8° (Acrotelm)	26.1° (Upper catotelm)	29.3°	1.95

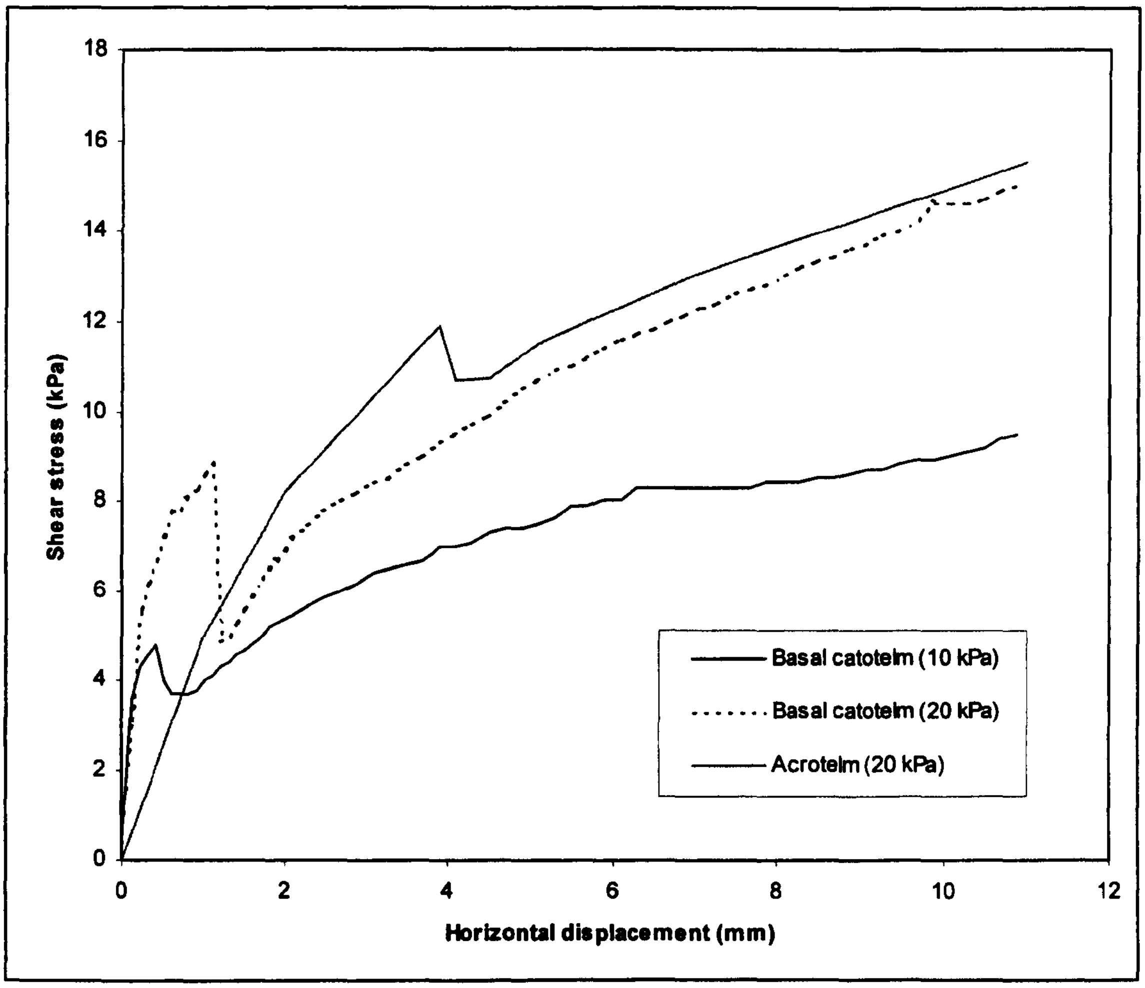
Table 4.10 Shear strength results for all Cuilcagh samples.

Sample	Number of Tests*	Cohesion (c)	Angle of internal friction (ϕ)
Acrotelm	2	3.7 kPa	30.6°
Upper catotelm	1	8.2 kPa	26.1°
Basal catotelm	2	3.4 kPa	29.6°
Mid catotelm (No PC)	1	4.6 kPa	21.6°
Organic clay (No PC)	1	1.3 kPa	2.6°
Organic clay residual values (No PC)	1	1.1 kPa	21.8°

PC = Pre-consolidation

* = Each test uses the results of 3-4 samples subjected to different loads.

Figure 4.32 The effect of fibre re-enforcement on the shearing behaviour of Cuilcagh peat samples.



of consolidation of the sample during the shearing process, as water is expelled from the structure and the fabric aligns itself in the plane of shear failure (Landva and Pheeney, 1980) to give higher bulk densities and lower moisture contents. Further testing was carried out using a laboratory shear vane to give an indication of the changes in total shear strength immediately before and after failure in the shear box apparatus. Prior to testing in the shearbox, total shear strength values were 0.2 to 0.7 kPa, with an average of 0.4 kPa. However, following consolidation and shear failure in the shearbox, total shear strength ranged from 5.5 to 14.3 kPa, with an average of 9.3 kPa (Table 4.11). Average moisture contents were noted to decline from 180% to 130% of dry weight and sample thickness decreased by up to 16%. This gives an indication of the considerable alteration to the material during the shearing process and highlights the role of water within the structure in affecting the strength of the material.

Thixotropic behaviour has been considered an important mechanism governing the deformation of granular amorphous peat (Barden, 1968). Mitchell (1993) defines thixotropy as the process of gradual re-orientation and flocculation of the soil structure with the re-orientation of water molecules to a more ordered structure which results in the material stiffening whilst at rest and softening or liquefying upon remoulding. This process is reversible and time dependent and occurs during conditions of constant composition and volume. The extent to which this process accounts for the sensitivity of organic material in the field is difficult to establish, but as described earlier, it is clear that the laboratory tests result in structural alterations to the material so that it differs greatly from the peat and organic clay found in the field.

It is also important to note that during some shear tests, the lid of the shearbox displayed a considerable degree of tilt usually in the direction of shearing. This was apparent on most of the basal catotelm and organic clay samples. This occurrence, together with shape of the shear stress/horizontal displacement curve i.e. with no peak strength being reached, indicates plastic deformation (creep) as opposed to a distinct shear plane developing within the material.

4.3 SUMMARY

1. Few studies have investigated the physical and geotechnical properties of blanket bog peat and their variation with depth. Hence samples collected at different locations on Cuilcagh Mountain were analysed to determine these characteristics.
2. As expected, humification increased with depth in relation to the sampled profile.
3. Dry bulk density ranged from 0.08 to 0.2 g/cm^3 and was most variable in the acrotelm as a result of differences in botanical composition and void spaces.
4. Mean organic content ranged from 80 to 99%. This parameter highlighted the difference between the two specific areas in which slope failure occurs on Cuilcagh Mountain. On East Cuilcagh where bog flows occur, organic content of the peat ranged from 93 to 99%, whereas on the northern slopes where peat sliding is more prevalent it ranged from 80 to 97%. It is thought that this reflects differences in vegetation and land use patterns.

Table 4.11 Details of the total shear strength determinations using a laboratory shear vane.

Sample	Material state	Torque (mm)	Rotation (°)	Shear Strength (kPa)
Pre-shear sample	Peak	37	003	0.7
	Residual	48	001	0.2
	Peak	41	002	0.4
	Residual	39	001	0.2
	Peak	40	001	0.2
	Residual	30	001	0.2
Sheared sample	Peak	65	025	5.5
	Residual	45	006	1.3
	Peak	60	031	6.8
	Residual	65	005	1.1
	Peak	60	031	6.8
	Residual	60	013	2.8
	Peak	46	059	12.9
	Residual	45	015	3.9
	Peak	56	065	14.3
	Residual	45	018	4.0

Vane shear strength (kPa) = M/K x 1000

Where: M is the maximum angle of the torsion spring (R) multiplied by the calibration factor (0.9415).
K is a constant which depends on the dimensions of the shear vane (4290)

5. The mean field moisture content ranged between 430 and 950% (dry weight), and was generally lower than the values quoted for various other ombrotrophic bogs.
6. Overall, the physical properties of the Cuilcagh peat varied vertically within the bog, and also horizontally over small distances. The transition between the acrotelm and catotelm did not appear as a distinct boundary, but occurred over approximately 20 cm forming a transition zone. Deep profiles of bog peat on East Cuilcagh displayed some different characteristics to the shallower depths of peat and clay found on the northern slopes.
7. Laboratory determined values of k_{sat} for the Cuilcagh peat ranged from 10^{-2} to 10^{-8} cm/s. Vertical k_{sat} (10^{-2} to 10^{-5} cm/s) exceeded horizontal values (10^{-3} to 10^{-8} cm/s) at all depths. Most variability was found within the root mat and acrotelm and diminished through the catotelm. Field k_{sat} values were found to be approximately two orders of magnitude lower than the laboratory determined k_{vert} at two sites and k_{horiz} at one site.
8. The magnitude of settlement for the Cuilcagh peat samples ranged from 1.6 to 8.3 mm (5.3 to 27.7% of sample thickness) with loads of 10 to 40 kPa. As expected, the acrotelm samples exhibited higher degrees of consolidation than the other samples as the higher proportion of intracellular water was drained from the structure. There was notable variability of apparently uniform peat, which was thought to result from variations in pore spaces, the proportion of the different distribution of water within the material and possible structural alignment of the peat fabric.
9. The main failure envelope for the pre-consolidated Cuilcagh peat ranged from $c = 2.7$ kPa, $\phi = 30.4^{\circ}$ to $c = 8.2$ kPa, $\phi = 26.3^{\circ}$. The majority of these samples had cohesion values around 3.0 to 4.6 kPa, and frictional values of approximately 30°. The fibrous acrotelm peat displayed similar strength behaviour to the decomposed amorphous peat from the basal catotelm, but generally, the basal catotelm samples exhibited slightly lower cohesion. However, considerable natural variability was noted in both the vertical and horizontal directions.
10. Samples of peat and organic clay subject to quick shear with no pre-consolidation resulted in lower friction values and similar values of cohesion as the pre-consolidated samples of peat. Further testing of the organic clay revealed the extent to which the material altered during shearing, with the average total strength increasing from 0.4 to 9.3 kPa associated with a decrease in average moisture content from 180% to 130% of dry weight.
11. Fibres within the peat matrix were noted to act initially as a reinforcement before either being pulled to their limit or sheared during failure. This behaviour was not restricted to the fibrous acrotelm, but was also noticed in samples from the lower catotelm.
12. The majority of the basal catotelm and organic clay samples displayed evidence of plastic deformation (as opposed to shear failure along a distinct plane) as no peak strength was reached and the lid of the shearbox tilted during the shearing process.

CHAPTER 5

BLANKET BOG HYDROLOGY AND INSTABILITY: FIELD CONDITIONS AND MODELLING

5.0 INTRODUCTION

Results obtained from the hydrological and geotechnical studies discussed in Chapters 3 and 4 form the basis for an analysis of the stability of peat slopes that will establish whether conventional methods of slope stability analysis (i.e. the safety factor using limit equilibrium methods as described in section 2.2.4) are suitable for use on peatland slopes. This chapter consists of a discussion of the available meteorological data, and the modelling of the hydrological and stability conditions within the Cuilcagh peatland. Meteorological data comprising daily, monthly and annual rainfall totals and potential evapotranspiration are used to assess seasonal variations and conditions prior to and during specific failure events. These antecedent conditions and storm characteristics are used to set boundary conditions for hydrological modelling which are necessary to determine long term and temporal stability conditions. The finite element hydrological modelling package, SEEP/W, is used to simulate hydrological conditions within the peat slopes, whereas the peat stability data are modelled using SLOPE/W which uses the theory of limit equilibrium to compute the factor of safety of the slope. This form of modelling has allowed the importance of critical threshold values for different parameters to be determined. The structure, capabilities and requirements of each model are outlined prior to the details of the modelling of the Cuilcagh peat. Analysis of the Cuilcagh slopes is then carried out using the Infinite Slope Model, so a comparison can be made to the performance of the SLOPE/W model. A sensitivity analysis is used to identify the influence of individual parameters on the stability of the slopes. Finally, the characteristics, mechanisms and significance of a modelled multiple peat slide (as described by Dykes and Kirk, 2000, 2001) are discussed.

The hydrology of peatlands is complex and depends significantly upon the morphology of the bog. Modelling of peatlands has traditionally been almost exclusively confined to lowland raised bogs, as they can be treated as a complete hydrological system. Within blanket bogs, however, the flow of water through different layers results in complex interactions between the acrotelm and catotelm, and the dominance of either lateral or horizontal flow according to local and regional topography and the permeability of the mineral substrate (Reeve *et al.*, 2000). This study is designed to integrate and model what is known about the hillslope hydrology of blanket peat and the stability of slopes comprising various depths of peat.

5.1 METEOROLOGICAL DATA

Meteorological data (actual and estimated) have been used to assess the importance of storm duration, as well as the climatic preparation of the slopes prior to, and during, three of the more recent failures on the mountain (bog flow E2, and peat slides N4 and NW10). In addition, meteorological data with corresponding field water table information (Chapter 3) have been used to validate the hydrological model. A network of raingauges on the slopes and summit of Cuilcagh Mountain and at Marble Arch Caves has been used to obtain data on rainfall characteristics. This has allowed a more accurate reconstruction of the hydrological and general slope conditions at the time of failure. The importance of the pre-conditioning of the slope is highlighted in Section 2.2.9. Rainfall data and discharge on a tributary of the Aghinrawn River (on a northern slope) have been continuously monitored since 1992. Together with estimations of evapotranspiration, these data have been used to develop a statistical model to calculate storm runoff events (Walker, 1998). These records have been used to generate input data for both steady state and transient hillslope hydrological analyses.

5.1.1 Annual trends and seasonal patterns

Annual precipitation on Cuilcagh Mountain ranges from 1500 to over 2000 mm/y (Figure 1.6) and evapotranspiration rates were estimated to be approximately 580 mm/y (Walker, 1998). This results in a net input of 920 to 1420 mm/y of rainfall onto the slopes. Cumulative annual precipitation for the north side of Cuilcagh Mountain for the years 1994 to 1999 is shown in Figure 1.7.

5.1.2 Storm events

Storm events are not unusual in western Ireland and three of the most recent recorded failures on Cuilcagh Mountain (E2, N4 and NW10) occurred during high magnitude rainfall events. Over a three year period, Walker (1998) recorded 159 stormflow events (using the hydrograph separation method (Hewlett and Hibbert, 1967)) on a sub-catchment of the Aghinrawn River on Cuilcagh Mountain. A summary of the descriptive storm hydrograph indices is given in Table 5.1.

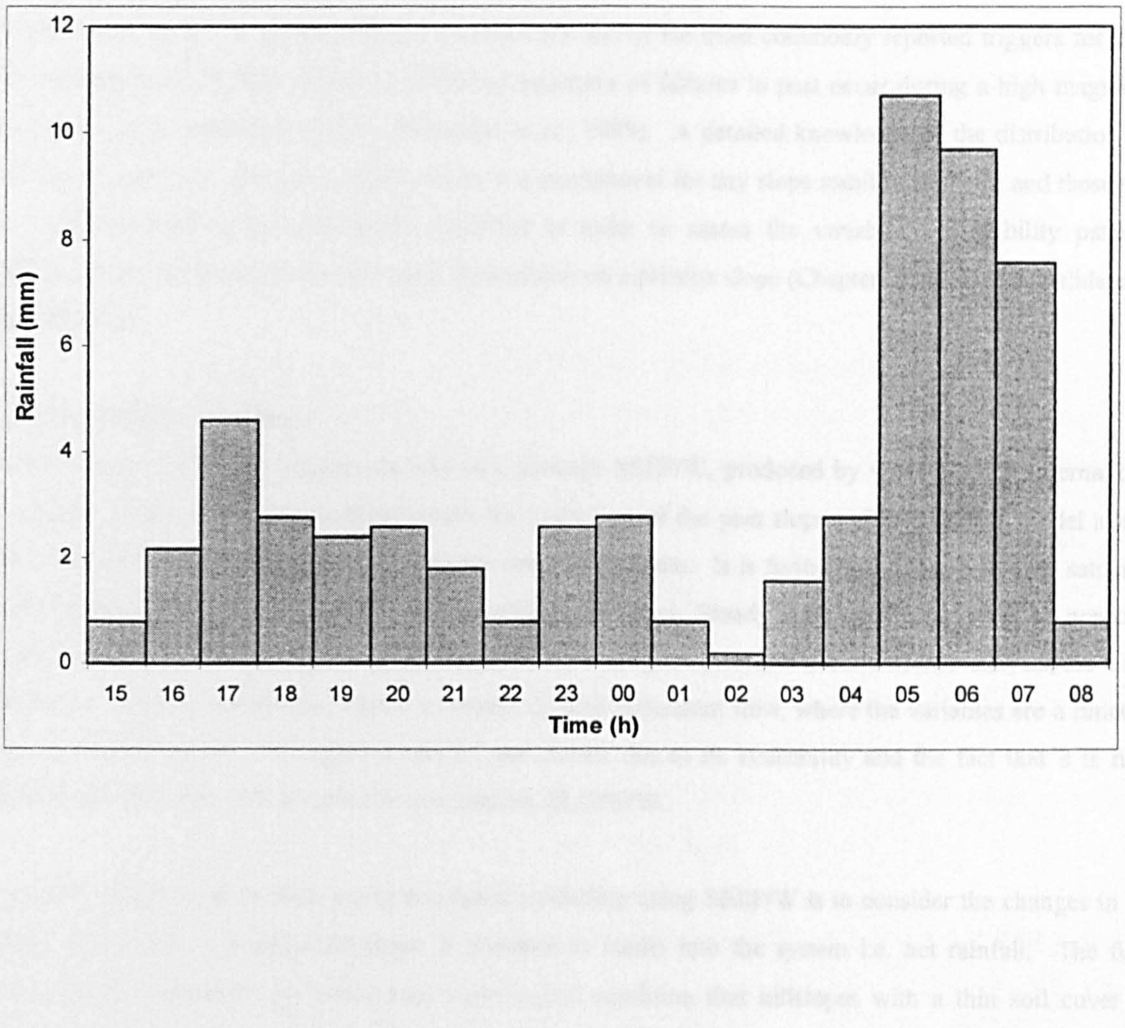
In August 1992, a major bog flow occurred on East Cuilcagh (E2) during a summer rainstorm event in which 58 mm of rainfall was recorded in an 18 hour period on the 21-22 August (Figure 5.1). This figure was produced from measurements at Marble Arch Caves, 6 km, from the failure site. Prior to this event, average conditions were recorded in July (total rainfall 115 mm with a long term average of 110 mm) which was followed by a wet August with a total of 230 mm precipitation compared with an average of 120 mm.

A multiple peat slide (N4) occurred on a northern slope of Cuilcagh Mountain in October 1998 and has been described in detail by Dykes and Kirk (2000). Between 23 and 26 October the raingauge at Marble Arch Caves received a total of 54.2 mm of rainfall. However, discharge from a continuously monitored flume 3 km from the failure site was used to back-calculate the details of the storm characteristics. Runoff from the storm event commenced on the 24 October and lasted approximately 29 hours. It was estimated that this resulted from rainfall of between 62.9 and 99.7 mm with a maximum 60-minute intensity of approximately 20 mm/h (Dr. C.

Table 5.1 Summary of descriptive storm hydrograph indices for a sub-catchment on Cuilcagh Mountain (Walker, 1998)

	Stormflow volume (depth equivalent - mm)	**Stormflow duration (h)**	**Precipitation (mm)**	**Time to peak (h)**
Mean	18.6	35.5	27.1	14.6
95% confidence level	± 3.0	± 2.3	± 3.1	± 1.7
Standard error	1.5	1.2	1.6	0.9
Median	13.8	31.3	20.9	11.2
Minimum	2.5	17.3	5.6	1.8
Maximum	103.4	88.7	118.0	51.3

Figure 5.1 Hourly rainfall totals associated with the 1992 bog flow (21-22 August 1992).



Walker, pers. comm.). A dry period occurred during the five weeks before the failure, but in the week immediately prior to the event over 80 mm of rainfall was recorded (Dykes and Kirk, 2001).

During March 2000, a peat slide that affected an area of 13,450 m^2 occurred on a north-western slope of Cuilcagh Mountain (NW10). The failure was associated with a high intensity rainfall event with 48.6 mm falling on the 2 March after a relatively dry period. It can be seen that these recent failures occurred during high magnitude rainfall events following either lower than average or higher than average rainfall conditions.

5.2 HILLSLOPE HYDROLOGY

High pore water pressures within hillslope materials are one of the most commonly reported triggers for slope failure (Brunsden, 1979) and almost all published examples of failures in peat occur during a high magnitude rainfall event (e.g. Tomlinson, 1981b; Alexander *et al.*, 1985). A detailed knowledge of the distribution and variability of pore water pressures within a slope is a requirement for any slope stability analysis, and these pore water pressures need to be realistically modelled in order to assess the variability of stability patterns. Therefore, field measurements of water table fluctuations on a pristine slope (Chapter 3) are used to validate the modelled results.

5.2.1 Introduction to the Model

The commercially available engineering software package SEEP/W, produced by GEO-SLOPE International Ltd. (Calgary, Canada) has been used to model the hydrology of the peat slopes. The SEEP/W model allows detailed analysis of a 2-dimensional groundwater seepage problem. It is formulated to analyse both saturated and unsaturated flow through steady state or transient analyses. Steady state conditions refer to non-time dependent flow, where the unknown variables are functions of space (i.e. for a 2-dimensional analysis, the x and y direction). Transient conditions refer to unsteady, or time dependent flow, where the variables are a function of time as well as space. The SEEP/W model was chosen due to its availability and the fact that it is fully integrated with the slope stability analysis programme, SLOPE/W.

The specific objective of carrying out hydrological modelling using SEEP/W is to consider the changes in the saturated zone within a peatland hillslope in response to inputs into the system i.e. net rainfall. The fully saturated profile represents the worse case hydrological condition that hillslopes with a thin soil cover on impermeable bedrock can experience with respect to slope stability (Francis, 1987). Therefore, a marginally (or conditionally) unstable slope is not expected to fail unless it is in a fully saturated condition. Although SEEP/W is an established engineering hydrology model, it is unlikely to have been applied to peatland slopes. Therefore, the model must first be adequately validated by means of transient analyses before the results can be used in a peat slope stability analysis.

5.2.2 Model Structure

The SEEP/W model uses a finite element analysis scheme that involves two distinct modelling steps. Firstly, the problem is specified. This involves the slope being divided into a number of elements that can vary in shape and size, so that the geometry of every material is represented in detail and a finite element mesh is created. The hydraulic properties (hydraulic conductivity and function) of each of the slope materials are then defined and all boundary conditions are specified. Secondly, the problem is analysed by solving the finite element equations with the use of total head throughout the modelled hillslope as the primary variable.

The physical basis for the SEEP/W model focuses on three components: Darcy's Law; a single governing equation based on continuity for the changing volumetric water content of each elemental volume (in terms of total head and hydraulic conductivity in the x and y directions); and for transient analyses a 'soil moisture characteristic' curve for each material in the problem (the relationship between volumetric moisture content and pore water pressure). Each of these is outlined in Appendix 6.

There are three main assumptions for the SEEP/W model:

1. Elements have constant thickness in a 2-dimensional analysis;
2. There is no loading or unloading of the soil mass;
3. During transient analyses, the pore air pressure remains constant at atmospheric pressure.

In addition to these, one further assumption implicit to the model is that any material defined by the input of field data is uniform and homogeneous throughout, and behaves accordingly with respect to its defined hydrological characteristics (GEO-SLOPE, 1995a).

5.2.3 Model Capabilities and Requirements

The main capabilities of SEEP/W are that it can perform steady state and transient analyses for both saturated and unsaturated flow conditions. Therefore, the model can be set-up to simulate 'long-term' hillslope conditions, or the response of a sequence of events generated over a given period of time to simulate temporal patterns. The results of the model simulations comprise the magnitude and direction of flow, the position of the water table and contours of pore water pressure illustrated on the finite element mesh.

A number of modelling requirements must be specified for successful modelling results (GEO-SLOPE, 1995a):

1. Flow entering and leaving the system;
2. Hydraulic conductivity function (k_{func}) for all slope materials;
3. Head differential from one side of the problem to the other, so flow will always occur;
4. An incremental time sequence for transient analysis.

Boundary conditions and actions must be specified for all margins of the mesh (according to the inputs and output to the system) and may be designated as total head (H), total nodal flux (Q), or flow per unit length along the side of an element (GEO-SLOPE, 1995a). For example, the upper boundary defines the input to the slope and therefore its action is given by q (unit flux) and a value of input (usually rainfall minus PET). Depending on the analysis type, inputs can be constant (steady state), or time stepped (transient analysis).

A hydraulic conductivity function (k_{func}) must be specified for all materials included in the analysis. This is the relationship between k and pore water pressure. The importance of using an approximated curve rather than a straight horizontal line for unsaturated conditions is considered to give a more accurate modelling solution if the exact relationship is unknown (GEO-SLOPE, 1995a). The soil moisture characteristic curve (for transient analyses) and the hydraulic conductivity function (k_{func}) are associated with the porosity and saturated hydraulic conductivity (k_{sat}) of the material. These are also related to the degree of anisotropy of the material that can be specified for each material type.

5.3 MODELLING THE HYDROLOGY OF THE CUILCAGH PEAT

5.3.1 Problem definition

The main aims in modelling the hydrological conditions within peatland slopes were to determine long term average and transient conditions, and more specifically, the range of pore pressure distributions present on the Cuilcagh peatland where slope instability has occurred. This was carried out to assess the variability of both water table and pore water pressure fluctuations within the peat and to ultimately perform slope stability analysis, which uses the pressure distribution within a slope to calculate the Factor of Safety.

The modelling of each slope problem involved the design of a mesh using the measured 2 dimensional profile through the centre line of a failure scar or slope showing signs of instability. The various required hydrological parameters were then assigned to each material within the slope problem. Analysis of the hydrological problem comprised three steps:

1. Transient analysis to validate observed field conditions.
2. Transient analysis to assess variability of pore water pressure i.e. recovery of the water table after a dry period and seasonal variability.
3. Steady state analysis to determine average 'long term' pore water pressure distributions within the slope.

5.3.2 Set-up

The hydrological modelling of the Cuilcagh peat requires the geometry and set up of the slope problem (design of the finite element mesh), the specification of boundary conditions, and hydrological properties of the materials within the slope. Since the model requires consistency in units for both the mesh and parameters, time in seconds and distances in metres have been used throughout. Therefore, net input into the slope (rainfall minus evapotranspiration) and values of hydraulic conductivity were defined using m/s, and the slope geometry was set up in metres. Positive and negative pore water pressures were defined in terms of kN/m^2 (kPa) and the unit weight of water took the value 9.807 kN/m^3.

The first step in the modelling process is the generation of a mesh design for each slope failure problem. The slope geometry was obtained in the field for each slope problem by measuring a transect along the maximum angle of slope up the centre of the particular failure using a clinometer and measuring tape. Depths of peat around the failure scar and upslope of the scar were measured to estimate the depth of peat prior to failure and drainage. Although no distinct boundary between the acrotelm and catotelm was observed in the field, due to their different physical and geotechnical properties they were treated as separate layers and modelled accordingly i.e. the upper 0.5 m of peat was defined as the acrotelm (see Chapter 2). The thickness of clay underlying the peat was estimated to be 2.0 m on the basis of a number of soil auger tests on several failure scars. The majority of the failed slopes that were analysed involved movement into a river at the foot of the slope and therefore fit the requirement for a head differential from one side of the problem to the other. In these cases, a near vertical bank of peat was used to delineate the downslope extent of the problem. Failures of sections of slopes not terminating in a river or stream were modelled in a similar manner, i.e. with the downslope extent ending in a topographic hollow, but with seepage at the foot of the slope being permitted.

Boundary conditions for the modelled materials within the slopes were specified according to the overall inputs and outputs relative to the time increment used. At the base of the modelled problem, flow was assumed minimal as the bedrock underlying the clay and peat was presumed to be effectively impermeable. Also, it was assumed that there was no lateral inflow to the profile at the crest of the slope. Therefore, the base and upper end of the profile were designated no-flow boundaries. At the surface of the slope a non-zero flux boundary simulated input conditions represented by net rainfall and infiltration capacity, and outputs in the form of evapotranspiration losses. Input was assumed to be constant for the duration of the respective time step. For steady state analysis, a conservative value of 4.4×10^{-8} m/s was given as the upper boundary condition, which equates to 1400 mm annual net input (1950 mm rainfall minus 550 mm PET). Inputs for both steady state and each transient time steps were lower than the values for infiltration capacity given by Walker (1998) and described in Chapter 1. To assess the variability and range of the pore water distribution within the slopes, and the recovery of the water table after a dry period, a number of transient analyses were carried out using actual recorded monthly rainfall and estimated PET rates based on temperature (Thornthwaite method as described by Walker, 1998). Monthly input ranged from 0 mm to 288 mm (1.1×10^{-7} m/s). Meteorological data for Cuilcagh Mountain for the years 1994 to 1996 were available from Walker (1998). The model was validated using daily rainfall totals measured during April 1999, i.e. corresponding with the period of dipwell monitoring. These meteorological data were recorded at Marble Arch Caves as data from the raingauges nearer the pristine slope were unreliable. Daily PET values were derived using the calculated average March and April monthly totals for 1994 to 1996 and subsequently subtracted from the associated daily rainfall figures. Tables 5.2 and 5.3 show the meteorological data used in the daily and monthly transient analyses. A correction value was used to allow for greater rainfall at the pristine slope at an altitude of 360-370 m OD, since the Marble Arch Caves raingauge is only at 175 m OD. This was calculated by distributing the estimated

Table 5.2 Meteorological data for the daily transient analysis using SEEP/W.

Date	Time step duration (s)	Time step duration (h)	Rainfall (P) (mm)	PET (mm)	Input (P-PET)	
					mm/d	m/s
28/03/99	8.6x10^{4}	2.4x10^{1}	11.1	0.8	10.3	1.2x10^{-7}
29/03/99	1.7x10^{5}	4.8x10^{1}	3.6	0.8	2.8	3.3x10^{-8}
30/03/99	2.6x10^{5}	7.2x10^{1}	2.2	0.8	1.4	1.6x10^{-8}
31/03/99	3.5x10^{5}	9.6x10^{1}	15.9	0.8	15.1	1.8x10^{-7}
01/04/99	4.3x10^{5}	1.2x10^{2}	1.1	1.3	0.0	0.0
02/04/99	5.2x10^{5}	1.4x10^{2}	2.1	1.3	0.8	9.5x10^{-9}
03/04/99	6.0x10^{5}	1.7x10^{2}	4.6	1.3	3.3	3.8x10^{-8}
04/04/99	6.9x10^{5}	1.9x10^{2}	7.1	1.3	5.8	6.7x10^{-8}
05/04/99	7. 8x10^{5}	2.2x10^{2}	3.3	1.3	2.0	2.3x10^{-8}
06/04/99	8.6x10^{5}	2.4x10^{2}	2.3	1.3	1.0	1.2x10^{-8}
07/04/99	9.5x10^{5}	2.6x10^{2}	1.9	1.3	0.6	7.2x10^{-9}
08/04/99	1.0x10^{6}	2.9x10^{2}	1.1	1.3	0.0	0.0
09/04/99	1.1x10^{6}	3.1x10^{2}	4.5	1.3	3.2	3.7x10^{-8}
10/04/99	1.2x10^{6}	3.4x10^{2}	4.3	1.3	3.0	3.5x10^{-8}

Table 5.3 Meteorological data for the monthly transient analysis using SEEP/W.

Date	Time step duration (s)	Time step duration (h)	Rainfall (P) (mm)	PET (mm)	Input (P-PET)	
					mm/d	m/s
Jan-95	2.6x10^{6}	7.2x10^{2}	305	17	288	1.1x10^{-7}
Feb-95	5.2x10^{6}	1.4x10^{3}	214	12	202	7.8x10^{-8}
Mar-95	7.8x10^{6}	2.2x10^{3}	210	21	189	7.3x10^{-8}
Apr-95	1.0x10^{7}	2.9x10^{3}	53	46	7	2.7x10^{-9}
May-95	1.3x10^{7}	3.6x10^{3}	83	54	29	1.1x10^{-8}
Jun-95	1.6x10^{7}	4.3x10^{3}	37	90	-53	0.0
Jul-95	1.8x10^{7}	5.1x10^{3}	148	98	50	1.9x10^{-8}
Aug-95	2.1x10^{7}	5.8x10^{3}	14	85	-71	0.0
Sep-95	2.3x10^{7}	6.5x10^{3}	107	68	39	1.5x10^{-8}
Oct-95	2.6x10^{7}	7.2x10^{3}	324	49	275	1.1x10^{-7}
Nov-95	2.9x10^{7}	7.9x10^{3}	215	25	190	7.3x10^{-8}
Dec-95	3.1x10^{7}	8.7x10^{3}	102	8	94	3.6x10^{-8}

long term average annual rainfall difference (450 mm) between the sites at a higher altitude, to the monthly totals according to their proportion of the average annual rainfall. Where values of PET exceed P (rainfall), an input value of zero was used as it was expected that evapotranspiration losses would be minimal during Spring once the water table has dropped a few centimetres below the surface because temperatures are generally low and water storage within the bog is thought to be near a maximum at this time of year (Walker, 1998).

Values of k_{sat} were taken from both laboratory and field results of peat at sites E2, E6, N4 and NW5 (Figure 5.2). As the k_{sat} values at each site demonstrate considerable variability, the values used in the modelling of each individual site consisted of averages for all of the Cuilcagh peat tested. Therefore, k_{sat} within the acrotelm peat (upper 50 cm) was given as 1.0 x 10^{-5} m/s to 1.0 x 10^{-6} and within the catotelm (below 50 cm), k_{sat} was given as 1.0 x 10^{-7} to 1.0 x 10^{-8} m/s. For two of the peat slides (N4 and NW10), a layer of pale coloured fibre-rich organic clay was noted at the base of the peat. In order for the importance of this layer to be assessed, an extra layer was modelled between the catotelm and the underlying basal clay. The k_{sat} for this upper clay was determined in the laboratory and gave an average value of 1.0 x 10^{-9} m/s. All parameters for the underlying clay were estimated on the basis of field inspection of the material *in situ* (Dykes and Kirk, 2001) and included a k_{sat} value of 8.5 x 10^{-9}. Other published data for similar clay materials (10^{-8} m/s) is given in GEO-SLOPE (1995b).

The degree of anisotropy of each material is specified in the model by giving the ratio of k_{sat} in the vertical direction to the horizontal direction. The Cuilcagh peat was found to be anisotropic, particularly in the catotelm. Contrary to Hobbs (1986), k_{sat} for the peat was found to be notably higher vertically than horizontally. Dai and Sparling (1973) reported this pattern to be consistent with a *Sphagnum*-dominated structure. The underlying clay was assumed to be isotropic. There was no discernible change in the pore water pressure distribution when the degree of anisotropy was reduced or increased by one or two orders of magnitude, regardless of which, k_{sat} values were used. Table 5.4 illustrates the parameters used for each site for the SEEP/W model.

All parameters for the peat slopes used in the modelling of SEEP/W have either been measured directly (e.g. geometry) or indirectly (e.g. k_{sat}) with the exception of the hydraulic conductivity function (k_{func}) and the soil moisture characteristic curve for transient analyses. The k_{func} was estimated from k_{sat} values and the physical properties of the materials. The inherent variability of the field conditions (Chapter 3 and 4) means that results in the output of the model would probably be no more accurate if detailed and time consuming laboratory determinations of relationships were used (Dykes and Kirk, 2001). The estimates of k_{func} were further supported by examples given in the SEEP/W manual obtained from materials with similar physical properties (GEO-SLOPE, 1995a). A relatively steep k_{func} was used to designate the acrotelm. Although this kind of behaviour is usually associated with coarse-grained materials with small capillary zones, it is expected that once the intracellular (free), and interparticle (capillary) water has drained from the peat structure, k decreases rapidly (Hobbs, 1986). The behaviour of the catotelm peat, however, is expected to be similar to clay. There is less free water available to drain from the structure as more water is tightly bound, giving a more gentle k_{func}

Figure 5.2 All saturated hydraulic conductivity (k_{sat}) determinations for Cuilcagh peat

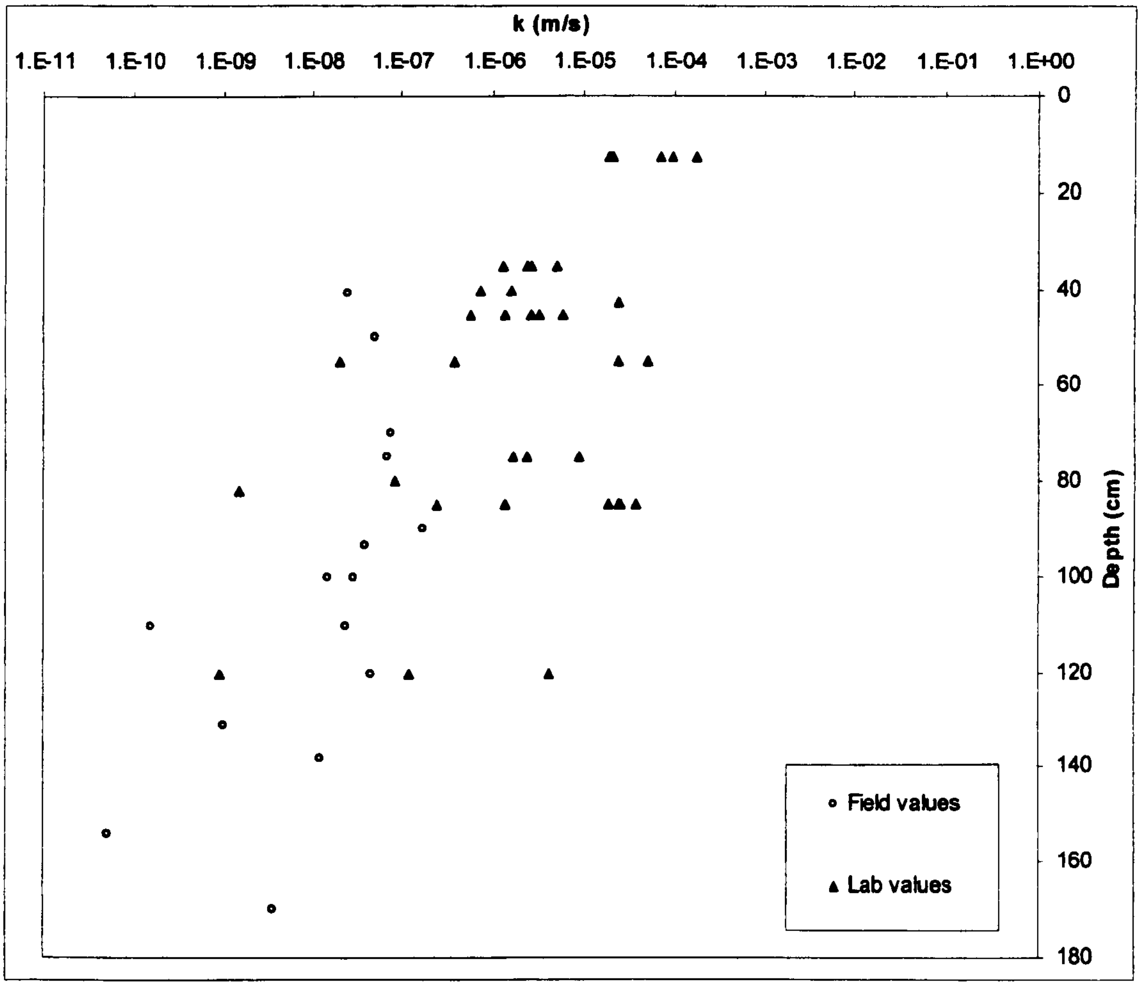


Table 5.4 Values of parameters used in hydrological model.

Site	Material	Average Thickness (m)	k_{sat} (m/s)	k-ratio (V:H)
E2	Acrotelm	0.5	10^{-6}	1.0
	Catotelm	1.5	10^{-6}	10.0
	Clay	2.0	10^{-7}	1.0
E3	Acrotelm	0.5	10^{-6}	1.0
	Catotelm	1.5	10^{-7}	10.0
	Clay	2.0	10^{-7}	1.0
E6	Acrotelm	0.5	10^{-5}	1.0
	Catotelm	1.5	10^{-7}	10.0
	Clay	2.0	10^{-7}	1.0
E7	Acrotelm	0.5	10^{-6}	1.0
	Catotelm	1.5	10^{-7}	10.0
	Clay	2.0	10^{-7}	1.0
Bulging Slope	Acrotelm	0.5	10^{-6}	1.0
	Catotelm	1.5	10^{-7}	10.0
	Clay	2.0	10^{-7}	1.0
N1	Acrotelm	0.5	10^{-5}	1.0
	Catotelm	1.0	10^{-6}	10.0
	Clay	2.0	10^{-7}	1.0
N15	Acrotelm	0.5	10^{-6}	1.0
	Catotelm	0.5	10^{-7}	4.5
	Clay	1.5	10^{-7}	1.0
N19	Acrotelm	0.5	10^{-5}	1.0
	Catotelm	0.5	10^{-6}	4.5
	Clay	1.5	10^{-7}	1.0
NW3	Acrotelm	0.5	10^{-6}	1.0
	Catotelm	1.0	10^{-7}	10.0
	Clay	2.0	10^{-7}	1.0
NW5 and NW6	Acrotelm	0.5	10^{-5}	5.0
	Catotelm	1.0	10^{-7}	10.0
	Clay	2.0	10^{-7}	1.0
NW10	Acrotelm	0.2	10^{-5}	1.0
	Catotelm	0.5	10^{-7}	4.5
	Clay	1.5	10^{-7}	1.0
Pristine slope	Acrotelm	0.5	10^{-5}	1.0
	Catotelm	1.5	10^{-7}	10.0
	Clay	2.0	10^{-7}	1.0

relationship. The k-functions and soil moisture characteristic curves used in the modelling procedure are illustrated in Appendix 7.

5.3.3 Validation

SEEP/W was validated by the testing of its performance by comparing simulated conditions within the peatland hillslope with conditions defined by water table levels in the field. Generally, peatlands are almost entirely characterised by saturated conditions, therefore high water table levels are expected to result from both transient and steady state analyses. Water table levels were obtained from a series of dipwells on a pristine slope at East Cuilcagh (see Chapter 3 for details). Steady state and transient analyses were performed on the modelled pristine slope. A further transient analysis was carried out on a section of slope that failed in 1992 (site E2).

Figure 5.3 illustrates the finite element mesh created for the modelled pristine slope using the geometry ascertained in the field. Values for k_{sat} and unit weight were taken from failure site E2, the scar of which is situated approximately 20 m north of dipwell A at the crest of the slope. The k_{func} and the soil moisture characteristic curve were estimated from k_{sat} values and the physical properties of the materials. The various required meteorological data (precipitation and estimated PET) were collected from Marble Arch Caves and other raingauges on Cuilcagh Mountain (Tables 5.2 and 5.3).

Initially, a steady state analysis was run to test the parameters and view the associated output. An input of 4.4×10^{-8} m/s (1400 mm/y) was given as the upper boundary condition (section 5.3.2). The output (Figure 5.4) indicated the average position of the water table and exhibited almost entirely saturated conditions throughout the slope profile. At the crest of the slope, the water table was at its lowest position (15 cm below the surface) but was mostly situated within the uppermost 5 cm of acrotelm.

The main model validation process involved a transient analysis using daily time steps and actual rainfall data to compare differences between observed (field) and simulated results. Using the steady state output as the initial condition, the transient analysis was set up with 14 daily time steps. Table 5.5 shows the upper boundary condition for each time increment in the analysis (28/3/99 until 10/4/99) calculated from the available meteorological data. These increments incorporate the dates in which the water levels in the dipwells were read (2/4/99, 3/4/99, 4/4/99, 6/4/99 and 10/4/99). The relative inaccessibility of the site prevented longer periods of continuous recordings. The simulated water table levels for each dipwell are also given in Table 5.5. The output of the model only illustrates the water table if it lies at or below the surface, within the generated mesh. Therefore, water table levels above the surface were estimated using the contour of water pressure within the slope (as water pressure is zero at the water table). In dipwells C, D, E and F, the simulated water table is situated between 0 and 5 cm above the peat surface for all of the time steps. At the top of the slope (dipwells A and B) however, simulated water tables are more variable but all lie below the surface. For example, at dipwell A, the water table varies between 5 and 45 cm below the surface for the used time steps. Table 5.6 shows the observed (field) and simulated water table levels. Although the simulated results do not accurately reflect the

Figure 5.3 The finite element mesh for the modelled pristine slope.

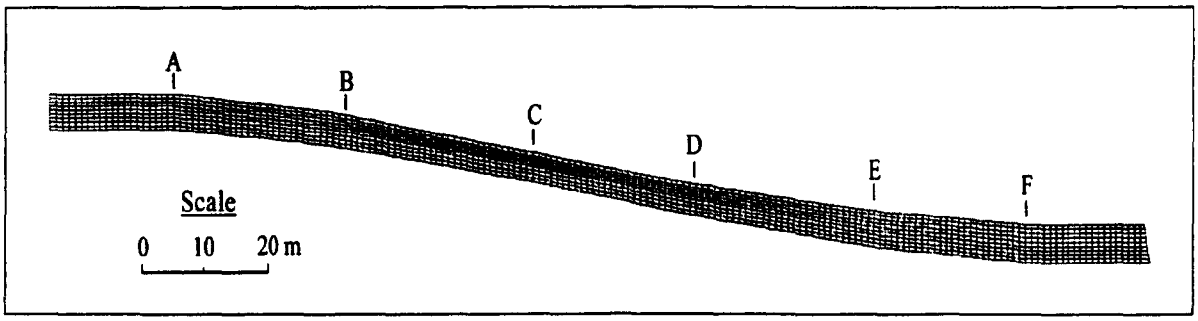


Figure 5.4 Average observed (field) and simulated (SEEP/W) water table levels for a pristine slope on East Cuilcagh.

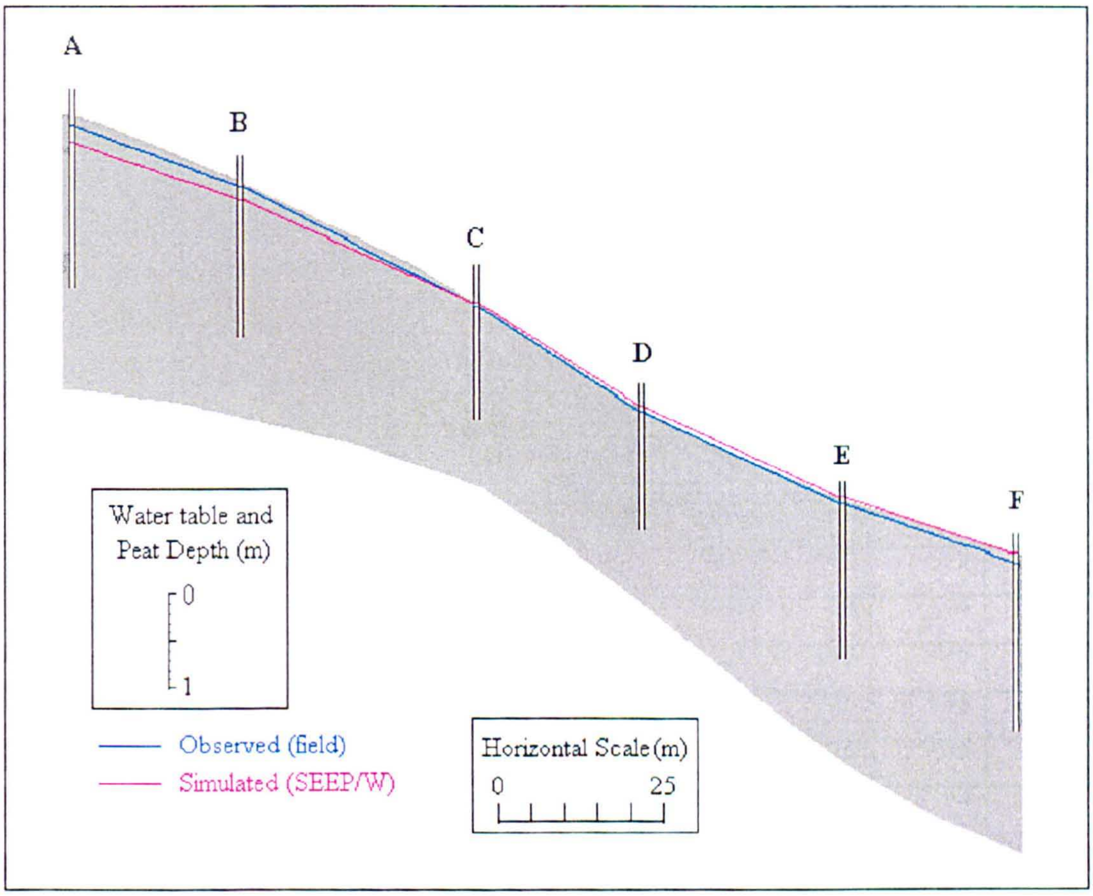


Table 5.5 Transient analysis results for model validation using actual rainfall data from Cuilcagh Mountain (28/3/99 to 10/4/99)

Date (daily time step)	Input (m/s)	Input (mm/d)	Simulated water table levels (cm)					
			A	B	C	D	E	F
28/03/99	1.2×10^{-7}	10.32	-10	-5	<+5	<+5	<+5	<+5
29/03/99	3.3×10^{-8}	2.82	-30	-20	0	<+5	<+5	0
30/03/99	1.6×10^{-8}	1.42	-35	-20	0	<+5	<+5	0
31/03/99	1.7×10^{-7}	14.62	-5	-5	<+5	<+5	<+5	<+5
01/04/99	0.0	0.00	-39	-22	0	+4	+5	0
02/04/99	9.5×10^{-9}	0.82	-45	-27	0	+2	+2	0
03/04/99	3.8×10^{-8}	3.32	-15	-7	+2	+2	+2	0
04/04/99	6.7×10^{-8}	5.82	-9	-4	<+5	<+5	<+5	<+5
05/04/99	2.3×10^{-8}	2.02	-20	-18	0	+2	+4	0
06/04/99	1.2×10^{-8}	1.02	-40	-26	0	<+5	<+5	0
07/04/99	7.2×10^{-9}	0.62	-45	-40	0	<+5	<+5	0
08/04/99	0.0	0.00	-25	-20	<+5	<+5	<+5	<+5
09/04/99	3.7×10^{-8}	3.22	-20	-9	+2	+2	+4	+1
10/04/99	3.5×10^{-8}	3.02	-20	-9	+2	+2	+4	+1

Table 5.6 Observed (field) and simulated (SEEP/W) water table levels for a pristine slope on East Cuilcagh.

Date	Result	Water table levels (cm)					
		A	B	C	D	E	F
02/04/99	Observed	-13	-4	-2	-2	-3	-12
	Simulated	-45	-27	0	+2	+2	0
03/04/99	Observed	-13	-5	-3	-4	-2	-13
	Simulated	-15	-7	+2	+2	+2	0
04/04/99	Observed	-12	-4	-2	-1	-2	-12
	Simulated	-9	-4	+2	+2	+2	0
06/04/99	Observed	-12	-4	+2	0	-1	-10
	Simulated	-40	-26	0	+2	+2	0
10/04/99	Observed	-12	-4	0	0	-2	-9
	Simulated	-20	-9	+2	+2	+4	+1

Table 5.7 Average observed and simulated water table levels.

Result	Average water table levels (cm)					
	A	B	C	D	E	F
Observed	-12	-4	-1	-1	-2	-11
Simulated	-26	-15	+1	+2	+2	0

observed values, they do bracket the range of conditions for the whole slope. Simulated results for the dipwells at the top of the slope lie below those observed in the field. At foot of the slope, the opposite is the case, i.e. the simulated levels are higher than the observed. Table 5.7 and Figure 5.4 illustrate the average simulated and observed water table levels on the pristine slope. The information in these tables indicate that the simulated values are closer to the observed values on the steeper part of the slope. At low gradients, specifically dipwells A and F, simulated values do not represent observed patterns. The water table at A is an average of 15 cm higher than the simulated value, although the difference ranges from 3 to 32 cm. At dipwell F, the simulated water table is consistently higher than the observed level by 10 to 13 cm. The differences between field and modelled results at dipwell F may be the result of error in the modelling set-up, more specifically the geometry and boundary conditions at the foot of the slope. Dipwell F is situated in a topographic hollow with the stream bank at the foot of the slope situated some distance downslope (approximately 80 m). The lower extent of the slope problem was modelled with seepage being permitted (i.e. a flux across the boundary equal to the amount of expected natural groundwater flow) approximately 20 m downslope of dipwell F. As simulated hydrological conditions are strongly affected by conditions at the boundaries, it is thought that the specifications at this lower boundary were unrealistic. It is possible that although situated in a topographic hollow, local variations in drainage may have resulted in divergence rather than convergence around dipwell F. This would account for the lower than expected observed water table at the foot of the modelled slope. Lines of convergence and divergence in drainage associated with varying topography are difficult to predict and model without time consuming detailed investigations of field conditions, i.e. it is difficult to incorporate 3-D effects into a 2-D analysis.

Overall, for transient analysis using daily time steps, the SEEP/W model was moderately successful at simulating water table levels and, therefore, pore water pressure distributions within the modelled slope. Although exact distributions were not modelled, conditions within the majority of the slope were approximately simulated with most of the slope being saturated almost to the surface. For all of the tested situations, 60% of the simulated values were within 5 cm of the observed field values, with 70% within 8 cm. The main differences may have been the result of an error in one of the set parameters, such as k_{sat}, k_{func}, or perhaps more likely the estimated soil moisture characteristic curve. The difference between observed and simulated results was not uniform: simulated water levels did not all over-, or under-estimate observed values. This suggests the disparities do not result from a single incorrect parameter and may have resulted from the assumed relationships with changing pressure, i.e. k_{func} and soil moisture characteristic curve. This would account for the apparent sensitivity of the model. Further errors may have resulted from the modelled slope not having sufficient detail as in reality a bog is not made up of two distinct layers, but graded gradually. For example, within the acrotelm k_{sat} varies considerably, from 10^{-1} m/s in the root mat to 10^{-5} m/s immediately above the assumed catotelm boundary (Hobbs, 1986). However, further detailed modelling which involved the slope profile being divided up into more layers resulted in no more accuracy in the model performance. Another source of error may have been related to the relatively crude estimates of evapotranspiration, which affect the model input, (upper boundary condition). As described in Chapter 1, ET can vary considerably with local changes in botanical composition and therefore estimates used in the modelling may be either higher or lower than the AET.

However, as the difference between observed and simulated readings was not uniform throughout the slope, it is unlikely that any inaccuracies in estimations of ET are large enough to cause notable errors.

There are uncertainties involved in the model process which are difficult to quantify due to the number of parameters within the model and the manner in which it uses a number of continuity equations to solve the problem. There are also inaccuracies involved in both reading the water levels in the dipwells (observed results) and the visual output from the SEEP model (simulated results). It is possible, however, to quantify a margin of error involved in the accuracy of these readings by recording repeat measurements at a single dipwell. The margin of error (precision) of reading the dipwells (observed values) was calculated to be a maximum of 8.5 mm, while the accuracy was calculated to be within 0.5 mm. The visual output from the SEEP model illustrates the water table on the slope mesh, but is limited to the scale at which the image can be viewed, which depends on the length of the slope problem. It is estimated that for the modelled pristine slope the water table was measured to the nearest 10 to 20 mm. Given these levels of uncertainties, the maximum known error is 29 mm. A total of 37% of simulated readings were within this margin of observed readings.

A further transient analysis was performed using monthly time steps on a modelled slope (E2) to assess the changes in water table and pore water distribution with changing inputs and also to determine the effectiveness of larger time steps i.e. simulating monthly rather than daily variations. Table 5.8 illustrates the results of the analysis using actual monthly rainfall from the Aghinrawn catchment on the northern slopes of Cuilcagh Mountain. The analysis comprised twelve monthly time-steps from January to December 1995. The resulting simulated water levels indicate almost entirely saturated conditions with the water table dipping below the surface only at the concavities at the crest and foot of the slope. At the crest of the slope, the lowest position of the water table over the twelve months was 15 to 20 cm below the surface. This is thought to be representative of actual conditions as the observed water levels in dipwells adjacent to the modelled slopes do not extend below approximately 15 cm. Table 5.8 also gives an indication of simulated recovery rates in the water table from low rainfall. There is no immediate drop in water level after one dry month, but after a run of more than one dry month e.g. April and May, there is a cumulative effect and the water table drops from around 5 to 15 cm below the surface. Further simulated dry periods (June and August) result in the water table falling to around 20 cm in depth. A steady state analysis of this slope revealed a similar output to the first three months of the transient analysis i.e. almost entirely saturated conditions with the lowest water table positioned at -5 cm at the crest of the slope.

Therefore, fully saturated conditions are widespread on results of both daily and monthly transient analyses and are validated by means of field water table values. The results of the steady state analysis carried out on the two modelled slopes (pristine slope and E2) were successful at simulating almost entirely saturated conditions and were thought to be representative of actual conditions given the transient simulated results and the observed data. As saturated conditions represent the worse case scenario for instability and the transient analyses were

Table 5.8 Results of transient analysis using actual monthly 1995 rainfall data on modelled slope E2

Monthly time step	Average input (m/s)	Total monthly input P-PET (mm)	Simulated hydrological condition	Lowest water table position (cm)	Range in pressure for the whole slope (kPa)	Range in pressure at the slip surface (kPa)
Jan-95	1.1×10^{-7}	288	Almost entirely saturated.	<-5	-2 to 40	19 to 20
Feb-95	7.8×10^{-8}	202	Almost entirely saturated.	-5	-2 to 40	19 to 20
Mar-95	7.3×10^{-8}	189	Almost entirely saturated.	-5	-2 to 40	19 to 20
Apr-95	2.7×10^{-9}	7	Almost entirely saturated.	<-5	-2 to 40	19 to 20
May-95	1.1×10^{-8}	29	Almost entirely saturated. Water table dips at crest and foot convexities.	-15	-2 to 40	18 to 20
Jun-95	0	0	Almost entirely saturated. Water table dips at crest and foot convexities.	-20	-2 to 40	18 to 20
Jul-95	1.9×10^{-8}	50	Almost entirely saturated. Water table dips at crest and foot convexities.	-15 to -20	-2 to 40	18 to 20
Aug-95	0	0	Almost entirely saturated. Water table dips at crest and foot convexities.	-15 to -20	-2 to 40	18 to 20
Sep-95	1.5×10^{-8}	39	Almost entirely saturated. Water table dips at crest and foot convexities.	-10	-2 to 40	18 to 20
Oct-95	1.1×10^{-7}	275	Almost entirely saturated. Water table dips at crest and foot convexities.	-10	-2 to 40	18 to 20
Nov-95	7.3×10^{-8}	190	Almost entirely saturated. Water table dips at crest and foot convexities.	-10	-2 to 40	18 to 20
Dec-95	3.6×10^{-8}	94	Almost entirely saturated. Water table dips at crest and foot convexities.	-10	-2 to 40	18 to 20

time consuming to perform and yielded no additional information, steady state analyses were used to simulate pore pressure distributions in the remaining slopes to be examined.

5.3.4 Simulations and Performance

Twelve slopes were set up for hydrological modelling. These comprised the most well defined scars on the blanket bog plus a slope that shows signs of instability and incorporated a range of flow and slide type failures. On East Cuilcagh bog flow failure sites E2, E3, E6, E7 and the bulging slope (site 2) were modelled (see Figure 3.1 for location of failures). On the northern slopes of Cuilcagh Mountain the modelled sites consisted of N1, N15, N19, NW3, NW5, NW6 and NW10. Peat slide N4 has been modelled separately (Dykes and Kirk, 2001) and its findings are discussed in Section 5.7.

Table 5.9 shows the results of the steady state analyses of the modelled slopes. The simulations indicated almost entirely saturated conditions within the slopes. Only a modelled section of the bulging slope that contained large tension cracks produced notable unsaturated conditions. In the modelled failed slopes on the north and north-west slopes of Cuilcagh where the peat is relatively shallow (as a result of steeper slopes), simulated water tables ranged from 0 to 25 cm below the surface, whereas the deeper areas of peat on East Cuilcagh were characterised by higher simulated water table levels (within upper 5 cm).

The differences in pore water pressures at the slip surfaces (as illustrated in Table 5.9) for each failure site are a function of the depth of peat in which the pressures are distributed. Therefore, the failures which occur in deeper areas of peat (e.g. the bog flows) have a range in pressure of 19 to 20 kPa, compared with the peat slide sites (N4 and NW10) which have a range of 4 to 10 kPa. With normal hydrostatic conditions, pressure varies according to the depth of material. For the Cuilcagh peat, water pressure increases by approximately 5 kPa for every 0.5 m of saturated material. Greater ranges in pressures were simulated within the bulging slope (from 2 to 26 kPa). This is a result of unsaturated conditions in which the water table dropped to one metre below the surface over the tension cracked area of the slope resulting in reduced pore pressure conditions.

5.3.5 Summary of transient and steady state analyses

The hydrological modelling of Cuilcagh Mountain blanket peat consisted of transient and steady state analyses on a number of slopes that have been subject to failure. This was carried out based on the assumption of normal hydrostatic conditions in the peat mass as there was no obvious piping (and hence no artesian conditions). The possibility of artesian conditions is addressed in the following chapter with reference to the 1998 multiple peat slide.

To summarise the results of the hydrological modelling on the Cuilcagh peat:

- Daily transient analysis of a modelled slope on East Cuilcagh was reasonably successful at simulating the observed water table positions within the slope. Approximately 60% of the simulated values were within 5 cm of the observed field values, which indicates that although exact distributions were not modelled, conditions within the majority of the slope were approximately simulated. Typically on the modelled

Table 5.9 Simulated hydrological conditions using a steady-state analysis (SEEP/W) with $q = 4.4 \times 10^{-8}$ m/s.

Site	Simulated hydrological condition	Lowest water table position (within failed section)	Total range in pressure for the whole slope (kPa)	Range in pressure along the slip surface (kPa)
E2	Almost entirely saturated.	<-5 cm at crest	-2 to 40	19 to 20
E3	Fully saturated, except at convex foot of slope.	0 cm at crest	-2 to 39	20
E6	Fully saturated, except at convex foot of slope.	<-5 cm at crest	-4 to 40	19 to 20
E7	Fully saturated, except at convex foot of slope.	0 cm	-19 to 39	20
BS	Fully saturated, except at cracked area.	-100 cm within cracked area	-10 to 46	2 to 26
N1	Almost entirely saturated. Water table dips at crest and foot convexities.	-10 to 15 cm at crest	-5 to 39	13 to 20
N15	Mostly saturated. Water table dips at crest and foot convexities.	-25 cm at crest	-4 to 24	6 to 10
N19	Mostly saturated. Water table dips at convexities.	-5 cm at crest	-1 to 29	9 to 10
NW3	Almost entirely saturated	<-5 cm at crest	-2 to 34	14
NW5	Almost entirely saturated.	-5 cm at crest	-4 to 34	14 to 15
NW6	Fully saturated.	0 cm	-3 to 34	13 to 15
NW10	Almost entirely saturated.	-20 at crest convexity	-3 to 23	4 to 6
Pristine slope	Almost entirely saturated	-15 cm at crest	-6 to 47	18 to 23

slope, the simulated water tables were situated near to or above the surface, with the exception of the crest of the slope where water tables were simulated considerably lower than those that were observed. This section of the slope (i.e. the crest) was also very sensitive to changes in the model inputs. For example, at the top of the slope simulated water tables during the 14 daily time increments varied from 5 to 45 cm below the surface, whereas on the middle section of the slope the water table varied only a few centimetres.

- The monthly transient analysis on a modelled failed section of slope resulted in pore pressure distributions that were thought to be representative of actual conditions. Simulated water table levels indicated almost entirely saturated conditions with the water table dipping a maximum of 15 to 20 cm below the surface at the convexities at the crest and foot of the slope. Observed water levels in dipwells adjacent to the modelled slopes did not extend below approximately 15 cm. The simulated seasonal range in conditions (given that meteorological data for 1995 is representative) suggest that after a dry period of more than one month, the water table levels in the summer extend to between 15 and 20 cm below the surface. Higher levels of precipitation during autumn and winter gradually raise the water table to within five centimetres of the surface. From this seasonal pattern, the highest water table levels during late winter and early spring would theoretically result in small decreases in stability.
- Steady state analyses on other modelled Cuilcagh slopes resulted in almost entirely saturated conditions within the slopes, which therefore represented worse case scenarios for slope instability. These simulated hydrological conditions are thought to be representative of natural conditions within the blanket peat slopes. Mostly small ranges in pore pressures were simulated along the slip surfaces. As the majority of the slopes were saturated, small alterations in pore pressures were mainly a function of changes in peat depth, specifically the depth of catotelm. An exception to this is the simulation of the cracked and bulging slope (site 2). Large variations in pore pressures existed between the unsaturated cracked area and the high pressures over the slope bulge.
- As utilised measurements of k_{sat} were obtained in the field and laboratory and the model is relatively insensitive to changes in the k-ratio, these parameters are unlikely to be sources of error. However, the estimated relationship with changes in pressure, i.e. the soil moisture characteristic curve, necessarily introduces some uncertainty into the interpretation of model outputs. Unfortunately this is unavoidable when working with such a variable and understudied material as peat. Further possible sources of error result from the modelling formulations and known inaccuracies from the reading of the observed and simulated values.
- In general, the hydrological model was successful at simulating observed and expected (mostly saturated) conditions on the modelled Cuilcagh slopes. Therefore, SEEP/W is thought to be adequate at simulating field values of pore pressures to be used in modelling slope stability. Deviations from observed and expected conditions have been accounted for by the identification of a number of potential inaccuracies and errors which resulted from the modelling set-up, formulation and output, and also from the reading of the dipwells in the field.

5.4 HILLSLOPE INSTABILITY

5.4.1 Introduction to the Model

SLOPE/W is a commercially available slope stability modelling software product which can be used to analyse a wide variety of slope problems and conditions (GEO-SLOPE, 1995b). SLOPE/W is fully integrated with SEEP/W and therefore allows the detailed slope geometry and complete pore water pressure distribution within the slope to be imported from the SEEP/W simulations. The Factor of Safety (F) of the slope can then be determined by SLOPE/W which uses a number of standard methods of stability analysis, based on limit equilibrium theory (Chapter 2) for 2-dimensional slope problems. Various methods of slices are used to perform effective stress analysis. This type of stability analysis involves passing a slip surface through the soil and dividing the failure mass into a number of vertical slices (Nash, 1987). A number of types of analyses can be used by SLOPE/W and range from the Ordinary Method of Slices (Skempton and Hutchinson, 1969) to the more mathematically rigorous Morgernstern-Price Method (GEO-SLOPE, 1995b). The main difference between these methods concerns the interslice forces. The Ordinary Method of Slices satisfies only moment equilibrium and ignores all interslice forces, a simplification that can result in an underestimation of F (Nash, 1987). The Morgernstern-Price Method can be applied to both circular and non-circular slip surfaces and assumes that the stresses and forces vary continuously across the slip. The method involves the use of normal and shear forces between slices to satisfy both moment and force equilibrium. The model also produces, by default, a Factor of Safety using Bishop's and Janbu's 'simplified' methods for every problem analysed (see Nash, 1987 for details of standard methods). The Factor of Safety is determined for each slice in the problem using the principles given by the Infinite Slope Model, details of which have been given in Chapter 2.

The SLOPE/W model is designed to compute the minimum Factor of Safety for a pre-defined section of slope. GEO-SLOPE (1995b) defines the Factor of Safety as the "Factor by which the shear strength of the soil must be reduced in order to bring the mass of soil into a state of limiting equilibrium along a selected slip surface". The model output is presented in the form of values of F calculated according to the assumption of either force (F_f) or moment (F_m) equilibrium for the various specified and default methods of analysis.

An infinite slope analysis conducted on a simple configuration of a slope problem in peat yielded a Factor of Safety which was within the (small) range of values produced by the methods in the SLOPE/W model (Dykes and Kirk, 2001). This indicates the general acceptability of the model results.

5.4.2 Model Structure

SLOPE/W is formulated to solve two Factor of Safety equations (overall force and moment equilibrium) using limit equilibrium theory. The formulation of the SLOPE/W model is based on three assumptions (GEO-SLOPE, 1995b):

1. Soil behaves as a Mohr-Coulomb material;

2. The Factor of Safety of the cohesive and frictional components of strength are equal for all soils involved;
3. The Factor of Safety is the same for all slices.

The direction, magnitude, and/or point of application of failure also need to be defined in order to render the analysis determinate. These are provided by the nature of the chosen slip surface.

Figure 5.5 illustrates the forces acting on a slice for a fully specified section of sliding mass. The sliding mass in the diagram could be equally well displayed in a planar form sliding along a straight slip surface to satisfy the infinite slope case. Details of the General Limit Equilibrium (GLE) equations used by SLOPE/W are given in Appendix 8.

5.4.3 Model Capabilities and Requirements

Six parameters are required for the analysis of the slope problems by SLOPE/W. Firstly, the necessary parameters concerning the geometry of the specified section of slope are depth to slip surface (z) and angle of slope (β). Secondly, the required material properties are effective cohesion (c'), angle of internal friction (ϕ') and unit weight of material (γ_s). Pore water pressure at the slip surface (u_w) is also required and is imported directly from the SEEP/W model along with detailed geometry of the slope. As mentioned previously, stability problems in undamaged peatlands involve almost exclusively saturated or near saturated conditions. Therefore, the unit weight of saturated slope material is used in the modelling. Slip surfaces in the analyses may be circular (defined around a centre of rotation), composite (a combination of circular and linear portions), or fully specified (defined by a series of straight lines) (GEO-SLOPE, 1995b).

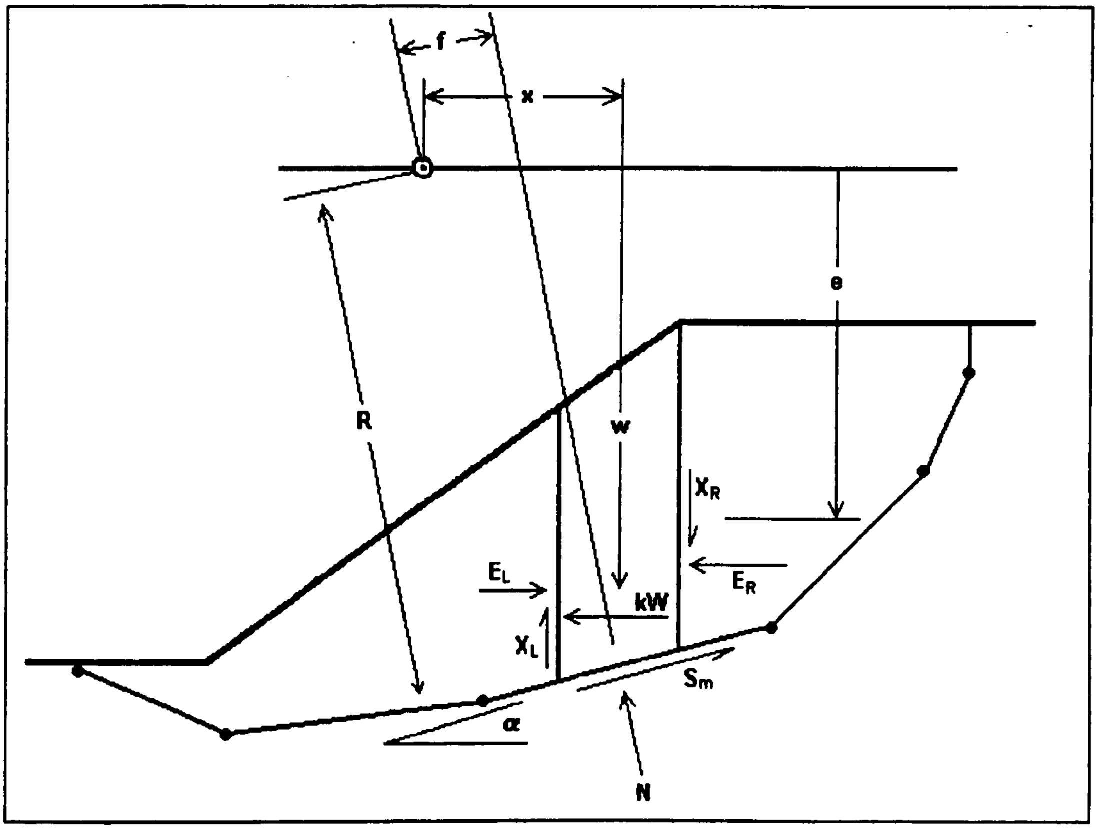
5.5 MODELLING THE STABILITY OF THE CUILCAGH PEAT

5.5.1 Problem definition

The main aims in modelling the stability of peat slopes on Cuilcagh Mountain were to ascertain whether conventional methods of slope stability analysis were suitable for modelling blanket bog environments and to obtain a range of simulated temporal and long term stability patterns to assess the susceptibility of peatland slopes to failure. Using stability analysis, the importance of individual forces involved in converting a slope into an actively unstable condition may then be assessed and allow any differences between failure types to be identified.

As all but one of the modelled slopes has failed, the slip surfaces have been fully specified according to their geometry to perform back analyses. The modelled slopes consist of three peat slides, four bog flows, three intermediate failures and a bulging slope identified in section 5.3.4.

Figure 5.5 Forces acting on a slice through a sliding mass defined by a fully specified slip surface (GEOSLOPE, 1995).



W = total weight of the slices of width **b** and height **h**.

N = total normal force on the base of the slice.

S_m = shear force mobilised on the base of each slice.

E = horizontal interslice normal forces. The **L** and **R** subscripts indicate left and right sides of the slice.

kW = horizontal seismic load applied through the centre of each slice.

X = vertical interslice shear forces. The **L** and **R** subscripts indicate left and right sides of the slice.

R = radius for a circular slip surface, or the moment arm associated with mobilised shear force, S_m for any shape of slip surface.

f = perpendicular offset of the normal force from the centre of rotation/centre of moments. It is assumed that **f** distances to the right of the centre of rotation of a negative (i.e. right facing) slope, with those on the left side positive. The signs are reversed for positive slopes.

x = horizontal distance from the centreline of each slice to the centre of rotation/centre of moments.

e = vertical distance from the centre of each slice to the centre of rotation/centre of moments.

h = vertical distance from the centre of the base of each slice to the uppermost line in the geometry (i.e. generally ground surface).

α = angle between the tangent to the centre of the base of each slice and the horizontal. When the slopes angles are in the same direction as the overall slope geometry, α is positive, and vice versa.

5.5.2 Set-up

SLOPE/W required six parameters for each stability analysis undertaken. Slope geometry (angle of slope and pore water pressure distributions) was imported directly from SEEP/W for each slope problem. The material strength properties of the acrotelm and catotelm peat and the underlying clay were obtained from laboratory analyses (Chapter 4). The strength parameters for each problem used in the modelling were taken from the nearest tested site with a similar failure type. Therefore, for the flow type failures and the bulging slope on East Cuilcagh, the parameter values were obtained from site E2, and the shallower failures on the northern slopes were given the same parameter values as site NW5. The unit weight of material (γ_s) was calculated using bulk density results obtained from individual failure sites (Chapter 4). Initially, the slip surface (z) for each slope problem was fully specified using the actual failure profile for each site in order to perform accurate back analysis. Typically, the slip surfaces were 2.0 m below the ground surface for the bog flow sites and 1.0 to 1.5 m deep for the peat slides. Other slip surfaces were then used to calculate the minimum Factor of Safety for the specific slope. For the bulging slope, a variety of slip surfaces were used to investigate the different Factors of Safety within the slope. Table 5.10 shows the parameter values used for each site in the SLOPE/W model, including the material strength parameters for the acrotelm and catotelm. The material properties for the underlying clay were tested from site N4 and were given as $c' = 2.8$ kPa, $\phi' = 27°$ and $\gamma_s = 16.5$ kN/m^3.

5.5.3 Simulations and Performance

The stability of ten slope failures on Cuilcagh Mountain (E2, E3, E6, E7, N1, N15, N19, NW5, NW6 and NW10) were back analysed using the outputs of the hydrological model SEEP/W. The stability of the bulging slope (Chapter 3) was also analysed using SLOPE/W. Table 5.11 and Figure 5.6 give values of F for each slope problem analysed, with slip surfaces located within the basal catotelm, at the peat-clay interface and within the underlying clay. All modelled slope problems resulted in a Factor of Safety over 1.0. Values of F using the slip surfaces determined from field investigations (i.e. back analyses) ranged from 1.3 to 2.0 and in most cases these results indicated the lowest calculated F. For example, the lowest calculated value of F for the bog flows E2, E3 and E6 was with the slip surface situated within the basal catotelm and for the peat slides N15, N19 and NW10 with the slip surface situated within the underlying clay. The range of computed values of F for the bog flows on East Cuilcagh lie between 1.3 and 2.0, whereas F for the peat and transitional slides on the northern slopes of Cuilcagh lie between 1.4 and 1.5. These computed F values for the peat slides are just above the limit of F suggested for marginal stability (1.0 to 1.3, Crozier, 1986; section 2.2). However, by lowering the slip surface further into the clay underlying the peat, a minimum value of F resulted in four (out of the six) failure sites being designated marginally stable. With the slip surface situated within the peat on peat slide sites, F increases to up to 4.5, indicating a high degree of stability for the peat on the northern slopes. Failures E2 and E7 were further modelled with a simulated failure of the lower section of slope (i.e. the foot). This reduced F to 1.1, indicating a marginal (or conditionally) stable slope. This does not however, explain the occurrence of the other flow type failures (such as E6) which have not failed from the foot of the slope. The slope profiles divided into vertical slices for each slope problem modelled are given in Appendix 9. Seasonal variations in pore pressure within the slope (as determined from the SEEP/W output) were thought to be of

Table 5.10 Parameter values used in the modelling of the Cuilcagh peat (SLOPE/W)

Site	Slope Geometry				Material properties of Acrotelm			Material properties of Catotelm			Pressure along slip surface	
Site	β (°)	z (m)	Length (m)	Height (m)	c' (kPa)	ϕ' (°)	γ_s (kN/m^3)	c' (kPa)	ϕ' (°)	γ_s (kN/m^3)	Min u_w (kPa)	Max u_w (kPa)
E2	7-8	2.0	105	9	4.2	30.8	9.8	2.6	30.4	9.9	18	20
E3	3-4	2.0	425	11	4.2	30.8	9.8	2.6	30.4	9.9	18	20
E6	5-6	2.0	110	6	4.2	30.8	9.8	2.6	30.4	9.3	20	20
E7	4-5	2.0	105	9	4.2	30.8	9.8	2.6	30.4	9.9	20	20
BS	4-10	1.5-2.7	90	10	4.2	30.8	9.8	2.6	30.4	9.9	2	26
N1	6-7	1.5	155	22	3.2	30.4	9.8	4.0	28.8	9.9	14	20
N15	7-8	1.0	90	11	3.2	30.4	9.8	4.0	28.8	9.9	8	10
N19	9	1.0	65	12	3.2	30.4	9.8	4.0	28.8	9.9	6	10
NW5	6-12	1.5	230	34	3.2	30.4	9.8	4.0	28.8	9.9	12	14
NW6	10	1.5	40	7	3.2	30.4	9.8	4.0	28.8	9.9	10	14
NW10	10	0.7	400	53	3.2	30.4	9.8	4.0	28.8	9.9	4	6

Underlying clay properties for all failures taken from lab tested clay from Failure N4 (Dykes and Kirk, 2001) in which c' = 2.8 kPa, ϕ' = 26.5°, and γ_s = 16.5 kN/m^3.

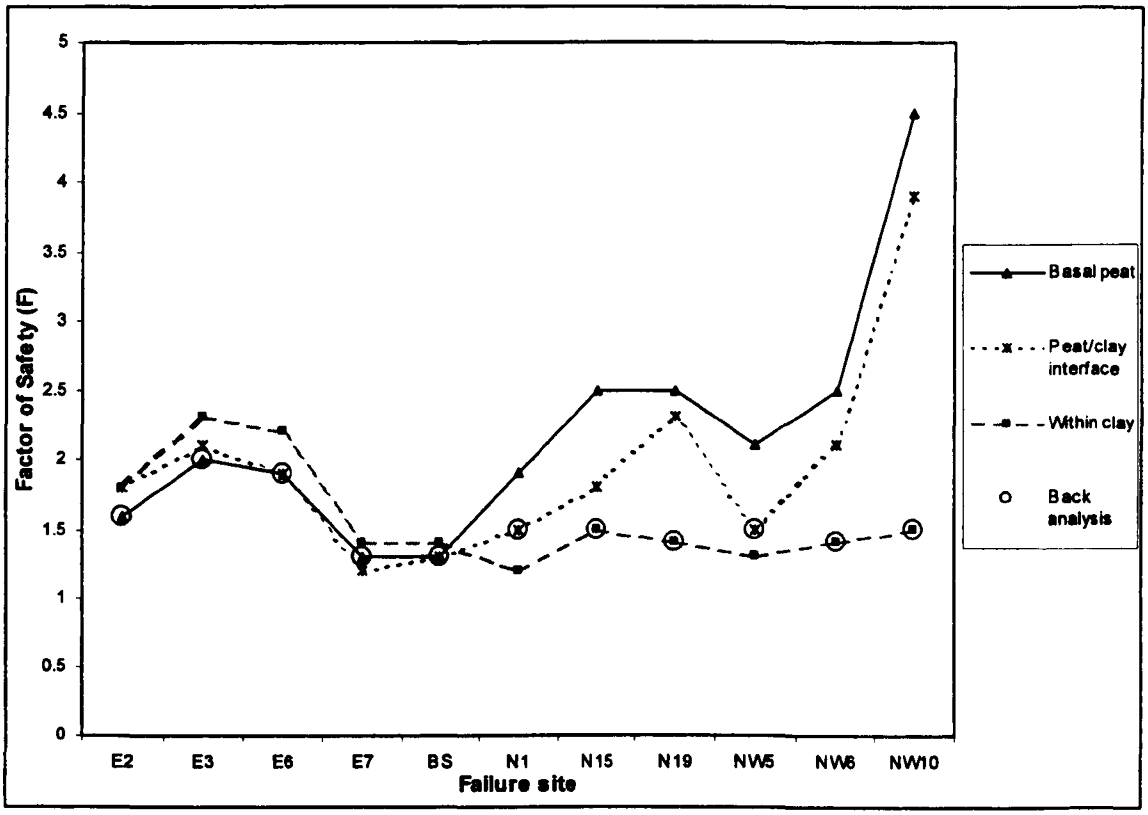
Table 5.11 Calculated Factors of Safety using SLOPE/W and the Infinite Slope Model.

Site	Calculated F using SLOPE/W			Calculated F using Infinite Slope Model**
	Within basal catotelm	At peat/clay interface	Within clay	
E2	1.6*	1.8	1.8	1.1
E3	2.0*	2.1	2.3	2.2
E6	1.9*	1.9	2.2	1.1
E7	1.3*	1.2	1.4	1.7
BS	1.3	1.3	1.4	1.3
N1	1.9	1.5*	1.2	2.4
N15	2.5	1.8	1.5*	2.3
N19	2.5	2.3	1.4*	2.0
NW5	2.1	1.5*	1.3	1.3
NW6	2.5	2.1	1.4*	1.3
NW10	4.5	3.9	1.5*	2.4

* Assumed position of actual failure surface.

** Using average failure depth.

Figure 5.6 Computed values of F using SLOPE/W for modelled failures on Cuilcagh Mountain.



little significance with respect to temporal stability patterns given the frequency of failures and the large timescales involved.

Figure 5.7 illustrates an example of the variations in calculated F using the different methods of slope stability analysis available with SLOPE/W. It is apparent that there is very little difference between the type of methods used with a maximum range of less than 2%. Therefore, the Morgernstern-Price method is used as it satisfies both force (F_f) and moment (F_m) equilibrium.

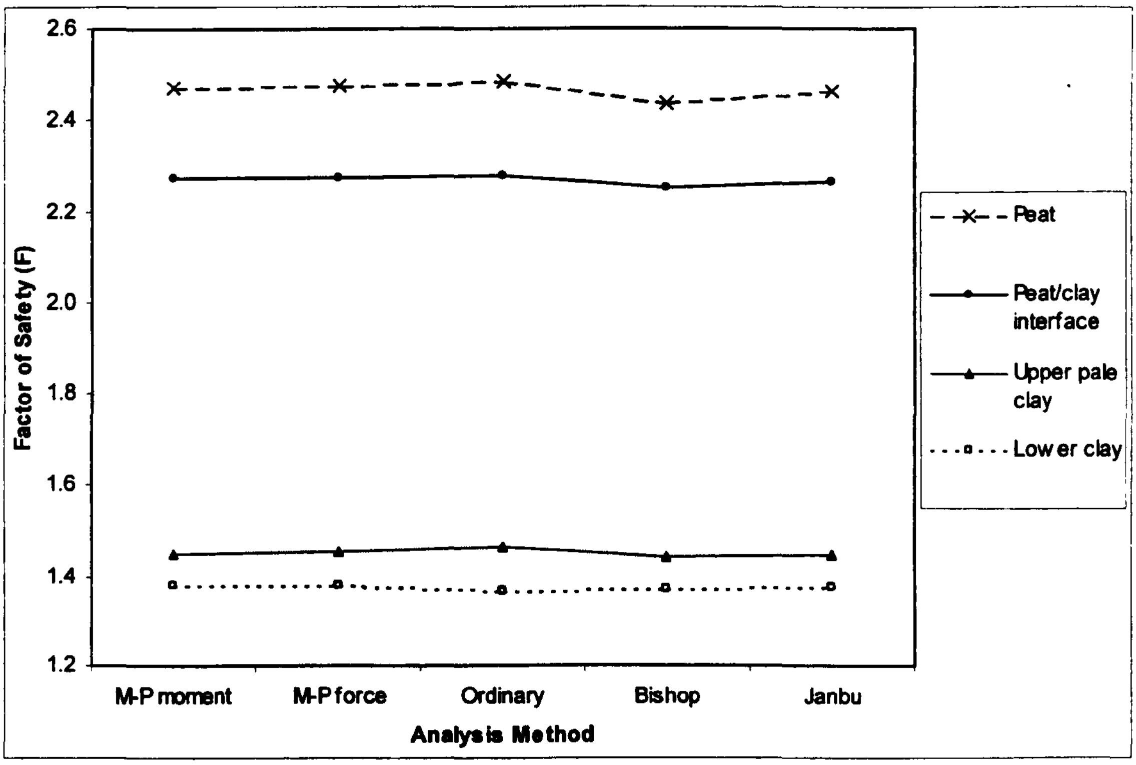
5.5.4 Summary of stability analyses

All modelled slope problems resulted in a Factor of Safety over 1.0 which implies they are stable, or marginally stable. Clearly, in reality many of the peat slopes on Cuilcagh may be close to failure by means of bursting and flowing, or sliding. Given the parameters used in the model, this indicates that either the overall levels of resistance (material strength) were too high, or the overall stress levels were too low for the model to simulate unstable conditions.

The possible reasons for the failure of SLOPE/W to produce values of F corresponding with observed occurrence of failures may have resulted from the following:

- Unrepresentative material strength parameters used in the modelling (given that the actual behaviour of peat under the influence of changing stresses is not known).
- Unsuitability of this form of stability analysis for analysing peatland slopes. It is possible that the SLOPE/W model is not appropriate for the analysis of peat stability as factors such as the possibility of progressive failure might be important in influencing the real F, but are not considered in the model formulation. Also, the theory of limit equilibrium of 'infinite slopes' may not be appropriate for analysing this type of problem, particularly if deformation is the main failure mechanism, as opposed to failure along a distinct shear plane in the form of a translational slide. The mechanism of deformation is relevant to both types of failure identified on Cuilcagh Mountain i.e. the weathering and possible micro-shearing of clays underlying the peat on the northern slopes, and deformation and creep of basal catotelm in the deeper areas of peat (East Cuilcagh).
- Possibility of artesian (as opposed to normal hydrostatic) conditions present within the peat slope to increase pore water pressure and initiate failure.
- An implicit assumption within the model is that each material is uniform and homogeneous throughout. As the results in Chapter 4 indicate, the physical and hydrological properties of the Cuilcagh blanket peat are variable over very small distances. This was found to be a major problem in the analysis of different types of hillslope material (e.g. Anderson and Burt, 1990 and Dykes, 1998).

Figure 5.7 An example of the variations in computed F using the different available methods of stability analysis by SLOPE/W.



5.6 INFINITE SLOPE ANALYSIS

5.6.1 Introduction

Although SLOPE/W can be used to analyse 'infinite slopes' (i.e. shallow translational failures), it does not perform the infinite slope analysis *per se* to investigate the stability of slopes. This section investigates the use of the Infinite Slope Model and then assesses the relative importance of various parameters used in modelling the stability of slopes by means of a sensitivity analysis. The Infinite Slope Model was used to analyse the same slopes modelled in the previous chapter using the standard Factor of Safety (F) equation (Skempton and DeLory, 1957):

$$F = \frac{c' + (\gamma_s - m\gamma_W)\, z \cos^2\beta \tan\phi'}{\gamma_s z \sin\beta \cos\beta} \qquad (5.1)$$

Where: **c'** = Effective cohesion,

γ_s = Unit weight of saturated material,

m = Vertical height of the water table above the failure plane, expressed as a fraction of material depth,

γ_w = Unit weight of water,

ϕ' = Effective angle of internal friction,

β = Slope angle,

z = Depth from ground surface to slip surface.

The values of the parameters used in the Infinite Slope Analysis are shown in Tables 5.12 and 5.13. The resulting calculated F for each slope problem is show in Table 5.11. Values for material strengths (c' and ϕ') in which the failure plane or zone was located were those determined in the laboratory (Chapter 4). Values for basal catotelm were used for the flow-type failures (E2, E3, E6, E7 and BS) and values for underlying clay for the peat slides (N15, N19, NW6 and NW10). Average saturated unit weight (γ) was calculated for each failure using the relative depths of material (peat and clay), and their corresponding values of unit weight. Other parameter values (z and β) were obtained from field surveys of individual failure sites (Chapter 3).

5.6.2 Performance of the Infinite Slope Model

The calculated Factor of Safety using the Infinite Slope Model for the eleven modelled failures on Cuilcagh Mountain ranged from 1.1 to 2.4, with an average of 1.7 (Table 5.11). Therefore, using the measured strength parameters five out of the 11 slopes were classed as marginally unstable during present conditions (with F between 1.0 and 1.3). The calculated F for the bog flows on East Cuilcagh ranged from 1.1 to 2.2, with the lowest values for E2 and E6, whereas calculated F for the peat slides ranged from 1.3 to 2.4. Therefore, as these were back analyses on failed slopes, calculated values of F were too high. Further tests were performed to assess whether over-estimations of F resulted from those sites with greatest field variability. This was not found to be the case with slope angle as the failures with most variability in slope angle had lower values of F. For example, at sites E2 and E6, slope angles range from 2.5 to 7.5° and 1.5 to 5.5° respectively, but still resulted in the lowest calculation of F using the Infinite Slope Model. Field variability in peat depth was found to be small on both areas prone to bog flows (East Cuilcagh) and peat slides (north and north-west Cuilcagh), although there is a possibility of bulging slopes in deeper areas of blanket peat. The results of the Infinite Slope Analysis are further discussed in section 5.6.4 with reference to the SLOPE/W stability results.

5.6.3 Sensitivity analysis of the Infinite Slope Model

Sensitivity analysis is the quantitative assessment of variables used in the modelling process. More specifically for the Infinite Slope Model, it allows the relative influences of each variable to be assessed by means of changes in the magnitude and direction (i.e. an increase or decrease in stability) of the computed Factor of Safety (F) in response to changes in one or more of those variables. Pearce and O'Loughlin (1985) have identified four steps in the process of carrying out a sensitivity analysis:

1. Select a realistic range of values for each variable;
2. Calculate a 'working' Factor of Safety using the median value of each variable;
3. Change each input variable individually across its range of values, holding all the other variables constant, and calculate the corresponding changes in the Factor of Safety;
4. Plot the results as relative percentages.

Therefore, the sensitivity analysis of the modelled Cuilcagh slopes involved alterations of the key parameters (β, z, c', ϕ', γ_s and water table height as a fraction of material depth, m) to evaluate the effect of each on F. In order to assess the differences between variables for the different types of failure identified on Cuilcagh Mountain, two sets of analyses were performed representing bog flows on East Cuilcagh and peat slides on North Cuilcagh. Median values for the parameters were calculated for all of the modelled sites and were then grouped according to their failure type. The resulting median parameter values and likely field ranges (based on results described in Chapter 3) are illustrated in Tables 5.12 and 5.13. Field ranges of effective angle of internal friction (ϕ') and effective cohesion (c') were estimated on the basis of the results from this study and published values of ombrotrophic peat (Hanrahan *et al.*, 1967; Landva and La Rochelle, 1983).

Figures 5.8 and 5.9 illustrate the results of the sensitivity analyses for bog flows and peat slides respectively. Figure 5.8 shows that for the bog flows the most critical variables for lowering F are reductions in cohesion and unit weight, and as expected, increases in material depth and slope angle, while even a slight drop in the water table results in a large increase in F. However, the sensitivity analysis also shows that an increase in the angle of internal friction results in a slight decrease in F. It is thought that this is a mathematical artefact arising from the unit weight of the saturated peat being less than the unit weight of water. As a result of this, effective stresses (obtained from (γ_s - mγ_w) in Equation 5.1) are negative. Therefore, tan ϕ' will be negative, and so as the angle of internal friction increases, tan ϕ' will become increasingly negative and the calculated value of F will become smaller. The relationship between effective angle of internal friction and F shown in Figure 5.8 can be seen to be unrealistic, but as the infinite slope model was formulated for use on mineral soils and sediments and not peat, perhaps this should not be surprising. Figure 5.9 shows the sensitivity analysis for the peat slides N15, N19, NW6 and NW10. This analysis shows broadly the same pattern as for the bog flows,

Table 5.12 Parameter values for the peat slides (N15, N19, NW6, NW10) on North Cuilcagh

	Average	Median	Range	Field Range
ϕ' (°)	26.5	26.5	-	15.0-40.0*
c' (kPa)	2.8	2.8	-	1.0-10.0*
γ_s (kN/m^3)	11	11.9	10.3 - 11.5	9.0-20.0
β (°)	8.8	8.5	7.0 - 10.0	1.0-40.0
z (m)	1.1	1.1	0.7-1.5	0.5-5.0

* Estimated values based on published results (Table 4.7).

Table 5.13 Parameter values for the bog flows on East Cuilcagh

	Average	Median	Range	Field Range
ϕ' (°)	30.4	30.4	-	15.0-40.0*
c' (kPa)	2.7	2.7	-	1.0-10.0*
γ_s (kN/m^3)	9.8	9.6	9.3 - 9.9	9.0-11.0
β (°)	5.3	5.5	3.5-7.5	1.0-25.0
z (m)	2.1	2.4	2.0-2.7	0.5-5.0

* Estimated values based on published results (Table 4.7)

Figure 5.8 Field variability and sensitivity analysis of parameters used in modelling bog flows.

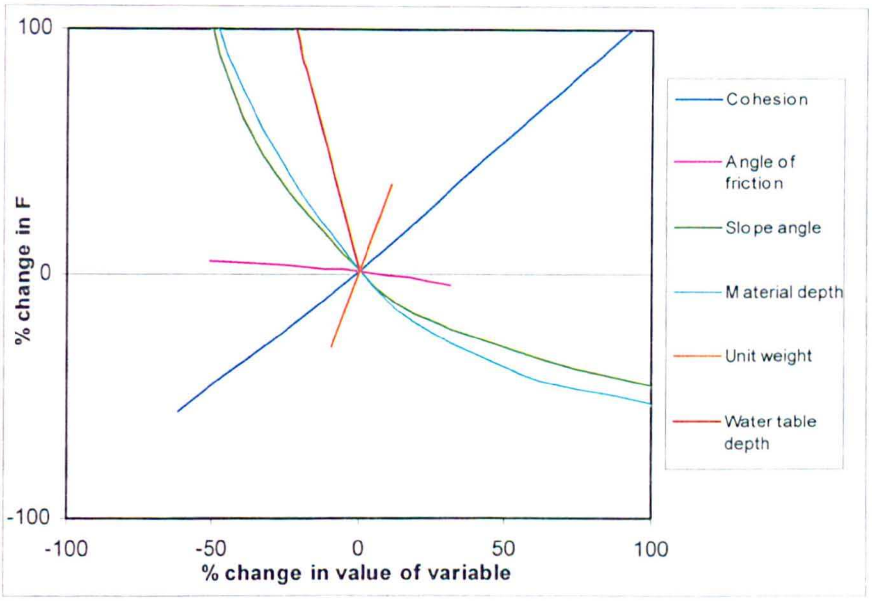
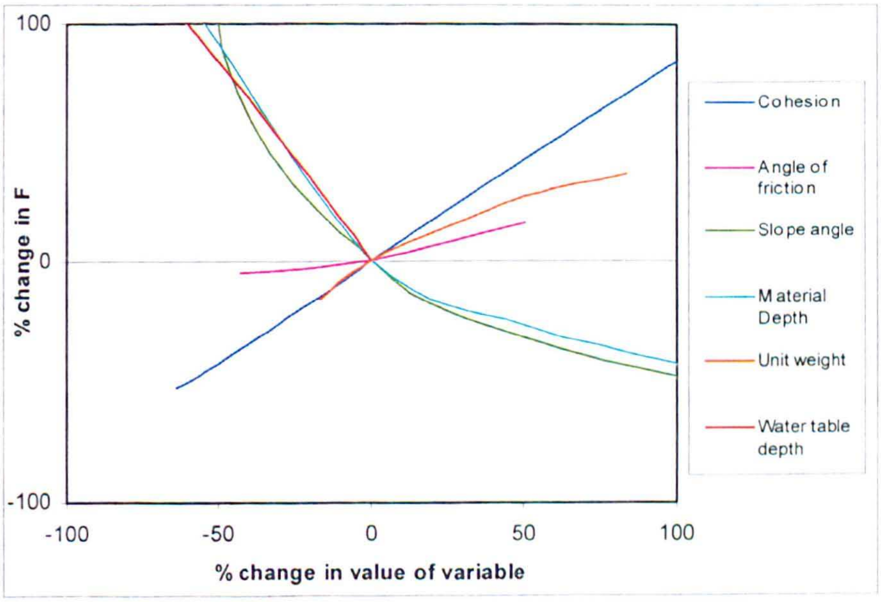


Figure 5.9 Field variability and sensitivity analysis of parameters used in modelling peat slides.



although an increase in the angle of internal friction results in a small increase in F, and F is less sensitive to unit weight. Therefore, as for the bog flows, factors that would result in significantly lowering of F are reductions in cohesion and unit weight, and positive changes in slope angle and material depth. To increase the stability of these slopes (prone to peat slides and bog flows), an increase in cohesion, and more importantly a decrease in water table height results in large increases in F. This sensitivity of F to the water table height suggests that the slope would be more susceptible to failure if the water table is at least at the surface; as peatlands are characterised by high water tables, this is a fairly common occurrence.

5.6.4 Comparison of Infinite Slope and SLOPE/W Results

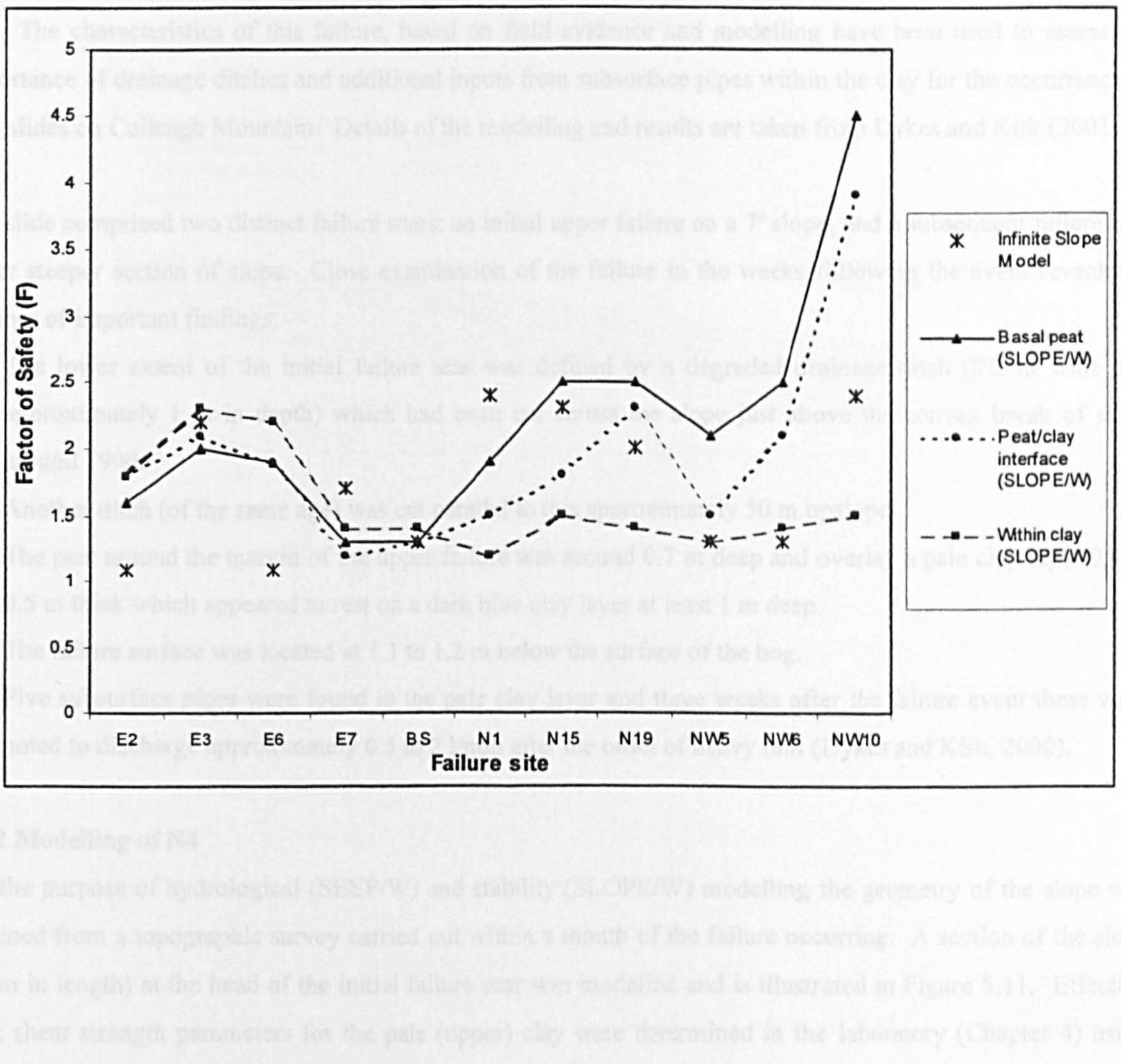
The Factor of Safety (F) results using the Infinite Slope Model are similar to those calculated using SLOPE/W for the modelled Cuilcagh failures. Table 5.11 and Figure 5.10 show all computed values of F for each failure using both analyses. The majority of the results fall within the range of F = 1.1 to 2.5 indicating marginally stable or stable slopes. In general, values of F calculated using the Infinite Slope Model were higher than those calculated using back analysis (SLOPE/W) for the peat slides and lower for the bog flows. As the values of F were variable but lay within a similar range, it is difficult to determine whether SLOPE/W is more accurate than the Infinite Slope Model, or whether the difference between the model results is marked by the inherent complexity of the natural peat slopes. However, it is clear that SLOPE/W is a more comprehensive analysis.

The Infinite Slope Model is a simple equation for analysing a simple type of failure compared with the more comprehensive SLOPE/W formulation. The Infinite Slope Model uses only a single layer in its analysis and assumes the hillslope material is constant and homogeneous throughout. It is possible to use average unit weight (γ) for the materials on the slope, but geometry (β and z), pore pressures (u) and strength properties c' and ϕ' are modelled as constant values. SLOPE/W on the other hand, uses detailed geometry (such as effect of a break of slope, length of slope and conditions at the foot of the slope) and a modelled distribution of pore pressures in its analysis. Material properties of each layer are also used and thus important differences in the acrotelm and catotelm can be identified and dealt with. Infinite Slope Model uses strength properties (c' and ϕ') only for failed material in the analysis, whereas again with SLOPE/W, the strength characteristics for all materials in the problem can be defined.

Therefore, the Infinite Slope Model may not be as appropriate as SLOPE/W because:

1. Geometry of the slope is not uniform: The shape of the slope is seldom straight, the slope materials and position of the slip surface are not at uniform depths throughout failure profile, and the length of slope is variable.
2. Hydrological conditions vary throughout the slope, particularly across the slip surface. These can be modelled separately and used by SLOPE/W.

Figure 5.10 Computed values of F using SLOPE/W and the Infinite Slope Model.



SLOPE/W uses a method of slices with a fully specified slip surface, whereas the Infinite Slope Model uses a planar surface. Although a straight slip surface is appropriate for analysing translational slides (peat slides), the failure surface in bog flows is likely to be more complex. However, the performance of the analyses on peat slides was no more successful than the results for the bog flow failures.

5.7 MODELLING OF THE MULTIPLE PEAT SLIDE (N4)

5.7.1 Introduction

A multiple slope failure (N4) that occurred in October 1998 is described in Chapter 3 and illustrated in Figure 3.2. The characteristics of this failure, based on field evidence and modelling have been used to assess the importance of drainage ditches and additional inputs from subsurface pipes within the clay for the occurrence of peat slides on Cuilcagh Mountain. Details of the modelling and results are taken from Dykes and Kirk (2001).

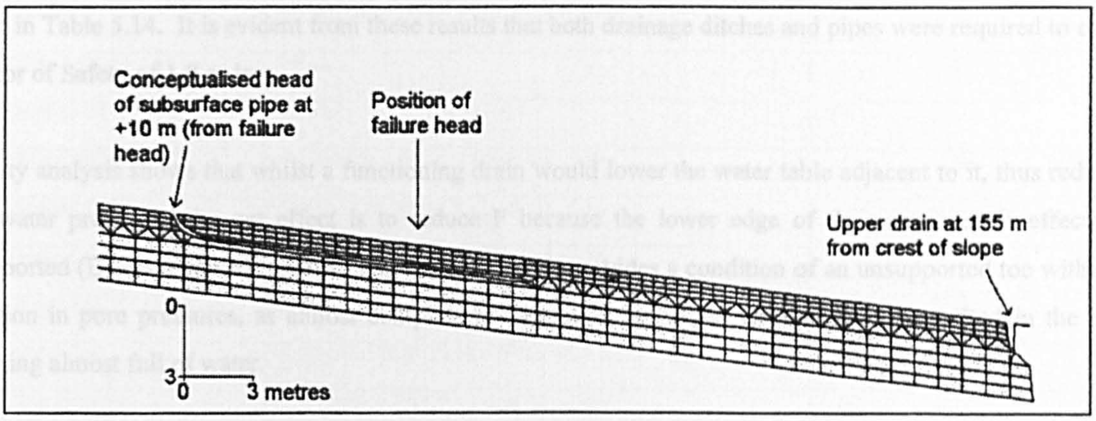
The slide comprised two distinct failure scars: an initial upper failure on a 7° slope, and a subsequent failure of a lower steeper section of slope. Close examination of the failure in the weeks following the event revealed a number of important findings:

1. The lower extent of the initial failure scar was defined by a degraded drainage ditch (0.2 m wide and approximately 1 m in depth) which had been cut across the slope just above the convex break of slope around 1990.
2. Another ditch (of the same age) was cut parallel to this approximately 50 m upslope.
3. The peat around the margin of the upper failure was around 0.7 m deep and overlay a pale clay layer 0.4 to 0.5 m thick which appeared to rest on a dark blue clay layer at least 1 m deep.
4. The failure surface was located at 1.1 to 1.2 m below the surface of the bog.
5. Five subsurface pipes were found in the pale clay layer and three weeks after the failure event these were noted to discharge approximately 0.5 to 2 l/min after the onset of heavy rain (Dykes and Kirk, 2000).

5.7.2 Modelling of N4

For the purpose of hydrological (SEEP/W) and stability (SLOPE/W) modelling the geometry of the slope was obtained from a topographic survey carried out within a month of the failure occurring. A section of the slope (25 m in length) at the head of the initial failure scar was modelled and is illustrated in Figure 5.11. Effective peak shear strength parameters for the pale (upper) clay were determined in the laboratory (Chapter 4) using direct shear apparatus. The hydrological properties of the peat and the saturated unit weight of the peat and pale clay are the same as those used in the other failures on Cuilcagh (Chapter 5). As shear strength characteristics of the Cuilcagh peat were unknown at the time of this modelling, published results were used, but these are within the limits given by the laboratory results in Chapter 4. All parameters for the dark basal clay underlying the pale clay were estimated on the basis of field inspection of the material *in situ* (Dykes and

Figure 5.11 The modelled upper section of the multiple peat slide (N4) (from Dykes and Kirk, 2001).



Kirk, 2001). Steady state and transient analyses were carried out using a net mean annual rainfall input of 1000 mm/y and actual daily rainfall respectively.

5.7.3 Results and significance

The two degraded drainage ditches were assumed to be full of water to just below the ground surface and the pipes were defined by the distances of their ends upslope (+) or downslope (-) from the position of the head of the upper scar. Figure 5.11 illustrates the finite element mesh with a modelled pipe from +10 to -5 m and the calculated F for failure within the pale clay, just above the interface with the blue clay is given in Table 5.14. Transient analyses comprising daily time steps using corresponding rainfall data were performed to calculate the stability of the slope at the end of a dry period and during the high intensity rainfall event. These results are also shown in Table 5.14. It is evident from these results that both drainage ditches and pipes were required to obtain a Factor of Safety of 1.0 or less.

Stability analysis shows that whilst a functioning drain would lower the water table adjacent to it, thus reducing pore water pressures, the net effect is to reduce F because the lower edge of the peat mass is effectively unsupported (Dykes and Kirk, 2001). The degraded ditch provides a condition of an unsupported toe without a reduction in pore pressures, as almost complete re-vegetation by *Sphagnum* species has resulted in the ditch becoming almost full of water.

Although, there are uncertainties concerning the precise nature, frequency and downslope extent of the pipes within the clay, the modelling revealed that they reduced F in two ways:

1. If it is assumed that the pipes were fed by free flowing water from ground surface upstream and fill completely, F would be lower the further upslope the pipe began, due to the greater hydrostatic pressure this would generate.
2. The further the pipe extends downslope (into the failure zone) the more rapidly F is reduced, as artesian pressures are not only enhanced by falling elevation but are maintained by the head of water instead of being dissipated by dispersed seepage into and through the surrounding clay.

Therefore, the morphological evidence and modelling both suggest a reduction in F for a segment of slope situated upslope of a degraded transverse ditch, with the failure zone located at or near the base of the pale clay layer underlying the peat (Dykes and Kirk, 2001). Lower down the slope, rapid loading by sliding of peat from the upper failure and erosion track is thought to have led to undrained shear failure of clay beneath the peat resulting in the deeply excavated channel. This in turn unloaded the toe of the steeper slope, which then failed thereby forming the secondary failure scar.

Table 5.14 Calculated Factor of Safety for the modelling of the multiple peat slide (N4) (from Dykes & Kirk, 2001).

Drain Details	Pipe Details	Factor of Safety
None	None	2.9
None	Extending from +10 m to -5 m	2.1
Functioning	None	2.5
Degraded	None	2.3
Functioning	Extending from +10 m to -5 m	1.6
Degraded	Extending from +10 m to -5 m	1.4
Functioning	Extending from +15 m to -5 m	1.3
Degraded	Extending from +15 m to -5 m	1.0
Degraded	Clay and peat pipes from +15 m to -5 m	1.0
Functioning	Extending from +10 m to -10 m	0.5
Degraded	Extending from +10 m to -10 m	0.2
Functioning	Extending from +15 m to -10 m	<0.1
Degraded	Extending from +15 m to -10 m	<0.1
Degraded*	Extending from +10 m to -5 m (Dry day)	1.7
Degraded*	Extending from +10 m to -5 m (Wet day)	1.4
Degraded*	Extending from +15 m to -5 m (Dry day)	1.3
Degraded*	Extending from +15 m to -5 m (Wet day)	1.0

* Indicates a transient analysis for 'wet' and 'dry' days.

5.8 SUMMARY

1. The meteorological data used in the modelling comprised daily, monthly and annual rainfall and potential evapotranspiration totals and was used to assess seasonal variations and conditions prior to and during specific failure events. Three of the most recent recorded failures on Cuilcagh Mountain occurred during high magnitude rainfall following either lower than average or higher than average rainfall conditions.
2. The hydrological modelling of Cuilcagh Mountain blanket peat using SEEP/W consisted of transient and steady state analyses on ten slopes that have been subject to failure. Simulated water table levels indicated almost entirely saturated conditions with the water table dipping a maximum of 15 to 20 cm below the surface at the convexities at the crest and foot of the slope. Observed water levels in dipwells adjacent to the modelled slopes did not extend below approximately 15 cm.
3. Daily transient analysis of a modelled slope on East Cuilcagh was reasonably successful at simulating the observed water table positions within the slope. Approximately 60% of the simulated values were within 5 cm of the observed field values, which indicates that although exact distributions were not modelled, conditions within the majority of the slope were approximately simulated. Monthly transient analyses on a modelled failed section of slope also resulted in pore pressure distributions that were thought to be representative of actual conditions. Therefore, the performance of the SEEP/W model was adequate at simulating field values of pore pressures that could be used in modelling slope stability.
4. Ten slope problems were modelled using SLOPE/W. Using back analyses, the range of computed values of F for the bog flow sites on East Cuilcagh lay between 1.3 and 2.0, whereas F for the peat and transitional slide sites on the northern slopes of Cuilcagh lay between 1.4 and 1.5, indicating stable slope conditions.
5. The high values of F indicate that either the peat and clay shear strengths were too high, or the overall stress levels were too low for the model to simulate actively unstable conditions, i.e. $F<1.0$. Possible reasons for simulated values of $F>1.0$ are: the use of unrepresentative material strength parameters; the mechanism of failure which may differ from the assumed shearing along a distinct plane; an implicit assumption within the model that each material is uniform and homogeneous throughout; or the fact that a temporary alteration to the material properties (e.g. increase in pore water pressure) may be sufficient to cross the failure threshold.
6. Infinite Slope Analysis was carried out on failed slopes on Cuilcagh Mountain and resulted in values of F similar to those calculated using SLOPE/W. These values ranged from 1.1 to 2.4 and indicated stable or marginally stable slope conditions.
7. Sensitivity analysis shows that for both bog flows and peat slides, the most critical variables for lowering F are reductions in cohesion and increases in material depth and slope angle, while even a slight drop in the water table results in a large increase in F. However, for bog flows, the sensitivity analysis shows an unusual relationship between effective angle of internal friction and F, with a decrease in friction leading to a small increase in F. This is thought to be a mathematical artefact arising from the unit weight of the saturated peat being less than the unit weight of water.
8. Overall, conventional methods of slope stability analysis (Factor of Safety using limit equilibrium methods) have been found to be adequate for use on peat slide failures. However, as a result of the mechanism of failure (deformation as opposed to shear) and more importantly, the unrealistic relationship between the

effective angle of internal friction and F used in the infinite slope model, conventional methods are considered not to be suitable for analysing slopes prone to bog flows.

9. Modelling of the multiple peat slide (N4) revealed the importance of drainage ditches and subsurface pipes (within the clay) in reducing the stability of the peat slope.

CHAPTER 6

PEAT SLOPE INSTABILITY

6.0 INTRODUCTION

This chapter gives a general overview of the controls of peatland slope failure and discusses the findings of the research by integrating the results of studies of the physical properties of the Cuilcagh peat and the hydrological and slope stability modelling. The first section comprises a comprehensive review and assessment of the most critical preparatory controls of failure in peatlands with reference to slope geometry, geotechnical and hydrological controls, indicating how they can change over time. The formation of critical slopes and the development of instability are then considered with the timing of failure events. The second section outlines the preparatory controls and triggering events identified as causing slope failure on the Cuilcagh Mountain blanket bog. These are discussed by focusing on the two main areas and types of failure.

6.1 CONTROLS ON THE FAILURE OF BLANKET BOG SLOPES

The importance of the development of instability has been highlighted by Crozier (1986), i.e. the conditions and preparatory factors that allowed the triggering factors and mechanisms to be effective. However, the evolution of hillslopes in the natural environment is complex and comprises environmental and geomorphic processes appropriate to different scales of time and space and which are not mutually exclusive. Past researchers have identified factors considered important for the occurrence of bog failures (see section 2.2.9). The present section discusses the range of controls on blanket bog failures in general in north-west Ireland. These can be considered under the headings: slope geometry; geotechnical controls; and hydrological controls. The long term controls on slope failure and the concept of threshold slope angles and critical slopes are then examined.

6.1.1 Slope Geometry

Commonly reported factors that influence slope failure are angle of slope and changes in slope geometry over time. For example, slope stability decreases with increasing slope angle, increasing material depth and slope undercutting. Blanket bog failures occur at a large range of slope angles (generally 1-25°) due to the existence of two main types of failure event. Peat slides generally occur on steeper slopes, whereas bog flows are initiated on shallower gradients. For both types of blanket bog failure, the stability of the slope appears to be moderately sensitive to changes in slope angle (e.g. Figures 5.8 and 5.9). As expected, increases in slope angle lead to decreases in the stability, and decreases in slope angle result in more significant increases in the stability of the slope.

The two main reported effects that result from the shape and changes in a slope are alterations in drainage and local stress conditions. The majority of reported bog failures occurred on convex slopes (Table 2.9) and include the escarpment failures reported by Mitchell (1935), Colhoun *et al.*, (1965); Thorn (1985) and Alexander *et al.* (1985, 1986). Convex slopes with a distinct break of slope (such as the escarpment ridges) produce an increase in tension within the overlying peat layer and can lead to cracking and reduced strength of the vegetation and root mat. Concave slopes can result in local variations in drainage (Gilman and Newson, 1980), which is discussed in section 6.1.3 with reference to pore water pressures and flushes.

Changes in slope geometry, particularly by the undercutting of a slope, have two effects: decreases in slope length (oversteepening) and more importantly the removal of lateral support. Crozier (1986) identifies the latter as one of the most common triggering causes of slope movements. The undercutting of a slope resulting from natural fluvial activity (Mitchell, 1938), peat cutting activities (Sollas *et al.*, 1897; Griffith, 1821; Delap and Mitchell, 1939); drainage ditch cutting (Dykes and Kirk, 2001) and gravel workings (Colhoun *et al.*, 1965; Tomlinson, 1981b) has provided an explanation for a number of bog failures (Table 2.9).

Depth of material is usually considered an important control in the occurrence of landslides (Selby, 1983). Figure 6.1 illustrates the critical slope angles for the peat slopes according to the depth of material given the parameter values used in the Infinite Slope Model (section 5.6). The modelled failures have also been plotted on the graph and with the exception of one bog flow (E2) and one transitional failure (NW5) indicate stability. As slope angle and depth of material were measured directly from the sites, this implies that the values of shear strength or pore water pressure varied sufficiently from the values used in the analysis to decrease the stability of the slopes. This is particularly the case for the bog flows. Essentially, this would consist of an increase in pore water pressure and/or a decrease in cohesion of the failed material, as F was found to be insensitive to changes in angle of internal friction. However, as with slope angle, the stability of the slopes is moderately sensitive to changes in material depth (Figures 5.8 and 5.9), and as long as peat is accumulating on the slope, this parameter is likely to be important in contributing to slope instability.

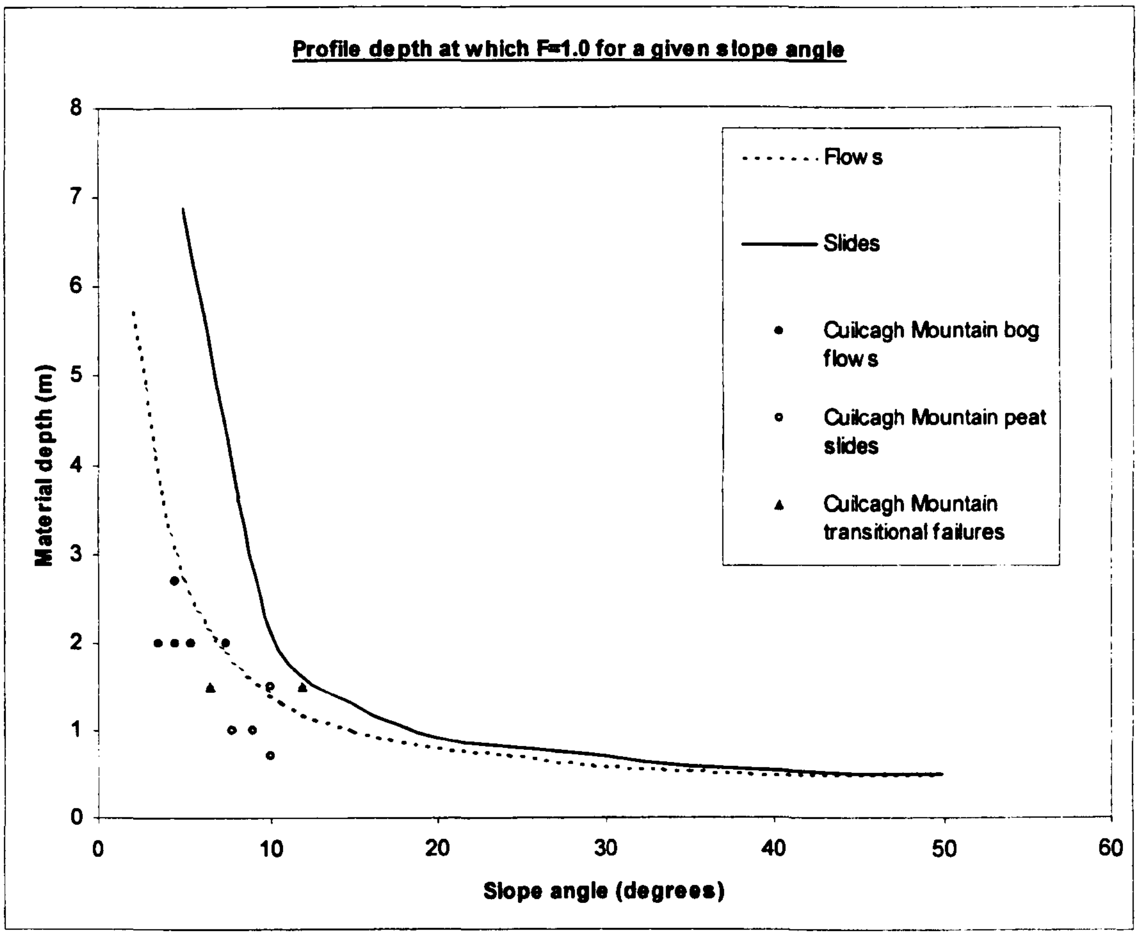
6.1.2 Geotechnical Controls

Critical to the understanding of blanket bog failures is the geotechnical behaviour of the materials involved. Therefore, for bog flows, the strength properties of the catotelm are most significant, whereas for the peat slides the presence and characteristics of the underlying clay is more important. However, the role of the acrotelm is also of importance for all failure types as it acts as a protective fibrous crust to the bog. Of particular importance in the failure of slopes are the factors that cause a reduced strength of these materials, most notably a decrease in the cohesive component of shear strength.

A reduction of the cohesive component of shear strength can be related to:

1. Humification of peat: the decomposition of solid organic matter into humus, humic acids and gases (Hobbs, 1986). Although there is an increase in chemical bonding with humification, decomposition results in the break down of the fibres that are an integral part of the peat structure. The variability of botanical composition leads to different degrees of humification within a small area, both horizontally and vertically (Landva and Pheeney, 1980).
2. Weathering of clay underlying the peat results in alterations to the bonding and therefore the cohesion between the clay particles (Mitchell, 1993). For example, physiochemical changes within clays as a result of progressive weathering, fluctuations in piezometric head and increases in the peat overburden are

Figure 6.1 Critical depth of material and slope angle used in the Infinite Slope Model.



reported to lead to strain softening and micro-shearing, reducing shear strength through time (Carling, 1986);

3. Slow mass movement of material is known to reduce the strength from a peak to a residual value (Chapter 2).

Thixotropic behaviour has been considered an important mechanism governing the deformation of granular amorphous peat (Barden, 1968). This is the process in which a natural soil with a high water content is rapidly transformed into a very low strength soil which fails easily, but on coming to rest, rapidly recovers strength (Selby, 1993). The extent to which this process accounts for the sensitivity of organic material is difficult to establish, but it is clear that the catotelm slurry noted in the field following a failure event remains in a fluid state for some considerable time. Therefore, the use of the term 'liquefaction' is perhaps more appropriate. The sudden loss of strength in this case results from the collapse of the internal structure of the material due to a disturbance and remoulding at a confined pressure and is usually associated with soils at high moisture contents and with high liquid limits. Although the basal peat has a high water content, its low hydraulic conductivity would allow little dissipation of pore water and provide the necessary conditions for this process to take place. Bishopp and Mitchell (1946) discussed the possibility of the highly humified basal peat undergoing a reversal of phase from solid matter to a liquid consistency. This was thought to have occurred as a result of disturbance following an initial slide movement. Failure then continued in the form of a bog flow as rafts of peat moved over the liquefied basal peat.

Over time, the production of gases (Burt *et al.*, 1990; Baird *et al.*, 1997) and increases in acidity (Al-Khafaji and Andersand, 1981) as a result of continuing decomposition can have the effect of reducing shear strength. It is possible that the gases produced by the process of decomposition (methane, ammonia, sulphuretted hydrogen, and other sulphides (Hobbs, 1986)) can become trapped and form pockets within the peat, particularly as a result of differential decomposition of the variety of plant species making up the peat (Galvin and Hanrahan, 1967; Waine *et al.*, 1985). These gases can act to reduce permeability of the peat (Baird *et al.*, 1997) and increase pore pressure. Bishopp and Mitchell (1946) suggest that a rapid drop in barometric pressure might lead to the release of trapped gases and that this in turn might trigger a bog failure. Al-Khafaji and Andersand (1981) found that deviations in pH of a fibre-rich clay soil from pH 7.0 resulted in reduced shear strength of the material. It is therefore possible that the presence of trapped gases and changes in acidity of the peat (and bog water) could result in large variability in strength related to the differential decomposition of plant species. The non-homogeneous nature of the peat and clay involved in bog failures also results from the presence of subsurface pipes and stones within the clay. Pearce and O'Loughlin (1985) state that complex flow and creep type failures in mineral soils are influenced by the presence of micro structures, macropore networks and pore water chemistry. It is thought that the complex failure of the catotelm in bog flows and of the underlying clay in peat slides might also be influenced by these factors.

The presence of an impermeable layer within the peat has been considered an important factor in the occurrence of bog slides (Delap and Mitchell, 1939; Colhoun, 1966; Wilson and Hegarty, 1993). This is usually a consequence of changes in environmental conditions that result in alterations to the botanical composition and produces horizontal layers with different permeabilities. Disturbances to the bog vegetation as a result of human interference, such as burning, can also cause a distinct horizon within the bog containing different strength and hydraulic characteristics. The permeability of peat is consequently highly variable over small distances (section 4.2.2). Similarly, early accounts often attribute the cause of bog failures to the build up of water at the boundary between the peat and underlying clay (Sollas *et al.*, 1897; Delap *et al.*, 1932; Delap and Mitchell, 1939). This idea results from the belief that the addition of rainwater accounts for the highly fluidised nature of the peat in a bog flow. However, it seems more likely that highly humified peat is either already in a fluidised state or transformed to a slurry on disturbance due to the breakdown of the peat matrix into a non-fibrous amorphous granular mass as a result of decomposition. Although there is no evidence of this from sampling at the margins of failures, the presence of large amounts of peat slurry immediately following bog flows, the low *in situ* shear strength exhibited within the bulging slope on East Cuilcagh (site 2) and the material extruded during soil augering suggest that the addition of rainwater is not required to transform the peat into a fluid mass.

Laboratory shear box determinations and the use of a field shear vane indicated that the peat with the lowest cohesion was mostly situated in the middle to upper catotelm. However, it was the basal catotelm which was noted to behave as a 'slurry' with very little coherence around the margins of the recent bog flow scars E2 and E6. This material was also absent from the base of deposited rafts at these sites. It is questionable, therefore, whether the material tested in the laboratory was representative of the material which failed in the field, which has implications for the slope modelling (as discussed in section 5.5.4). This also indicates that the material may have altered into this slurry-like state during failure. The laboratory testing of both peat and clay produced significant changes in the sample volume so that the material in the field differed greatly from the sample material subjected to consolidation and shear testing. These changes are a result of water being expelled from the structure and the fabric aligning itself in the plane of shear failure (Landva and Pheeney, 1980) to give higher bulk densities and lower moisture contents. The use of unrepresentative material parameters (more specifically, the over-estimation of strength) is one of the reasons suggested for the failure of the SLOPE/W model to simulate realistically low values of F (section 5.5.4).

6.1.3 Hydrological Controls

The modelling of the slopes involved the assumption of constant pore water pressures across the slip surface and therefore normal hydrostatic conditions. However, the outcome of the modelled N4 failure was considerably different from the other modelled slopes (Chapter 5) in that it indicated the generation of artesian conditions within the pipes in the clay which were probably responsible for converting the slope into an actively unstable condition (Dykes and Kirk, 2001). The significance of this highlights the importance of pore water pressures on the stability of peatland slopes.

Selby (1993) referred to convergence of drainage as an important factor in promoting slope instability as water is concentrated in hollows leading to higher pore water pressures than in surrounding areas. However, Crisp *et al.* (1964) suggested that the primary cause of instability in an area characterised by peat sliding was the lack of water courses on the slopes, implying that adequate drainage would reduce the frequency of slides. The occurrence of flushes in peatlands has been suggested as contributing to failure (Sollas *et al.*, 1897; Selkirk, 1996; Warburton and Higgitt, 1998), where peat slides are more prevalent (Table 2.9). Fluctuating pore pressures in granular material generated as a result of grain re-arrangement during the shearing process were seen to modify grain contact stresses and promote significant deformation to maintain a failure mechanism once movement has been initiated (Iverson and LaHusen, 1989). This process is considered particularly relevant to flow type failures (Selby, 1993). It is uncertain, however, if this process applies to well humified peat or whether the process of liquefaction is more appropriate for this material.

In previously reported bog failure events, the pre-conditioning of slopes to failure is usually controlled by antecedent meteorological conditions at a variety of timescales (days, weeks and months). Table 2.9 shows that out of the 34 tabulated failure events, 18 cases of high and 9 cases of low antecedent rainfall conditions were considered important in contributing to the bog failures. In a natural bog environment, water table variations result from changes in the local topography but are usually confined to the upper 30 cm of the peat mass. The amount of rainfall required to saturate the slopes and cause surface water also depends on local topography and vegetation, as well as rainfall intensity, duration and the infiltration capacity of the acrotelm. High water tables are particularly important in maintaining an active bog surface. Increased rainfall variability is considered as an important factor for the promotion of instability (Selby, 1993). For example, too much rainfall can result in accelerated gully and hag formation, and possible slope unloading, while a decrease in rainfall can reduce the growth of the sensitive peat forming vegetation. The hydrological modelling of the peat slopes revealed that over 28 days of low rainfall were required to significantly reduce the water table due to the large store of water retained within the bog and the low hydraulic conductivities of the peat. Water table decreases are important for increasing the stability of the slope, especially for bog flows, as prolonged low antecedent rainfall conditions can affect the acrotelm leading to a drying out of bog surface and destruction of the moisture absorbing *Sphagnum* mosses causing the bog to shrink. Once this has occurred, the onset of intense rainfall may lead to excess surface water and accelerated runoff due to restricted infiltration. This would be expected to reduce the chance of failure. Droughts have also been reported to cause cracking of the bog surface (Alexander *et al.*, 1986; Carling, 1986; Wilson and Hegarty, 1993). Although the cracks allow the rapid transfer of rainwater into, or to the base of, the peat, they usually result in significant lowering of the water table and consequent drying out of the vegetation. The cracked area of bog associated with the bulging slope on East Cuilcagh (site 2) was noted to be characterised by high shear strengths in comparison to the surrounding bog. Therefore, it is thought that low antecedent rainfall conditions are unlikely to be a significant factor associated with bog failure events, although their role in instigating erosion on a smaller scale is not in question here.

Small subsurface pipes in the underlying clay were found to have a strong influence on the stability of the multiple peat slide (N4). However, they are impossible to detect unless observed immediately following a (slide) failure event in which the entire depth of peat and a depth of clay have been excavated. Peat pipes of various sizes are common on Cuilcagh Mountain. The largest (up to 1.5 m in diameter) are found within the deeper areas of peat on East Cuilcagh. Small pipes within the basal peat (approximately 5 cm in diameter) were noticed on East Cuilcagh at failure sites E2, E6 and E7 during extraction of samples for laboratory analysis. Although Dykes and Kirk (2001) found that small pipes within the peat did not reduce F sufficiently to contribute to the failure of a modelled northern slope (N4), small pipes within the basal catotelm of deep areas of peat (e.g. on East Cuilcagh) may generate artesian pressures similar to those within the clay at site N4. Larger peat pipes can usually be detected by the presence of linear depressions containing wet-based vegetation species on the ground surface (such as *Sphagnum cuspidatum*) and are prone to collapsing; they can therefore act as lines of weakness in the acrotelm and surface vegetation mat. Storm flow in large pipes, blow-out, collapse (Nield, 1993) and subsequent rupture of the acrotelm may possibly contribute to slope failure. However, this is unlikely as these occurrences would also produce a reduction in pore water pressures. Gilman and Newson (1980) state that pipes may promote instability by providing 'perforations' along which the ground tears during failure. The role of natural piping within the peat and underlying material has been further highlighted by Carling (1986).

The influence of drainage ditches on slope instability in peatlands has been addressed by Wilson and Hegarty (1986), Dykes and Kirk (2001), Tomlinson and Gardiner (1982) and Carling (1986). Although a functioning ditch would lower the water table, thus reducing pore water pressures, ditches also produce a means for the rapid transfer of rainwater to the lower layers of the bog and underlying clay, and if transverse can act to remove lateral support as the lower edge of the peat mass is effectively unsupported (Dykes and Kirk, 2001).

6.1.4 Long term controls and the timing of failures

In a dynamic and sensitive peatland environment, the factors that control the stability of slopes are continuously changing, altering the balance between the strengths and stresses of the slope. These factors transform the slope condition until a time when a temporal increase in stress or decrease in strength is sufficient to cause instability and failure of the slope. The most important preparatory factors that alter the stability of slopes over time are:

1. Weathering and slow mass movement (creep) processes which alter the strength of the material from peak to residual strength;
2. Prolonged loading in which soils with high water contents can exhibit plastic flow (Crozier, 1986);
3. Compression by loading increases the pore water pressure and thereby decreases the strength of the material;
4. Increases in the depth of material. Continuing peat accumulation results in an increased overburden pressure and coupled with other factors can lead to changes in clay fabric underlying the peat (Carling, 1986);
5. Decreases in the length of slope usually by channel undercutting and bank erosion progressively remove the lateral support and can oversteepen the slope.

Although slope failure can occur as a result of several contributory factors which gradually reduce F until the critical stability threshold is reached, in almost all reported events initiation occurred during high magnitude rainfall events. In these cases, slope failure was most likely initiated by an actual trigger event, such as the undercutting and unloading of the slope (removal of lateral support); or increased pore water pressure of the material (either within the catotelm or underlying clay depending on failure type).

6.1.5 Critical slopes and threshold slope angles

Critical slopes are usually defined by their limiting threshold angle. This is the angle of slope above which rapid mass movement will occur from time to time, and below which the slope material is stable with respect to rapid mass wasting processes (Carson, 1975). If a distinct style of landsliding has been widespread in an area then many slopes may be inclined at angles which are similar to those which could be predicted from stability analyses of slope soils (Francis, 1987). Therefore, by measuring the slope angle and material depth of slopes in an area characterised by a particular form of mass failure, assumptions can be made regarding the critical threshold angle for the slopes. However, it is questionable whether the concept of threshold angle slopes can be applied to both types of failure in peatland areas. Firstly, bog and escarpment flows only involve the accumulated peat mass that blankets the slopes and not the whole of the regolith overlying the parent material. Therefore, these types of failure cannot change slope inclination, but can only remove the upper 1-2.5 m of slope material as a single layer of peat. Further slope failure on the same section of slope is then prohibited until peat has accumulated once again. Secondly, the sensitive nature of the basal peat means that there is a complex relationship between the slope stability parameters and time. Ongoing changes to the state of peat (particularly effective cohesion) are important, and therefore for bog flows, threshold slopes are not simply a relationship between slope angle and depth of material. As peat accumulates, increasing overburden pressure and continuing differential decomposition cause non-uniform changes in the properties and conditions of the basal catotelm and lead to a reduction in the strength of the material over time. Therefore, critical depth is not just a function of slope angle, but is also affected by the conditions within the basal peat. Similarly (although not to the same extent), the clay underlying the peat can also undergo physiochemical changes over time (with increasing overburden) and has been reported to play an important role in the occurrence of peat slides (Carling, 1986). However, Carling (1986) was successful at producing theoretical stability curves (critical state intrinsic stability curves) for peat and clay. Peat at 1 and 2 m in depth was noted to be mechanically stable on slopes over 25°, while clay with an overburden of peat in excess of 1 m was stable over 20-25°. However, residual strength clay was noted to be unstable on slopes greater than 7°. Carling (1986) suggests that weathering and stability of clay may be a constraining factor limiting peat depth on some slopes. Therefore, the relationship between slope angle and material depth is complicated by the changing nature of the slope materials (clay and peat) as a result of weathering, deformation (slow mass movement) and the non-uniform process of decomposition.

6.2 PEAT SLOPE INSTABILITY ON CUILCAGH MOUNTAIN

Peat slope instability has been studied by integrating the physical properties of the peat with the results of the hydrological and slope stability modelling. This has indicated a range of possible factors influencing peatland stability. This section discusses the relative importance of the stability factors (section 6.1) on the preparation, control and initiation of failures on Cuilcagh Mountain. These are discussed with reference to the two distinct types of failure that have been identified on Cuilcagh Mountain (bog flows on East Cuilcagh and peat slides mainly on the northern slopes). Firstly, the nature of the failures and the possible factor(s) which varied sufficiently to be responsible for converting the slopes to an actively unstable condition are considered with the use of specific examples of failed slopes. Secondly, the initiation and the timing of the failure events are discussed.

6.2.1 East Cuilcagh

The failures identified on East Cuilcagh are classed as bog flows (Figure 6.2) with the failure zone being located *within* the peat mass and a resulting rapid debris flow of peat downslope. The nature of the failed material (catotelm peat) is thought to be a slurry-type plastic flow in which the viscosity decreases with increasing rate of shear (Selby, 1993). However, the behaviour and mechanism of the failing peat mass as a whole is complicated as a result of the diplotelm characteristics (the two-layered nature of the bog). The break up of the peat mass and the ratio of deposited rafts to the amount of peat slurry moved is dependent on the fibrosity of the acrotelm, the location of the boundary zone between the acrotelm and catotelm, the thickness of the catotelm at the time of initiation, and the velocity of the failure event. Figure 6.3 illustrates a possible vertical velocity profile for this type of failure with turbulent flow occurring towards the base of the failing mass due to friction of the deforming mass over its base and the acrotelm behaving as a rigid block.

On East Cuilcagh, the low angle slopes provide the conditions necessary to promote accumulation of the greatest depths of peat on the Cuilcagh blanket bog (mainly as a result of excessive waterlogging and the types of peat-forming vegetation). The aerobic acrotelm is usually up to 30 cm in depth, although the transition into the catotelm does not appear as a distinct boundary, it occurs over approximately 20 cm forming a transition zone (Chapter 4). A balance between the relatively high rates of decomposition in the aerobic zone (in comparison to the anaerobic zone within the catotelm) and peat accumulation at the surface of the bog results in the acrotelm being maintained at a more or less constant depth (Clymo, 1984a, 1992). Therefore, as peat accumulation continues, it is the catotelm that increases in depth.

All but one of the bog flows on East Cuilcagh occurred on concave sections of slope. Gilman and Newson (1980) associated concave slopes with concentrated drainage (section 6.1.1), which results in localised high pore water pressure (Selby, 1993) and therefore act to reduce effective shear strength. However, given that peatlands are characterised by generally high (low variation) water tables, this is thought to have a limited effect. The majority of the bog flows fail directly into a stream at the foot of the slope. These failures leave a scar area on the middle section of the slope generally surrounded by large tension cracks (sometimes tens of metres in length) partially filled with water and liquid peat, and subsided acrotelm and upper catotelm peat. Some rafts of torn peat and vegetation are deposited towards the foot of the slope and the others get transported further downstream with the flooding out of the basal peat. In this type failure, the flow mechanism progressively extends the failure upslope and outwards from the initial disturbance as removal of lateral support and the movement of the flowing catotelm stretches and tears the overriding acrotelm. This form of movement has been termed 'slope unravelling' which is preferred to the more general term 'slope failure feedback' used in early literature concerning bog failures (e.g. Mitchell, 1935). A large proportion of the affected area of the 1992 bog flow (E2) consisted of subsided and cracked peat (Figure 3.4 and Plate 3.3) which is situated immediately adjacent to, but not upslope of, the bare scar area. In this case, it is thought that once failure had been initiated the rapid movement of the fluid-like catotelm peat removed all of the peat from the now bare scar area and left only the upper peat layers torn into long transverse strips on the western flank. Slope unravelling of this form is noted to be particularly important in the escarpment flows identified in north-west Ireland at Geevagh (Alexander *et al.*, 1986) and on a northern slope of Slieve Anierin (Chapter 3). However, these failures occurred on a convex

Figure 6.2 Illustration of a bog flow based on field evidence from Cuilcagh Mountain.

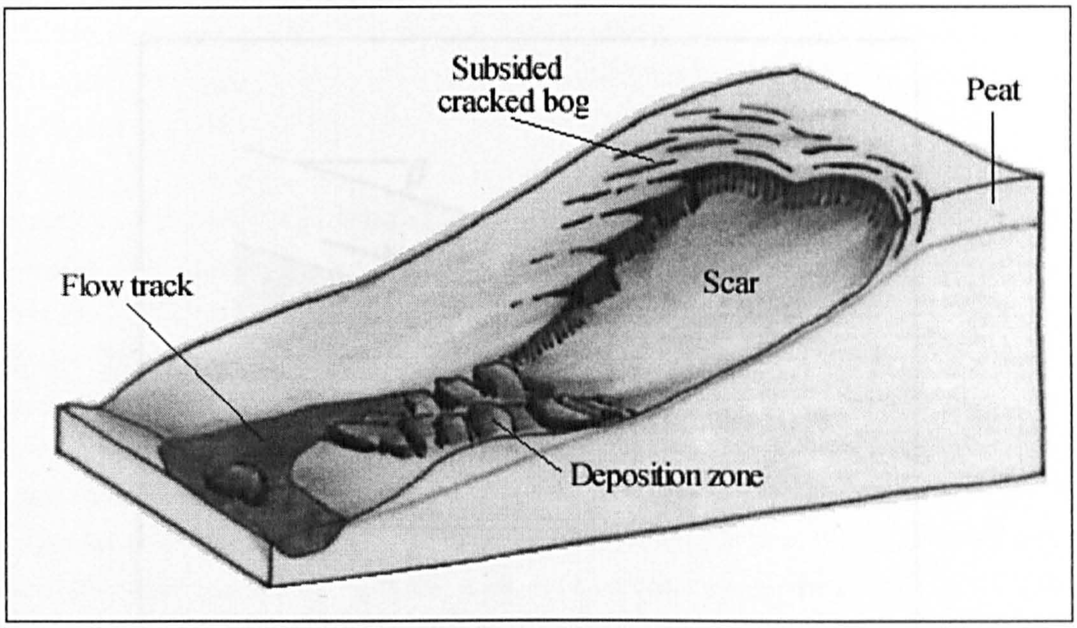
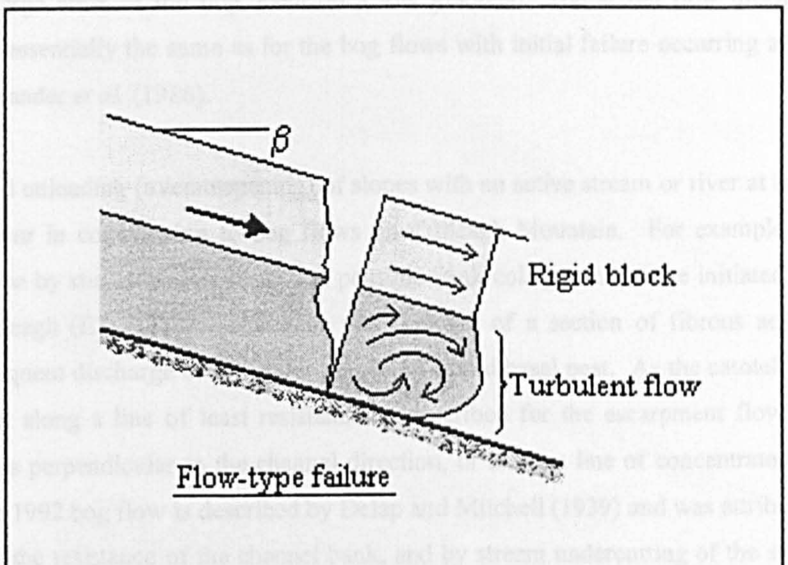


Figure 6.3 Possible vertical velocity profile for a bog flow.



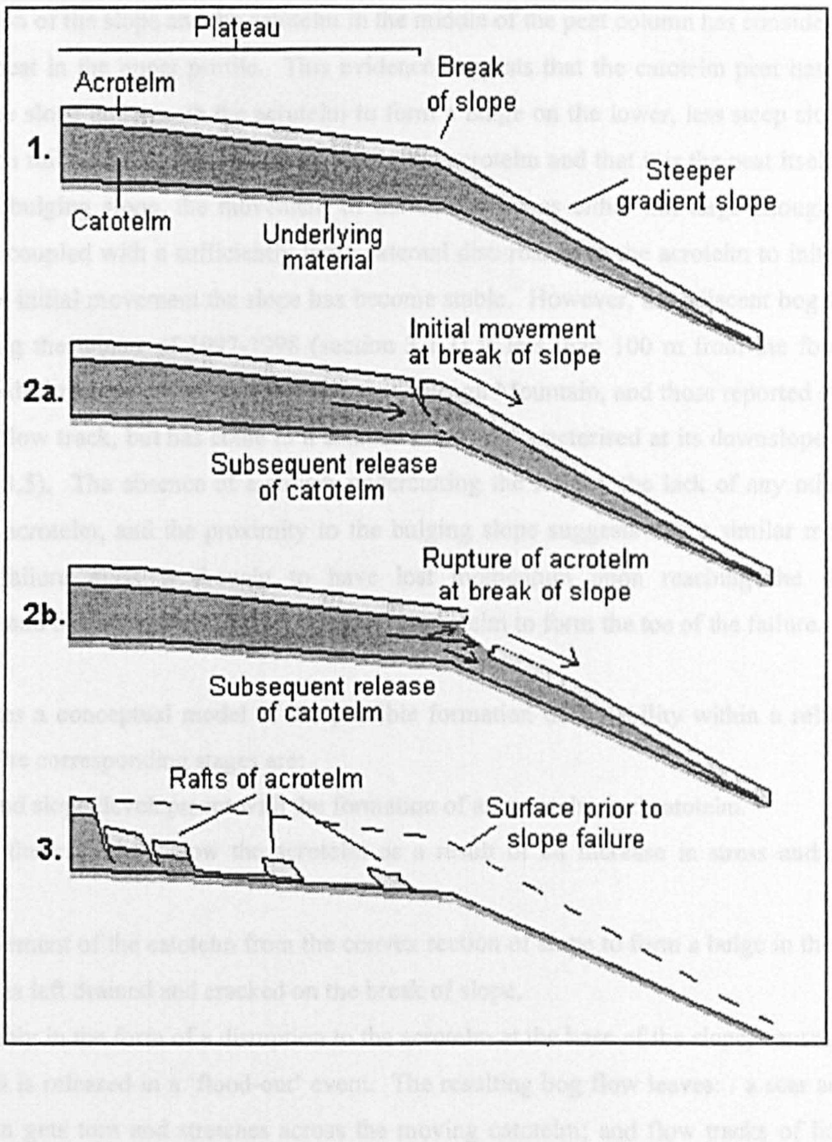
break of slope at the plateau edge and are therefore more likely to be related to variations in tension within the peat layer. Slope unravelling on bogs can be maintained on low gradients such as those on the plateau areas drained by the escarpment flows. Firstly, the topography of the plateau and impeded drainage promote favourable conditions for peat accumulation and can sustain a relatively great depth of peat (over 2.5 m). Failure of the supporting bank (situated across the break of slope) as a result of increased pressure from the accumulating peat on the plateau, removes lateral support (either by an initial movement, or disturbance to the acrotelm) and allows the basal peat under confined pressure to be released (Figure 6.4). The formation of rafts depends on the slope angle and velocity of flow as they may be carried downslope or become deposited on the scar area. The margins of the flow scar subside and crack as a result of the removal of some of the underlying material and ponding of liquid peat usually occurs behind some of the larger rafts. Slope unravelling has the potential to affect large areas of the bog, even on a low gradient. The actual flow mechanism involved in escarpment flows is essentially the same as for the bog flows with initial failure occurring at the break of slope as described by Alexander *et al.* (1986).

The undercutting and unloading (oversteepening) of slopes with an active stream or river at their foot appears to be an important factor in contributing to bog flows on Cuilcagh Mountain. For example, it is thought that unloading of the slope by stream undercutting and possible bank collapse may have initiated the 1992 bog flow failure on East Cuilcagh (E2). This disturbance and removal of a section of fibrous acrotelm would have resulted in the subsequent discharge of the underlying semi-liquid basal peat. As the catotelm was released, the slope would unravel along a line of least resistance as described for the escarpment flows. This advancing failure usually occurs perpendicular to the channel direction, or along a line of concentrated drainage. A flow failure similar to the 1992 bog flow is described by Delap and Mitchell (1939) and was attributed to gravitational stresses overcoming the resistance of the channel bank, and by stream undercutting of the slope. Similarly, the flow took place on the outside of a bend in the stream where undercutting was expected to be most vigorous after high rainfall during the week prior to the slope failure. Another example of slope failure by unloading is the bog flow E7 (Figure 3.1) which was also thought to be undercut by a stream. Other forms of disturbance to the acrotelm resulting from grazing pressures and drainage ditches will have an effect on vegetation coverage and therefore slope stability.

Another possible explanation for the 1992 bog flow on East Cuilcagh is that bank collapse may have led to the temporary damming of the stream, leading to increased pore water pressure and build up of water within, or immediately underlying the basal peat. This may have caused the bog to momentarily lift off its base and initiate slope instability. However, this seems unlikely as there is no clearly defined boundary between the peat and underlying clay where water could potentially build up.

Pockets of gas may form within the catotelm as a result of differential decomposition and botanical variability and have an effect on the stability of peatland slopes, as described in section 6.1. Compression of the peat mass (with continued loading) and the presence of gas within the pores of the peat would have the same effect as high pore water pressures (reducing shear strength and decreasing the stability of the slope). This could be particularly important given that gas can make up as much as 10 % of the peat mass in the catotelm (Clymo,

Figure 6.4 Slope failure in the form of an escarpment flow based on literature and field evidence.



1984b). Although the presence of trapped gas and changes in acidity have been reported to affect the overall strength of the material at depth within the peat mass (Bishopp and Mitchell, 1946; Al-Khafaji and Andersand, 1981), these are difficult to determine in the field. Therefore, their role in decreasing the stability of peatland slopes remains speculative.

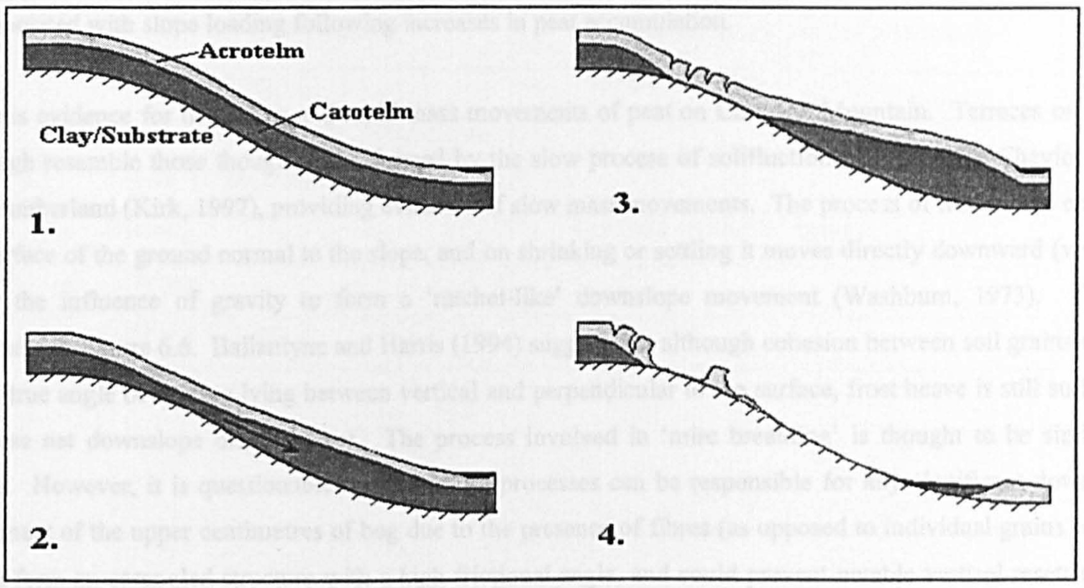
The section of bulging slope (section 3.3.3 and Figure 3.7) is thought to be significant in understanding the behaviour of peat in a two layered system (diplotelm). The slope lies adjacent to two relatively fresh (post-1985) failure scars on East Cuilcagh. Deep cracks have developed near the crest of the slope causing drainage and subsidence, forming a semi-circular depression approximately 70m in diameter. The bulge is located in the middle-lower section of the slope and the catotelm in the middle of the peat column has considerably lower shear strength than the peat in the upper profile. This evidence suggests that the catotelm peat has moved from the upper section of the slope underneath the acrotelm to form a bulge on the lower, less steep slope. This implies that a peat slope can fail without external disturbance to the acrotelm and that it is the peat itself that is unstable. In the case of the bulging slope, the movement of the catotelm was either not large enough to induce mass failure, or was not coupled with a sufficiently large external disturbance to the acrotelm to initiate mass failure. Therefore, after the initial movement the slope has become stable. However, the adjacent bog flow failure (E6) that occurred during the winter of 1997-1998 (section 3.1.2) is less than 100 m from the foot of the bulging slope. This failure differs from the other bog flows on Cuilcagh Mountain, and those reported elsewhere, in that it does not have a flow track, but has come to a standstill and is characterised at its downslope extent by a well defined toe (Plate 3.5). The absence of a stream undercutting the failure, the lack of any other evidence of a disturbance to the acrotelm, and the proximity to the bulging slope suggests that a similar mechanism was in operation. The failure mass is thought to have lost momentum upon reaching the shallow gradient (approximately 1°) and has undermined a wide section of acrotelm to form the toe of the failure.

Figure 6.5 illustrates a conceptual model of the possible formation of instability within a relatively deep peat mass on a slope. The corresponding stages are:

1. Typical peatland slope development with the formation of an acrotelm and catotelm.
2. Movement of the catotelm below the acrotelm as a result of an increase in stress and/or a decrease in strength.
3. Complete movement of the catotelm from the convex section of slope to form a bulge in the concavity. The acrotelm crust is left drained and cracked on the break of slope.
4. Trigger (probably in the form of a disruption to the acrotelm at the base of the slope) causes the slope to fail as the catotelm is released in a 'flood-out' event. The resulting bog flow leaves: - a scar area; cracked bog as the acrotelm gets torn and stretches across the moving catotelm; and flow tracks of liquefied catotelm with deposited rafts made up mostly of acrotelm peat.

It is possible that this scenario has occurred in other areas of deep peat prior to slope failure in the form of a bog flow, such as the 1992 flow (E2). However, this is difficult to determine as the evidence for slope bulging is destroyed once failure occurs.

Figure 6.5 Model illustrating the possible development of instability in deep peat.



The critical hydrological and geotechnical controls that may lead to movement of the catotelm peat (stage 2 of the model) and disruption to the acrotelm (stage 3) are thought to be mainly associated with reduced cohesion and increased pore water pressure. The possible factors responsible for the changes in these parameters are shown in Table 6.1. A decrease in cohesion of the catotelm can result from decomposition of the peat structure (section 6.1.2) and from slow mass movement. Reduced vegetation cover and disruption to the acrotelm (stage 4) can result from grazing and burning, or naturally by climatic changes, such as reduced rainfall and large increases in temperature. The most important factor in the generation of high pore water pressures is thought to be associated with slope loading following increases in peat accumulation.

There is evidence for both slow and rapid mass movements of peat on Cuilcagh Mountain. Terraces on North Cuilcagh resemble those thought to be formed by the slow process of solifluction of peat in the Cheviot Hills, Northumberland (Kirk, 1997), providing evidence of slow mass movements. The process of frost heave expands the surface of the ground normal to the slope, and on shrinking or settling it moves directly downward (vertical) under the influence of gravity to form a 'ratchet-like' downslope movement (Washburn, 1973). This is illustrated in Figure 6.6. Ballantyne and Harris (1994) suggest that although cohesion between soil grains results in the true angle of settling lying between vertical and perpendicular to the surface, frost heave is still sufficient to cause net downslope displacement. The process involved in 'mire breathing' is thought to be similar in nature. However, it is questionable whether these processes can be responsible for any significant downslope movement of the upper centimetres of bog due to the presence of fibres (as opposed to individual grains of soil) which form an entangled structure with a high frictional angle, and could prevent notable vertical resettlement. Nevertheless, the role of these processes in disrupting the protective surface vegetation layer and producing tension within the fibrous structure may be more significant. Within the catotelm, the process of deformation creep appeared to be dominant during shearing of samples in the laboratory (Chapter 4). It is recognised that the bog flows on Cuilcagh Mountain were rapid events. Evidence of this is based on the morphology of the failures and the surrounding bog. For example, the thrusting up and undermining of the acrotelm by the moving rafts of peat and the subsequent formation of a well defined toe on failure E6 (Plate 3.5) could only have been produced in a rapid failure event. Walker and Gunn (1993) estimated the peak velocity of the 1992 bog flow (E2) to be 4.9-5.5 m/s 200 m downstream of the failure scar. This is considered to be too high, but it is clear that the movement of the peat-laden water was very rapid. A wide range in the rate of failure and subsequent release of material has been reported in literature in association with bog flows, from an instantaneous outburst and flood event (e.g. Bishopp and Mitchell, 1946), to a gentle oozing which has been likened to a volcanic lava flow and has been reported to continue for days (Sollas *et al.*, 1897). On Cuilcagh Mountain, although different types of failure are in operation, there is no evidence to suggest that peat slope failures can occur at an intermediate rate. The occurrence of slow mass movement of the basal peat or underlying clay, and the rapid failure of the peat mass in the form of sliding or flowage have been recognised. The two extremes of failure rate are not thought to be mutually exclusive as there is a possibility that slow mass movements may lead to more rapid failure events as a result of decreases in material strength (e.g. from peak to residual).

The possible events leading up to a bog flow are illustrated in a flow diagram (Figure 6.7). The cycle begins with peat accumulation on a slope and the development of the characteristic peatland diplotelm. Continued peat

Table 6.1 Possible factors responsible for reduced cohesion and increased pore water pressure.

Reduced cohesion	**Increased pore water pressure**
◆ Decomposition	◆ Peat accumulation
◆ Slow mass movement, 'progressive failure' of slope materials	◆ Mire breathing
◆ Burning	◆ Confined subsurface pipes
◆ Grazing	
◆ Climatic changes	

Figure 6.6 The mechanism of frost creep (after Ballantyne & Harris, 1994).

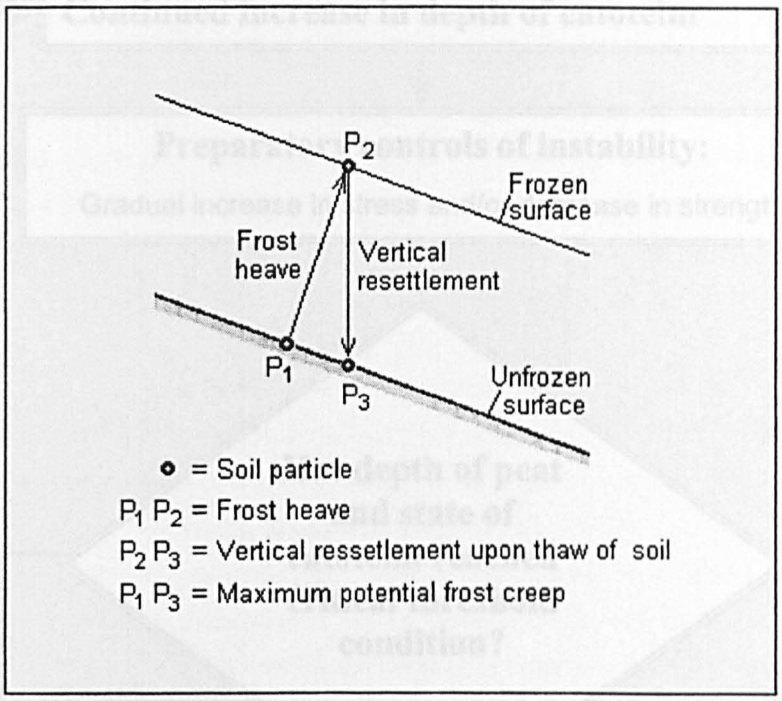
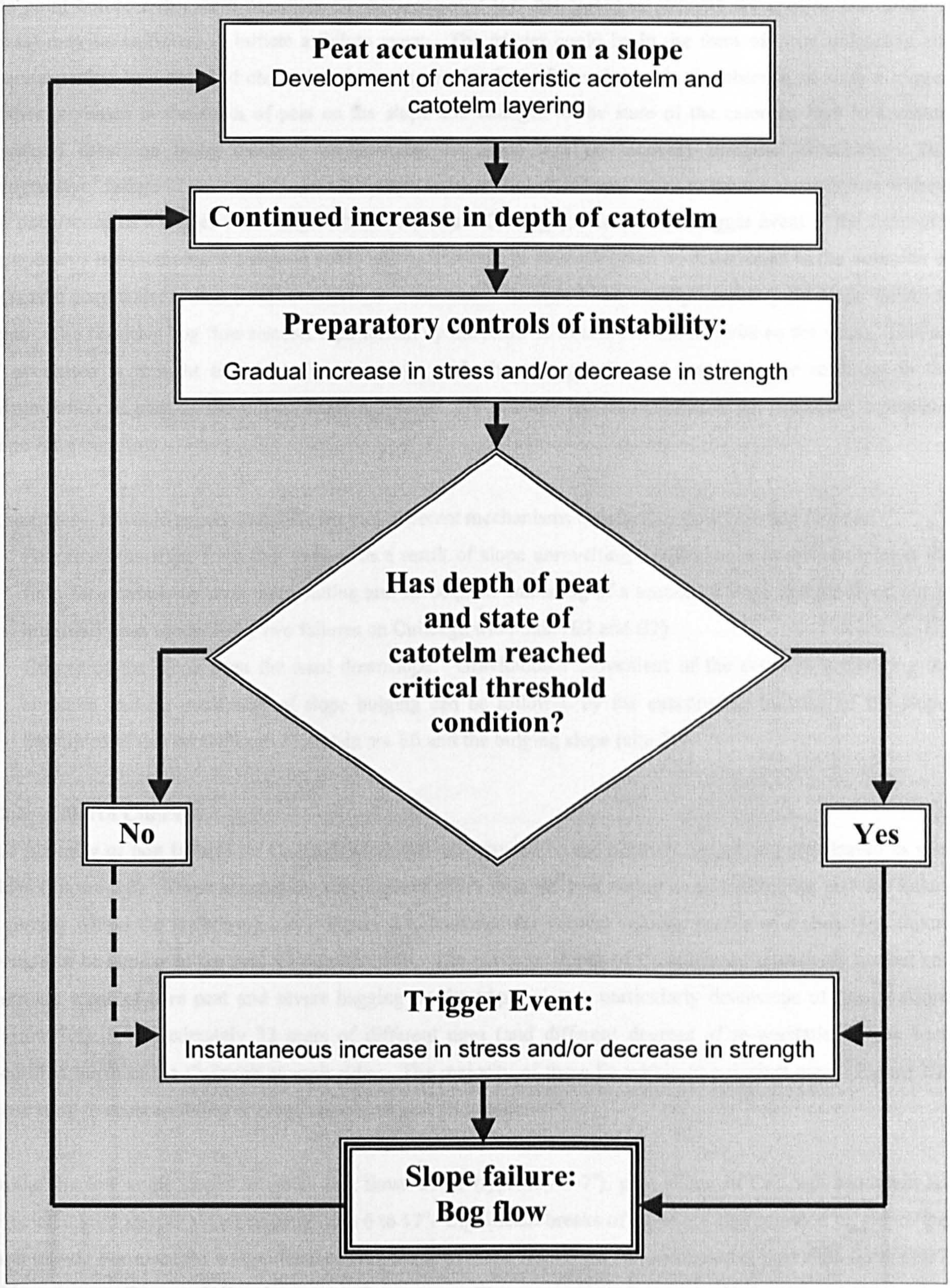


Figure 6.7 Flow diagram illustrating the possible events leading to a flow type bog failure.



accumulation increases the depth of the catotelm, and alterations to the state of this layer, mainly from decomposition, result in a gradual reduction in F (a decrease in strength and/or increase in stress). A trigger at this point before a threshold condition has been reached (i.e. the forces of strength are greater than those of stress) may be sufficient to initiate a failure event. The trigger could be in the form of slope unloading and oversteepening as a result of channel undercutting at the foot of the slope. In the absence of such a trigger, further increases in the depth of peat on the slope and changes to the state of the catotelm lead to a critical threshold condition being reached, transforming the slope into an 'actively unstable' condition. This 'progressive' failure of the catotelm peat is thought to be sufficient in some cases to initiate slope failure without the occurrence of a trigger event (e.g. failure E6 on East Cuilcagh). However, a trigger event in the form of a (temporary) instantaneous increase in stress and/or decrease in strength (such as disturbance to the acrotelm or increased pore water pressure within the slope materials) is thought to be usually necessary for slope failure to occur. The resulting bog flow restores equilibrium by the removal of some of the material on the slope. This set of processes is thought to be cyclic over time, with the re-vegetation of the bare scar resulting in the accumulation of peat on the slope. Table 6.2 shows the possible factors responsible for preparing a peatland slope for a bog flow.

In summary, it would appear that there are two different mechanisms involved in flow type bog failures:

1. Failure of the slope from foot to head as a result of slope unravelling. Disturbance to the acrotelm at the foot, for example by river undercutting and subsequent unloading of a section of slope and the flood out of humified peat, accounts for two failures on Cuilcagh Mountain (E2 and E7).
2. Failure of the slope from the head downslope. Gravitational movement of the catotelm underlying the acrotelm and the possibility of slope bulging can be followed by the catastrophic bursting of the slope. Examples of this on Cuilcagh Mountain are E6 and the bulging slope (site 2).

6.2.2 North Cuilcagh

The majority of bog failures on Cuilcagh Mountain are situated on the northern slopes and are classed as peat slides (Figure 6.8). These are shallow translational slides with the peat acting as an overburden and the failure occurring within the underlying clay. Figure 6.9 illustrates the vertical velocity profile of a slide type failure thought to be similar to the peat slide mechanism. The northern slopes of Cuilcagh are intensively eroded and there are areas of bare peat and severe hagging on the upper slopes, particularly downslope of Lough Atona (Figure 3.1). Approximately 32 scars of different ages (and different degrees of re-vegetation) have been identified north of the Cuilcagh summit ridge. The majority of these lie within two distinct areas (Figure 3.1) illustrating the susceptibility of certain slopes to peat slide failures.

Unlike the low angle slopes in which bog flows occur (typically 1-7°), peat slides on Cuilcagh Mountain are associated with steeper slopes ranging from 6 to 17°. Significant breaks of slope are also common on slopes that have failed. For example, a significant convex break of slope from 9° to 16° was noted at peat slide failure N17. Although peat slides on Cuilcagh appear to be more common on convex slopes (e.g. N15, N19 and NW5), they have also been initiated on concave (NW10) and straight sections of slopes (NW6). As discussed previously, the presence of transverse drainage ditches on a slope contributed to peat slide N4. Similarly, unloading as a result

Table 6.2 Possible factors responsible for preparing a peatland slope for failure on Cuilcagh Mountain.

	Bog flows	Peat slides
Slope Geometry	Slope unloading; Slope loading (peat accumulation); Extensive peat pipe networks (disturbance and removal of material within profile, blow outs).	Slope unloading; Slope loading (peat accumulation).
Geotechnical controls	Decrease in cohesion of basal catotelm peat (decomposition, slow mass movement); Disturbance to acrotelm and surface vegetation.	Decrease in cohesion of clay (weathering, slow mass movement)
Hydrological controls	Pipe network (concentrated seepage); Lateral pressure from water in cracks; High antecedent rainfall conditions; Low antecedent rainfall conditions; Common drought episodes.	Pipe network in clay; Lateral pressure in drains; High antecedent rainfall conditions.

Figure 6.8 Illustration of a peat slide based on evidence from Cuilcagh Mountain.

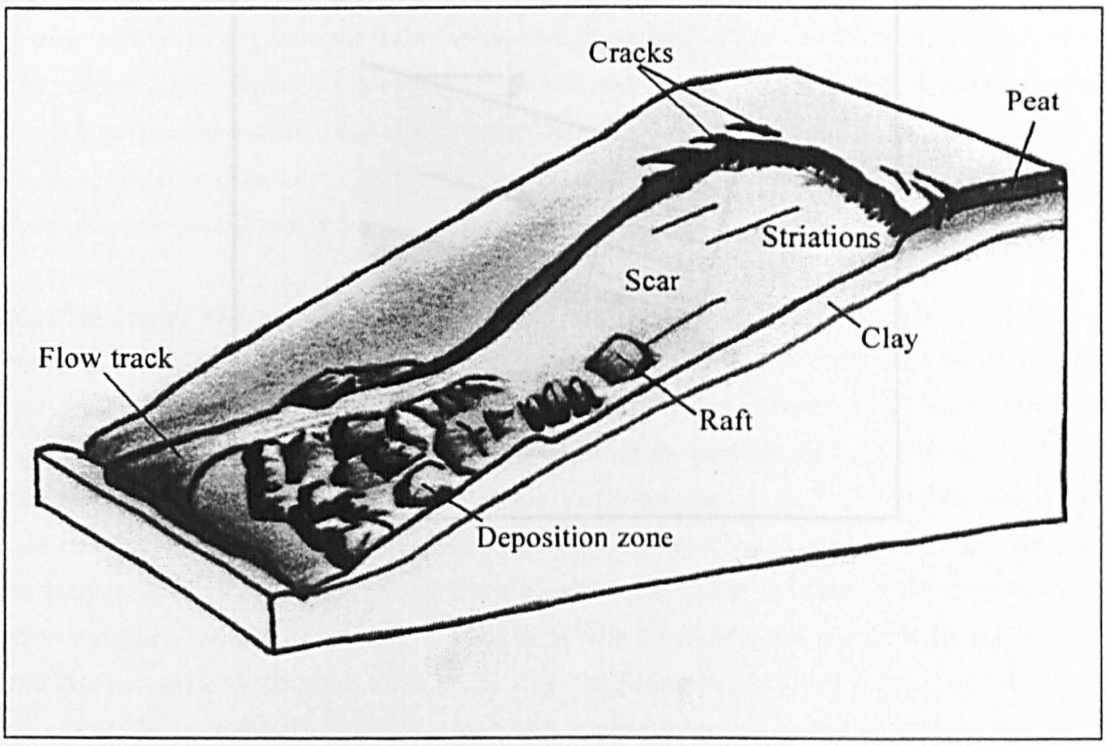
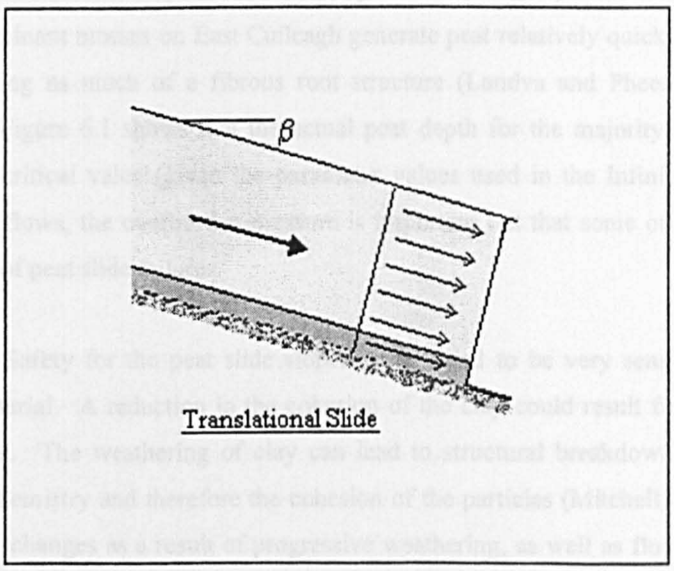


Figure 6.9 Possible vertical velocity profile for a peat slide (after Selby, 1993).



of channel undercutting by fluvial action is thought to be an important control on the failure of several slopes within a small area where peat has accumulated on a relatively steep incised channel on North Cuilcagh. These four failure scars (N15, N17, N19 and N20) are at different stages of re-vegetation and are situated on convex slopes immediately upslope of an actively eroding river (Figure 3.1).

In comparison to the bog flows on East Cuilcagh, the peat on the northern slopes is relatively thin (usually around 1.0 m) and was noted to be more fibrous with a less well defined zone between the acrotelm and catotelm. There was also an absence of the well humified amorphous peat towards the base of profiles as found on East Cuilcagh. The generally more fibrous and thinner peat is thought to be a consequence of the steeper slopes and, hence, better drainage encouraging different peat-forming vegetation species. The heather and grasses which dominate the northern slopes have relatively extensive root systems that lead to higher tensile strengths, whereas the dominant mosses on East Cuilcagh generate peat relatively quickly and are broken down more easily without leaving as much of a fibrous root structure (Landva and Pheeney, 1980). Given the generally steeper slopes, Figure 6.1 shows that the actual peat depth for the majority of modelled peat slide slopes was less than the critical value (given the parameter values used in the Infinite Slope Model). This implies that, like the bog flows, the overburden pressure is important but that some other controls were more critical for the occurrence of peat slide failures.

The modelled Factors of Safety for the peat slide slopes were found to be very sensitive to changes in the cohesion of the failed material. A reduction in the cohesion of the clay could result from weathering or slow mass movement processes. The weathering of clay can lead to structural breakdown and alterations to the bonding and pore water chemistry and therefore the cohesion of the particles (Mitchell, 1993). Carling (1986) states that physiochemical changes as a result of progressive weathering, as well as fluctuations in piezometric head and increases in the peat overburden led to strain softening and micro-shearing of clay and reduced shear strength through time. Slow mass movement processes are responsible for altering the material from peak strength to a residual strength (section 2.2.3). Field shear vane results of *in situ* peat and clay at site 4 (NW10) indicated that residual strengths were considerably less than peak strengths (section 3.3.5, Figure 3.12). The addition of rainwater into the clay layer may also result in a reduction in the shear strength of the material as electrostatic bonds are reduced by the more pure rainwater (Selby, 1993). If this is the case, the presence of pipes and cracks that facilitate the transfer of rainwater into the underlying clay are of particular importance.

Field evidence for the occurrence of slow mass movement processes comprises not only the presence of terraces on North Cuilcagh (see previous section), but also from an initial slope movement which took place prior a peat slide which occurred in March 2000 (NW10) (as detailed in section 3.1.3). In the latter case, progressive failure of the underlying clay is thought to have led to slow mass movement and disruption to the surface vegetation and a water pipe within the peat layer two years before the mass failure of the slope. Actual slope failure may then have been initiated either by a trigger event that increased the confining pressure and forced the water pipe to give way at the join, or by further slow mass movement of the underlying clay that pulled the pipe apart. The subsequent inflow of water into the peat layer and absence of the water pipe holding the upper slope in place would have further destabilised the slope.

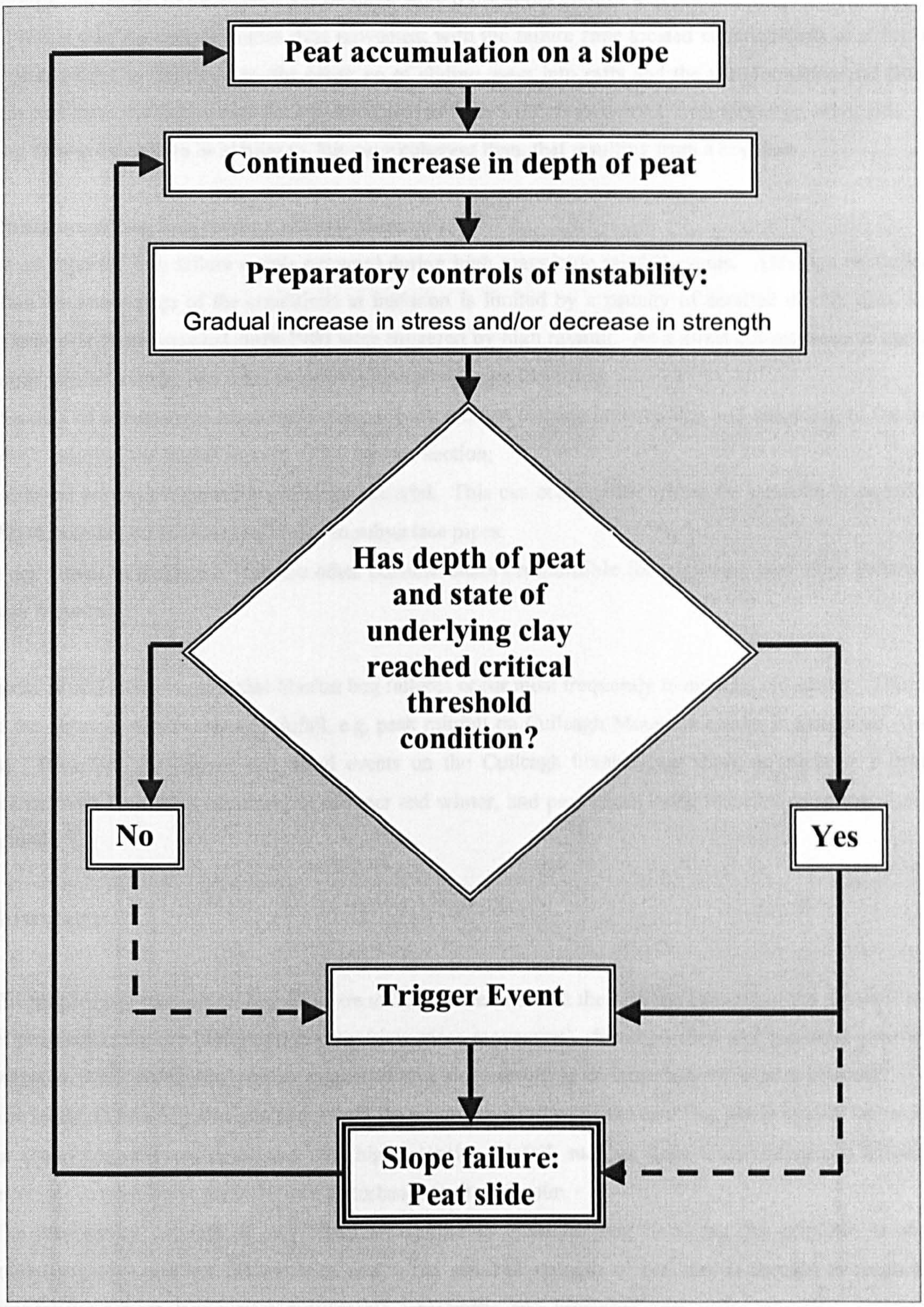
The occurrence of slow mass movements within the clay not only reduces the strength of the material but also disrupts the overlying peat layer and can lead to the formation of tears and cracks (Carling, 1986). As for all bog failures, the strength of the acrotelm and living vegetation layer are important in forming a strong, fibrous, protective crust on the slopes. The northern slopes of Cuilcagh Mountain have been subject to considerable human and agricultural activities. Intensive grazing, trampling and periods of uncontrolled burning result in the weakening and in some cases destruction of the living vegetation and acrotelm and therefore these areas are more susceptible to erosion and weathering processes. These activities can result in the lowering of the water table and subsequent intensified decomposition as a result of increased biological activity (Eggelsmann *et al.*, 1993) and can also lead to the formation of cracks. The development of cracks is also reported to result from short term desiccation during periods of reduced rainfall (e.g. Beven *et al.*, 1978). Cracks within the peat have often been reported to contribute to the occurrence of peat slides (e.g. Carling, 1986; Acreman, 1991; Warburton and Higgitt, 1998), their role being to allow rapid access of rainwater to the relatively impermeable clay beneath the peat causing high pore water pressures. Standing water in cracks is reported to exert a lateral, hydrostatic pressure to the peat downslope of the crack, particularly if the peat is undersaturated (Wilson and Hegarty, 1993). Cracks would also facilitate the process whereby the input of purer water reduces the electrostatic bonding within the clay (Selby, 1993).

The effects of high pore water pressure and artesian conditions as a result of sub-surface pipes are described in section 5.7 with reference to peat slide N4. The likelihood of similar effects contributing to the occurrence of other peat slides on the northern slopes of Cuilcagh Mountain is high as the underlying till was found to have the same physical characteristics at a more recent failure (NW10). The maintenance of high water tables on the slopes throughout the year provides conditions necessary for failure to occur.

The possible events leading up to a peat slide are shown in Figure 6.10. This cycle of events is similar to that describing bog flow failures (Figure 6.7). However, there are two main differences. Firstly, for peat slides, the depth of the peat layer (and not the development of the diplotelm) is important in producing an overburden pressure. More significantly, the emphasis is on the state and condition of the underlying clay as opposed to the catotelm. The cycle begins with the development and growth of peat on a slope. Alterations to the strength of the clay over time due to slow mass movement and weathering processes gradually reduce F. At this stage, it is questionable whether a trigger event, such as channel undercutting and subsequent unloading of the slope, could lead to slope failure before the slope is in a critical condition. It is more likely that failure would occur in response to a trigger event once the slope had attained an actively unstable condition. Although there is no field evidence on Cuilcagh Mountain, it is possible that progressive failure of the underlying clay may initiate slope failure without a trigger event occurring. Table 6.2 shows the possible factors responsible for preparing a slope for a peat slide on Cuilcagh Mountain.

For transitional bog slides to occur, the presence of an impermeable layer, or more resistant material overlain by less resistant peat is required to produce a slide plane for the material to fail along within, or at the base of the peat layer. Although there is no evidence of a distinct shear plane at failure sites N1 and NW5 (due to

Figure 6.10 Flow diagram illustrating the possible events leading to a peat slide type failure



weathering), the nature of the scars suggests these were transitional failures and possibly bog slides (see section 3.1.2). If this was the case, an initial slide movement with the failure zone located either towards or at the base of the peat, would be followed by the break up of sliding mass into rafts and the transformation and flow of catotelm peat from the failure scar (as it is disturbed) to form a debris flow-track with levees on either side. The resulting flow is thought to be similar to, but more coherent than, that resulting from a bog flow.

6.2.3 Initiation of bog failures on Cuilcagh Mountain

Almost all reported bog failure events occurred during high magnitude rainfall events. Although on Cuilcagh Mountain the knowledge of the conditions at initiation is limited by a paucity of detailed rainfall data, those events known to have occurred since 1980 were triggered by high rainfall. As a direct consequence of the high magnitude rainfall events, two main associated mechanisms are identified:

1. Flooding of streams and accelerated channel bank erosion causing undercutting and unloading of the slope which removes the lateral support of the upslope section;
2. Increased pore water pressure within the material. This can occur either within the catotelm or underlying clay depending on failure type, or due to subsurface pipes.

These are shown in Table 6.3 with the other possible factors responsible for triggering peat slope failures on Cuilcagh Mountain.

Alexander *et al.* (1986) suggest that blanket bog failures occur most frequently in autumn and winter. This may reflect the seasonal distribution of rainfall, e.g. peak rainfall on Cuilcagh Mountain occurs in December (Gunn, 2000a). However, the known and dated events on the Cuilcagh blanket bog show no signs of a distinct seasonality, with bog flows occurring in summer and winter, and peat slides being recorded in spring, summer and autumn.

6.3 SUMMARY

1. The preparatory controls on *bog flows* are mainly concerned with the reduced strength of the peat as a result of progressive failure (deformation creep/slow mass movement), decomposition and increased pore water pressure. Also, continuing peat accumulation on a slope results in an increased overburden pressure.
2. The initiation of a *bog flow* can occur from the progressive failure of the catotelm, but is usually the result of an actual trigger event associated with high intensity rainfall, such as slope undercutting and unloading, increases in pore water pressure, or a disturbance to the acrotelm.
3. The preparatory controls of *peat slides* are similar to those for bog flows but the emphasis is on the underlying clay and not the catotelm peat. The reduced strength of the clay is thought to result from progressive failure (slow mass movement), weathering and increased pore water pressure. Continuing accumulation of the overlying peat layer also results in an increased overburden pressure.
4. Although it is possible that *peat slides* may result from the progressive failure of the underlying clay, an actual trigger event is thought to be usually required to initiate slope failure. Again, this is usually in the form of a high intensity rainfall event causing increased pore water pressure and possible slope undercutting and unloading.

Table 6.3 Possible factors responsible for triggering peat slope failures on Cuilcagh Mountain.

	Bog flows	**Peat slides**
Slope Geometry	▪ Undercutting by a river; ▪ Disturbance to acrotelm.	▪ Undercutting by a river;
Geotechnical controls	▪ Increase in pore water pressure within the basal peat;	▪ Increase in pore water pressure within peat and clay.
Hydrological controls	▪ Increase in pore water pressure in subsurface pipes.	▪ Increase in pore water pressures in subsurface pipes.

CHAPTER 7

CONCLUSIONS

7.0 INTRODUCTION

This project was initiated to investigate a phenomenon that had not previously been subjected to detailed investigation, and therefore contributes the first integrated study of the stability of slopes in peatlands. A variety of types of slope failure in peatlands have been reported in literature, differing in mechanisms and magnitudes and offering a suite of contrasting destabilising factors to explain their occurrence. Many of these accounts are purely descriptive with only vague suggestions of mechanisms and causes. This study was developed to integrate research on slope instability with the variable properties and characteristics associated with peat and hence to provide an improved understanding of the controls and mechanisms of blanket bog failures. This was carried out by studying the different types of slope failure on Cuilcagh Mountain blanket bog in north-west Ireland. Cuilcagh Mountain has been described as one of the best examples of a blanket bog ecosystem in Northern Ireland (Gunn, 1995). Field observations and literature have also indicated that Cuilcagh Mountain is representative of other upland blanket bogs in Ireland. Hence, research concerning hillslope failure in this area has wide applicability.

This chapter presents the conclusions of the research and assesses the stability of the Cuilcagh peat with the consideration of continuing peat accumulation on the blanket bog slopes. The implications of these findings for peatland evolution and the management and restoration of blanket bog environments are then discussed.

7.1 CONCLUSIONS OF THIS RESEARCH: CONTROLS AND MECHANISMS OF BLANKET BOG FAILURES

The major aims of the project were to determine the hydrological and geotechnical properties of the Cuilcagh peat, use slope stability analysis to determine the controls on the failure of peatland slopes, to study and gain a better understanding of the mechanisms of failure, and to assess the importance of bog failures in the development of blanket bog on Cuilcagh Mountain. The findings of this research, relating to the specific objectives stated in section 1.6, are as follows:

1. **To map and describe the morphometry of the peat slope failures on Cuilcagh Mountain and to determine the likely mechanisms of failure.**

A total of 47 failure scars were identified on Cuilcagh Mountain blanket bog with the use of aerial photographs. Detailed field investigations revealed two main types of peatland slope failure on Cuilcagh, which are characterised by morphology and reflect the failure mechanism involved. At least 60% of the failures were shallow translational peat slides associated with the failure of clay underlying the blanket peat. Peat slides were more prevalent on the steeper northern slopes that are blanketed with up to 1.5 m depth of peat. These failures were usually characterised by a bare, striated clay failure scar and a clearly defined depositional area that consisted of transported rafts of coherent peat at the foot of the slope. Bog flows were found exclusively on the deeper areas of peat on East Cuilcagh. The failure zone for bog flow failures is located within the peat layer itself. The mechanism of failure is complex as a result of the diplotelm characteristics. During failure, the catotelm peat is thought to behave as a slurry-type plastic flow with the over-riding fibrous acrotelm breaking up into rafts and acting as rigid blocks in the failing mass. Large areas of subsided and cracked bog at the margins of the failure scar, crescent-shaped rafts of acrotelm peat and well defined flow tracks with levees comprising deposited rafts characterised bog flow sites. It is also possible that two failure scars on North Cuilcagh may have been bog slide failures as they contain similar morphological characteristics to both peat slides and bog flows. The failure mechanism in this case would be an initial sliding movement of the peat mass between the basal peat and the underlying clay which is thought to result in disturbance to the humified catotelm peat and the transformation of the failing peat mass into a flow-type mechanism.

2. To determine the magnitude and frequency of failure events on Cuilcagh Mountain.

The magnitudes and frequencies of bog failure events on Cuilcagh Mountain are highly variable. Between 1981 and 1991, an estimated total of 54,700 m^3 of peat was moved in 18 failure events, while between 1991 and 2001, an total of 45,200 m^3 of peat was moved in just 5 slope failures. This difference in magnitude of bog failures is a reflection of failure type. Peat slides occurred most frequently during the 1980's and disrupted relatively small areas of bog (average volume of 3,000 m^3), whereas bog flows occurred mostly between 1991 and 2001and tended to be larger in scale (average volume of 16,000 m^3) but were more infrequent events. It has been estimated that in total the failure events identified on Cuilcagh Mountain involved the movement of over 300,000 m^3 of peat.

3. To investigate the physical properties of the blanket bog peat and how these vary with depth from the surface.

It has been demonstrated that the physical properties of the Cuilcagh peat (degree of humification, bulk density, organic content and field moisture content) vary vertically within the bog, and also horizontally over small distances. The transition between the acrotelm and catotelm is not a distinct boundary, but occurs over approximately 20 cm forming a transition zone. It was also noted that some of the physical properties of the deep bog peat on East Cuilcagh displayed some different characteristics to the shallower depths of peat found on the northern slopes of Cuilcagh. This is thought to result from differences in the botanical composition of the peat, which is related to topography and hydrological conditions, and to differences in land use practices in these two areas. The vegetation cover on the steeper northern slopes of Cuilcagh consists mainly of heather and grass species. Consequently, a thin layer of fibrous peat blankets these slopes. On East Cuilcagh, the low gradient slopes are mainly dominated by *Sphagnum* mosses which generate peat relatively quickly and are broken down more easily without leaving as much of a fibrous root structure, facilitating the accumulation of blanket bog up to 2.5 m in depth. More intensive grazing pressures and the occurrence of uncontrolled burning in the past on North Cuilcagh and some north-western slopes were thought to cause differences in bulk density, organic content and field moisture content, in comparison with the more undisturbed sites on East Cuilcagh.

4. To investigate the hydrological and geotechnical properties of blanket bog peat and assess how these vary with depth from the surface.

Investigations into the hydrological properties of blanket bog peat have given an indication of water levels in a pristine bog slope and an area disturbed by a failure event, and have allowed the comparison between field and laboratory values of hydraulic conductivity. Water levels in an undamaged bog slope, i.e. not disrupted by a failure event, were usually within 5 cm of the surface. However, lower and less fluctuating water tables (up to 13 cm below the surface) characterised areas of deep peat at shallow gradients. Drainage of the peat mass up to 15 m upslope of failure scars resulted in variable water tables, typically of the order of 15 and 40 cm below the surface. Field determinations of hydraulic conductivity (k) using piezometers varied over three orders of magnitude from 10^{-6} cm/s in the lower acrotelm and upper catotelm to 10^{-9} cm/s in the lower catotelm. Most of these values were found to be approximately two orders of magnitude lower than the laboratory determined hydraulic conductivity, although both measurements illustrated a similar pattern of decreasing k with depth through the peat profile. It is usually assumed that peat is hydraulically anisotropic, with horizontal permeability exceeding the vertical, given the nature of peat accumulation (e.g. Hobbs, 1986). However, laboratory determinations of vertical hydraulic conductivity exceeded horizontal values at all depths. This indicates a less significant role for the supposed aelotropic (banded) nature of blanket bog peat at the sites tested which is usually thought to cause hydraulic anisotropy. Hydraulic conductivity was found to be most variable within the root mat and acrotelm, with laboratory values ranging from 10^{-2} to 10^{-5} cm/s in the upper 40 cm of the peat profile.

The consolidation and shearing behaviour of the Cuilcagh peat has provided evidence of the differences in geotechnical properties of peat found in the acrotelm and the catotelm. The magnitude of settlement of the peat samples ranged from 5 to 28% of sample thickness with loads of between 10 and 40 kPa. Samples of acrotelm peat exhibited higher degrees of consolidation (mainly during the primary stage) than the samples from the catotelm, reflecting the higher proportion of intracellular (free) water in the acrotelm. However, as with the other properties there was notable variability in apparently uniform peat. Very few studies have been carried out on the shear behaviour of blanket bog peat, particularly humified peat. Surprisingly, it was found that samples of peat from the fibrous acrotelm displayed similar strength behaviour to the decomposed amorphous peat from the basal catotelm, only the latter exhibited slightly lower values of cohesion. Although some natural variability was noted throughout the peat profile and horizontally over small distances, the majority of the Cuilcagh peat samples had cohesion values around 3.0 to 4.6 kPa, and internal friction angles of approximately 30°. However, there was evidence of plastic deformation, as opposed to shear failure along a distinct plane, on a number of basal catotelm and clay samples. Fibres within the peat matrix had the effect of initially acting as a reinforcement (resistance to shear) before either being pulled to their limit or sheared during failure. This behaviour was not restricted to the fibrous acrotelm, but was also detected in samples from the lower catotelm, highlighting the importance of fibres for providing considerable strength to the peat mass.

5. To model the stability of the blanket bog slopes on Cuilcagh Mountain using the determined geotechnical and hydrological properties of the peat.

The calculated Factor of Safety (F) using limit equilibrium analyses (SLOPE/W) on a number of modelled failed peat slopes on Cuilcagh Mountain ranged from 1.1 to 2.0, indicating marginally stable or stable slope conditions. A number of factors have been identified as possibly causing over-estimations of F. These are: (i) the use of unrepresentative strength parameters (given that the actual behaviour of peat under the influence of changing stresses is not known and the mechanism of failure is thought to be deformation as opposed to shearing along a distinct plane); (ii) an implicit assumption within the model that each material is uniform and homogeneous throughout, or (iii) the fact that a temporary alteration to the material properties (e.g. increase in pore water pressure) may have been sufficient to cross the failure threshold.

A quantitative assessment of the variables used in the stability modelling was carried out using a sensitivity analysis. The most critical variables for lowering F for both bog flows and peat slides are reductions in cohesion and increases in material depth and slope angle. Small decreases in the water table are noted to produce a large increase in F. This suggests that the slope would be most susceptible to failure if the water table is at least at the surface; as peatlands are characterised by near saturated slopes, this is a common occurrence. However, the sensitivity analysis when applied to bog flow failures shows an unusual relationship between effective angle of internal friction and F, with a decrease in friction leading to a small increase in F. This is thought to be a mathematical artefact of the model arising from the unit weight of the saturated peat being less than the unit weight of water.

6. To establish whether conventional methods of slope stability analysis are suitable for blanket bog environments.

Although the stability analysis using the SLOPE/W model did not represent expected conditions, i.e. slope instability ($F<1.0$), it can be argued that for the peat slide failures, the results were close enough to be accounted for by the factors identified and therefore, conventional methods of slope stability analysis are adequate for use on this form of bog failure. However, as a result of differences in the mechanism of failure (deformation as opposed to shear) and the unrealistic relationship between the effective angle of internal friction and F used in the infinite slope model, it is thought that conventional methods are not suitable for analysing slopes prone to bog flows.

7. **To investigate the geotechnical and hydrological controls and identify the various destabilising factors (preparatory, triggering and controlling) involved in converting the blanket bog slopes to an actively unstable condition.**

The results of the investigations into the physical, hydrological and geotechnical properties of the Cuilcagh peat, together with the slope stability modelling, have given an indication of the variability of blanket bog peat and the sensitivity of these environments. These results indicate the most important preparatory control contributing to the occurrence of bog flows is the reduced strength of the catotelm peat. This can result from progressive failure (deformation creep/slow mass movement), decomposition and humification, and increased pore water pressure. In addition, the role of continuing peat accumulation on a slope, resulting in an increased overburden pressure, is thought to be important in contributing to the reduced stability of a slope. It appears that initiation of bog flows can occur from the progressive failure of the catotelm, but there is more evidence to suggest that flows are more frequently initiated as a result of a specific trigger event usually associated with high intensity rainfall. Trigger events thought to be most likely to produce rapid decreases in the stability of the East Cuilcagh slopes are slope undercutting, increases in pore water pressure, and a disturbance to the acrotelm. Previously, it had been thought that the controlling factor in this type of failure was an inflow of water into the peat layer leading to the subsequent loss of the contained water in the form of a bog flow (Bishopp and Mitchell, 1946; Bowes, 1960; Colhoun *et al.*, 1965). However, analysis of the Cuilcagh peat has shown that it is the reduced strength of the peat itself that is most important in transforming the slope into an actively unstable condition.

The preparatory controls on the failure of slopes in the form of peat slides are thought to be similar to those for bog flows, but the emphasis is on the underlying clay and not the catotelm peat. Reduced strength of the clay may result from progressive failure (slow mass movement), weathering and increased pore water pressure. Although the peat layer has a more passive role in peat slides, as actual failure occurs within the underlying clay, the effect of an increasing overburden pressure from the accumulating peat mass is considered important in reducing the overall stability of the slope. Like bog flows, it is possible that peat slides may be activated without an external disturbance. This can occur as a result of progressive failure and/or weathering of the underlying clay beneath the accumulating peat mass. However, a specific trigger event is usually required to initiate slope failure. Again, this is usually in the form of a high intensity rainfall event that triggers slope instability either directly by increasing pore water pressures within the clay, or indirectly from associated slope undercutting. Other key factors in contributing to instability in areas prone to peat sliding are the presence of transverse drainage ditches, tines and subsurface pipes which lead to increased pore water pressure.

7.2 PEATLAND EVOLUTION

This section discusses the implications of the research findings for the evolution of the Cuilcagh Mountain blanket bog and includes an assessment of the susceptibility of the slopes to mass movement. These results then provide an indication of the importance of bog failure events for peatland development in general.

7.2.1 Importance of failures in the development of the Cuilcagh Mountain Blanket Bog

The magnitude and distribution of failures identified on Cuilcagh Mountain reflect the extent and occurrence of bog failure events in the peatland. The resulting 'patchwork' effect on the bog surface created by recovering failure scars, together with the disruption caused by land use practices, further highlights the importance of mass movements in the development of the Cuilcagh blanket bog.

The two distinct types of failure, peat slides and bog flows, are not confined to steep slopes or marginal areas of bog, as suggested by Tallis (1965b), but appear to be an integral part of the natural evolution of peatland environments. Given the preparatory controls and likely trigger events identified in section 7.1, the slopes on Cuilcagh Mountain most susceptible to bog flows appear to be those with a low gradient on East Cuilcagh, where the greatest depths of peat have developed. Slopes that are undercut by a river are considered most prone to failure. Peat slides occur on the steeper slopes of Cuilcagh Mountain, such as those found immediately north of the summit ridge. They occur where the peat is underlain by a layer of clay. The presence of drainage ditches and pipes in the clay have been critical in contributing to at least one recent peat slide (Dykes and Kirk, 2001). Undercutting by rivers or dissecting by transverse drainage ditches can cause unloading of a slope section which therefore increases the risk of peat sliding.

During the 1980's there were two bog failures per year on average, compared with an average of one every two years in the 1990's on Cuilcagh. Using the data for this entire 20 year period (1981 to 2001), the frequency is just over one failure per year. The presence of several re-vegetated scars containing up to 45 cm of accumulated peat indicates that bog failures have been occurring on Cuilcagh Mountain for the last few hundred years, although these have not been dated. A total of 27 failure scars were identifiable on the 1981 aerial photographs, but only 18 of these were completely re-vegetated which suggests that although failure events occurred on Cuilcagh prior to the 1970's, they were less frequent.

Although it has been estimated that a total of over 300,000 m^3 of peat have been involved in failure events, much of this material was redistributed, as opposed to removed from the bog. Material transported during peat slides was usually confined to within a few hundred metres of the failure scar. In contrast, during flow type failures, the majority of the rafts of acrotelm and upper catotelm (0.6 to 1.0 m in depth) remained in the proximity of the scar but others, together with large amounts of catotelm peat slurry, were transported down river and deposited along the river corridor. In the case of the 1992 bog flow (E2) on the Owenbrean river, the volume of peat slurry together with the river water caused much disruption as it flooded through the Marble Arch Cave system, leaving a thick peat deposit throughout the show caves. In comparison with the failure scar, the deposited catotelm from E2 was noted to re-vegetate relatively quickly. The eventual re-vegetation of both peat slide and bog flow failure scars results in the re-accumulation of peat on the slope, indicating the cyclic nature of these events in the evolution of the peatland.

7.2.2 Importance of failures in peatland development

All peatlands are dynamic and sensitive systems. It has been demonstrated that bog failures are widespread on the Cuilcagh Mountain blanket bog and form an integral part of the peatland. Evidence from numerous reports indicates that they are also a common feature of other areas of upland blanket bog in Ireland (e.g. Colhoun *et al.*, 1965; Tomlinson and Gardiner, 1982) and Britain (e.g. Bowes, 1960; Acreman, 1991). In many of these areas several recovering failure scars have been identified (e.g. Mitchell, 1938; Bishopp and Mitchell, 1946; Alexander *et al.*, 1985, 1986) further highlighting the importance of mass movements and the cycle of events (erosion, re-vegetation and peat accumulation) on slopes as part of the evolution of blanket bog environments.

Many peat slides have been reported in the English Pennines (e.g. Crisp *et al.*, 1964; Carling, 1986; Warburton and Higgitt, 1998). The mechanisms and controls of these slides are thought to be similar to those identified for the peat slides on the northern slopes of Cuilcagh Mountain. Failure occurs on slopes with an accumulating peat mass, which are underlain by clay, in response to alterations to the clay that reduce its strength. An external factor, usually associated with a high intensity rainfall event, is normally required to initiate slope failure. Bog flows occur in areas of deep peat, and are therefore generally confined to gentle blanket bog slopes (mainly in Ireland) and the few raised bogs that remain with their natural depth of catotelm. It is thought that bog failures are less frequent in blanket bogs in Britain compared to Ireland as a result of differences in peat accumulation rates. For example, in some areas of the Southern Pennines, peat accumulation has ceased and the bog is actively eroding. The reduction in peat depth increases the stability of the slope and therefore decreases the likelihood of slope failure.

Various theories have been suggested for the overall cause and timing of the onset of blanket bog erosion (i.e. the removal of peat by any geomorphic process) in Britain and Ireland, including: (i) a climatic change (either as a result of slowing peat accumulations or erosion through increased storminess) (e.g. Conway, 1954; Bower, 1962); (ii) the intrinsic properties of the peat mass causing instability once a critical depth is reached (e.g. Bower, 1961; Tallis, 1965a); (iii) human interference (grazing, burning, pollution) (Bowler and Bradshaw, 1985). Bowler and Bradshaw (1985) and Bradshaw and McGee (1988) established that in Ireland there have been significant accumulations of blanket peat in last 150 years, and concluded that erosion is an integral part of the blanket bog system under the present climate. Like many other authors (e.g. Mitchell, 1938; Bower, 1962; Tallis, 1995), they suggest that erosion occurs as the natural end-point to peat development, i.e. once a critical depth for the given slope angle is reached. It has been demonstrated in this thesis that on Cuilcagh Mountain the relationship between slope angle and material depth is complicated by the changing nature of the slope materials (clay and peat). This occurs as a result of time-dependent and irregular processes such as weathering, deformation (slow mass movement) and the non-uniform process of organic decomposition. The reduced strength of the material acts as a constraining factor limiting peat depth on the slopes. Therefore, it is thought that the stability of the peat mass is dependent on the 'critical depth' of the peat, which is determined not only by slope angle but also the variable processes that alter the strength of the material over time.

7.3 MANAGEMENT AND RESTORATION

Most bog failures are natural events in the evolution of blanket bogs. However, it appears that human interference can increase susceptibility to failure, as over-grazing and burning reduce the strength of the acrotelm. More importantly, the presence of drainage ditches, peat cut scarps and machine-cut tines have been reported to contribute to bog failures (e.g. Sollas *et al.*, 1897; Tomlinson, 1981b; Carling, 1986; Alexander *et al.*, 1985). Since the mid-1980's one of the major human impacts on areas of upland blanket bog has been the mechanised extraction of peat for fuel. On Cuilcagh Mountain, various attempts have been made to restore some of the mechanised cut-over areas since the mid-1990's. Although Alexander *et al.* (1985) attributed a bog failure to a high intensity rainfall event and the presence of machine-cut tines, to date no mass movements have been reported from restored cut-over areas. This section assesses the risk of bog failures in areas damaged by mechanised peat cutting and discusses the implications of the research findings for the management and restoration for blanket bog peatlands.

7.3.1 Mechanised Peat Cutting

Two methods have been employed for the mechanised extraction of peat on Cuilcagh Mountain. In the first, the surface vegetation and acrotelm are removed to expose the more calorific peat at depth prior to cutting, and in the second the vegetation is left *in situ*. In both cases mechanically incised tines (deep slits) are cut through the acrotelm to remove the basal peat. Each of these methods of peat extraction result in severe disturbance to the acrotelm. The weight and movement of the actual cutting machinery can also cause damage to the sensitive structure of the bog. On some parts of Cuilcagh a dense network of drainage ditches was excavated prior to the mechanised extraction in an effort to dry out the bog.

Machine cut tines have been noted to open up due to the natural swelling of the bog (mire-breathing), but more importantly they are thought to facilitate the rapid transfer of rainwater to the lower layers of the bog and can act as lines of weakness if cut across the slope. The latter two factors were considered important in the failure of a slope in south-west Leitrim (Alexander *et al.*, 1985). However, it seems likely that once cutting has ceased and a considerable amount of the basal catotelm peat has been removed from a depth of bog, much of the internal stress within the peat mass has been removed, leading to increased stability. Theoretically, areas more at risk to failure are slopes which have been affected by the movement of heavy cutting machinery, as disturbance and in some cases the complete destruction of the living vegetation layer occurs where no peat has been removed. Evidence has been presented for the failure of slopes in areas of deep peat without the occurrence of an external disturbance. Therefore, those slopes which contain their natural depth of (catotelm) peat and have undergone disturbance to their protective acrotelm (and possibly further alterations to the structure of the underlying catotelm as a result of machinery vibration) are thought to be more susceptible to failure in the form of a bog flow.

The most intensively mined area of bog on Cuilcagh Mountain was in Legnabrocky Townland where the surface vegetation was removed and over 7 km of drainage ditches excavated, giving a drainage density of 465 m/ha compared to 86 m/ha in the natural catchment (Walker, 1998). This area has been leased by Fermanagh District Council and is included in the CMP. Peat cutting has been stopped and dams installed at regular intervals along most of the ditches in an effort to reduce stormflow and raise the water table. There was concern that an increased water level as a result of the damming and subsequent changes in vegetation would lead to increases in pore water pressure, thereby reducing the effective strength of the structurally altered peat. However, results from this thesis indicate that removal of much of the basal catotelm peat will promote stability of the cut-over areas. Hence, it is considered unlikely that this area of restoration is at major risk from bog failure events, particularly as there are few transverse drainage ditches and the re-vegetation of the area is being encouraged to once again form an intact, protective acrotelm layer.

7.4 RECOMMENDATIONS FOR FURTHER RESEARCH

This study has identified key factors that contribute to hillslope failure in blanket bog peatlands. In many areas, bog failures are not considered a hazard since they rarely affect humans. However, much of the bog on North Cuilcagh (and some on East Cuilcagh) lies within the catchments that drain into the Marble Arch Cave system. Hence it may be advisable to undertake further modelling to enable more detailed risk assessments to be performed on the tributaries of the three rivers that drain into the public show cave at Marble Arch Caves. The identification of slopes most susceptible to bog failures would enable the development of more accurate warning systems to be placed in the areas most at risk from failure events. Detailed risk assessments and hazard mapping of the Cuilcagh bog should be based on the preparatory controls and triggering events identified in this thesis and involve the study of slope geometry, sedimentology, topography, and peat characteristics. The presence of a marked break of slope, slope undercutting and degraded transverse drainage ditches have also been significant in promoting instability in peatlands. This approach may then be carried out in other peatland areas that are thought to be prone to bog failures and pose a threat of disruption to human populations.

This study has highlighted the importance of the catotelm peat in bog flow failure events and its role in the failure of peat masses. However, further research concerning the characteristics of humified peat prior to, and during failure is required to gain a full understanding of the behaviour of this material. There is also a need for a comprehensive study of the relationship between the botanical composition of peat and its shear strength at different stages of decomposition. There is much scope for the latter as the characteristics of peat strongly reflect the peat-forming vegetation and the environment in which it has accumulated. Within the Cuilcagh Mountain blanket bog, peat properties varied over small horizontal distances as a result of topography and surface hydrology (e.g. hummocks of grasses and pools containing *Sphagnum* mosses). Detailed studies of the properties of other blanket bog and raised bog peats are required to ascertain the variability of peat and the relationship between botanical composition, geotechnical behaviour and degree of humification. On a global scale, investigation of the properties of peat from different peatland types e.g. fen peat or Canadian Muskeg, is necessary before a full understanding of the behaviour of this variable material is achieved.

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APPENDIX 1

Failure Types

The major classes of slope mass movement (after Nash, 1987) are: falls, slides flows, and creep and are discussed Chapter 2 and included in Table 2.4. Details of each of these are given below.

Falls are abrupt free-fall movements of material away from steep slopes such as cliffs (Hansen, 1984). The materials are usually described as moving en masse and can involve rock, soil and debris. Related to falls are topples, which consist of a forward movement about some pivot point or hinge on a hillslope (Dikau *et al.*, 1996). These are rapid to very rapid events.

Slides are movements of material along recognisable shear surfaces and can be translational or rotational in nature. The failure surface of a translational slide is usually located on a planar slip surface, frequently along a pedological or geological discontinuity. They are characteristic of slopes made up of largely frictional material, where increasing shear strength with depth prevents more deep seated failures (Hutchinson, 1968). Translational slides are the most common form of landslide/mass movement in soils and nearly always occur during heavy rain (Selby, 1993). These slab slides are typically rectangular or triangular in plan view and have an arcuate, vertical back scar which degrades with time to a lower angle. Rotational slides involve a rotational movement of the soil mass over a curved failure plane. Failures of this type can develop as single, multiple, or successive slides and are also known as slumps. Deep seated rotational failures can occur in cohesive soils where shear stress is zero at ground surface and increases linearly with depth (overburden). Increases in shear strength with depth occur at a slower rate, therefore at a critical depth, shear stress exceeds shear strength and failure is possible (Selby, 1993).

Flows behave as fluidised masses (Dikau et al., 1996), whereby intergranular movements predominate over shear surface movements (Hansen, 1984). Depending on the classes of material involved, the terminology commonly used for flow-type failures include 'debris flow', 'earthflow' and 'mudflow'. Debris flows are associated with the movement of coarse granular solids mixed with minor amounts of clay, entrained water and air (Varnes, 1958; Johnson & Rodine, 1984), whereas Schrott *et al.* (1996) uses the terms 'earthflow' and 'soil flow' to describe flow mechanisms with a significant lack of coarse grained substances. The tendency for these types of failures to develop may be accentuated by the following factors (Selby, 1993): remoulding of clays during landsliding; the presence of clays with high liquid limits in areas of high rainfall; the presence of clays with low liquid limits in areas of low rainfall; soils with open fabrics resulting from flocculation during deposition; thawing of soil ice; or undrained loading. A characteristic of many flow failures is the ability to travel great distances over very low slopes, often following pre-existing drainage channels.

Complex failures such as flow-slides or slump-earthflows are principally a combination of two or more types of mass movement as there is a change in the behaviour of the material as it moves downslope. This is distinguished from a compound failure, which consists of more than one type of movement from the onset, for example a rotational-translational slide (Dikau et al., 1996).

Creep is defined by velocity, owing to the slow nature of movement (Hansen, 1984) but also differs from sliding failures by means of process. There are three types of creep processes common to mass wasting: particle creep; depth creep; and soil creep (Selby, 1993). Particle creep involves the movement of single particles over an exposed bedrock or soil surface mainly by freeze-thaw activity. Depth creep describes very slow, but continuous movements, which affect the main body of material (including rock) above the zone of deformation (Selby, 1993). Soil creep is the slow downslope movement of superficial soil and rock debris and can be attributed by a number of mechanisms. Seasonal soil creep which is affected by changes in soil moisture and temperature, results in expansion and contraction of the soil (either by freeze-thaw or wetting and drying processes). Other processes such as the activity of soil animals and plant roots may also be important (Selby, 1993).

APPENDIX 2

Determination of shear strength: Laboratory and field methods

Laboratory methods

Direct shear, ring shear and triaxial apparatus can be used in the laboratory determination of shear strength. A brief summary of this equipment and the methods used are given below.

Direct shear test

The direct shear equipment consists of a square box split horizontally at the level of the centre of the sample. The sample is held between metal and porous plates and a normal stress is applied by a vertical load. A horizontal force is applied to the lower section of the box at a constant rate until the sample fails. As this occurs, the shear load is divided by the cross-sectional area of the sample to give the shearing stress (Selby, 1993). Values for c' and ϕ' can then be determined from a graph of samples tested at different normal stresses. This apparatus also measures changes in volume during consolidation and shearing. Although this test is relatively quick and straight forward to perform, there are a number of drawbacks with the method: it is difficult to install undisturbed sample into the apparatus; the stress distribution across the sample is complex; failure only occurs along a plane dictated by the design of the apparatus; the area under shear reduces during the test; and there is no direct control over drainage conditions in the sample (Petley, 1984). Shear strength values obtained from direct shear apparatus can, however, be fully acceptable for use in stability analysis provided uncertainties are identified and taken into account during the interpretation.

Ring shear test

The ring shear test uses a split annular ring shaped sample container which is similar in principle to the shear box. The lower half of the ring is rotated, while the upper half reacts via a torque arm so displacement can be measured (Selby, 1993). Although this test is prone to the same problems associated with sample extraction and installation, it has two main advantages over the shear box: there is no change in cross-sectional area of the shear plane during the shear stage; and samples can be sheared through an uninterrupted displacement of any magnitude (Selby, 1993).

Triaxial compression test

In this test, the apparatus consists of a cylindrical sample enclosed in a rubber membrane, contained within a flooded perspex cell. Tests may be carried out under different conditions of drainage, e.g. porous plates can be used for a drained (slow) test, and drainage can be prevented if an undrained (quick) test is required. A measured pressure head is applied to the water to simulate confining pressure and a vertical load is applied at a constant rate until the sample fails (Selby, 1993). The recorded principle stresses are plotted on a graph using Mohr-circle procedure, enabling values of c and ϕ to be calculated. Although the triaxial test allows the complete control of pore water conditions, the cross-sectional area of the tested sample is difficult to estimate, and uncertainties can arise over confining pressure (Selby, 1993).

Field Methods

The main types of shearing apparatus used in the field determination of shear strength consists of a field penetrometer, shear vane and the direct *in situ* shear box.

Penetrometer

The Vicksburg penetromer is popular among geomorphologists and consists of a long rod tipped with a cone at one end and a proving ring handle at the other (Petley, 1984). As the cone is pushed into the soil, the compression of the proving ring indicates the resistance to penetration. This is a useful indicator of bulk density, bearing capacity and usually shear strength can be calculated by means of standard equations given by Terzaghi (1943).

Shear vane

The shear vane consists of four blades set at right angles to each other and mounted on the end of a stainless steel rod. The vane is pressed into the soil until at the required depth. A torque is then applied to the shaft, and increased until, at a maximum value, the soil shears along a cylindrical surface enclosed at depth by the vane. The total shear strength may then be calculated using the calibrated spring. This method has a number of advantages: it is relatively straight forward and quick to perform; it is relatively light weight to transport in the field; it can be used to indicate degree of anisotrophy within a material; it can be performed at any depth; and it causes minimal disturbance to vegetation. However, this method is usually only successfully used on fine grained soils without roots, clasts, or strongly developed structures, and are only used to determine total stresses, i.e. they cannot provide independent values of c' and ϕ' (Selby, 1993). The field shear vane can also be used to calculate residual strength. The vane is rotated rapidly through several rotations, until the material becomes remoulded and residual shear strength can be determined. From this, the sensitivity of the material can be calculated (peak divided by residual strength). However, these results are not directly comparable with laboratory sensitivity results as the degree of disturbance differs according to the technique used (Terzaghi and Peck, 1967).

Direct shear *in situ*

A field shear box may be used to determine the shear strength of large intact *in situ* samples, in which preservation of the natural condition of the soil is important, and also to assess the contribution of plant roots to strength. This test involves the shear box being erected around a block of soil prepared in a pit. Normal stress and horizontal shear force are then applied with the use of kentledge and hydraulic jacks (Petley, 1984).

Other apparatus for measuring *in situ* soil strength includes the pressuremeter and the bore-hole shear device. The pressuremeter is a device which is inserted into a borehole and expanded laterally allowing the load-deformation characteristics to be determined. The bore-hole shear device contains an expandable head with two plates which enable a normal stress to be applied and the soil on the sides of the bore-hole to be sheared (Selby, 1993). Pore water pressures during shearing can also be measured. The widespread use of these techniques is limited as they rely on the availability of boreholes.

APPENDIX 3

Saturated hydraulic conductivity: Field determinations using piezometer tubes

Using a formula derived from Darcy's Law, field hydraulic conductivity can be determined.

$$k = \frac{2.3\,\pi r^2}{A(t_2 - t_1)} \log_{10} \frac{h_1}{h_2}$$

(Dai & Sparling, 1973) (A3.1)

where: k = Hydraulic conductivity (cm/min).

r = Internal radius of the piezometer (cm).

A = Shape factor given as a geometric function which depends on the characteristics of the piezometer and chamber. In this case, A has been calculated from Young's (1968) determinations.

h_1 and h_2 = Height difference from original water table level (cm).

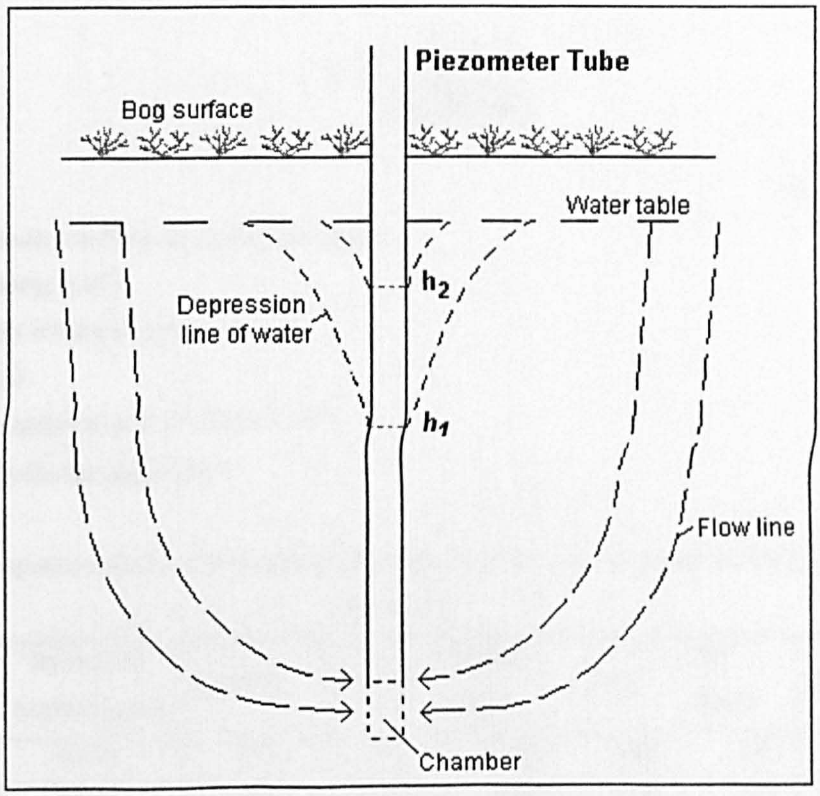
t_1 and t_2 = Time difference (mins) corresponding to h_1 and h_2.

Figure A3.1 illustrates the field equipment used in the determination of field k_{sat}.

Table A3.1 Components used in the determination of k_{sat} using piezometers on Cuilcagh Mountain.

Piezometer	r (cm)	A	h_1 (cm)	h_2 (cm)	t_1 (min)	t_2 (min)	Field k (cm/min)	Field k (cm/s)
A1	2.5	46.5	29.9	29.5	5	275	2.1×10^{-5}	3.5×10^{-7}
A2	2.5	46.5	23.4	21.7	5	120	2.8×10^{-4}	4.6×10^{-6}
A3	2.5	46.5	25.5	23.7	5	180	1.8×10^{-4}	2.9×10^{-6}
A4	2.5	46.5	16.1	14.4	5	120	4.1×10^{-4}	6.8×10^{-6}
B1	2.5	46.5	26.5	25.3	5	275	7.2×10^{-5}	1.2×10^{-6}
B2	2.5	46.5	36.8	35.9	5	11525	9.1×10^{-7}	1.5×10^{-8}
B3	2.5	46.5	19.9	18.7	5	30	1.0×10^{-3}	1.7×10^{-5}
B4	2.5	47.5	18.9	19.1	5	11525	-	-
C1	2.5	46.5	38.9	38.7	10	7180	3.0×10^{-7}	5.1×10^{-9}
C2	2.5	46.5	20.5	20.0	10	85	1.4×10^{-4}	2.3×10^{-6}
C3	2.5	46.5	18.1	12.7	10	1650	9.1×10^{-5}	1.5×10^{-6}
C4	2.5	49.0	13.3	12.5	10	175	1.5×10^{-4}	2.5×10^{-6}
D1	2.5	46.5	24.4	22.9	10	4330	6.2×10^{-6}	1.0×10^{-7}
D2	2.5	46.5	13.8	12.6	10	175	2.3×10^{-4}	3.9×10^{-6}
D3	2.5	46.5	14.8	13.2	10	115	4.6×10^{-4}	7.7×10^{-6}
D4	2.5	48.5	17.3	16.0	10	115	3.0×10^{-4}	5.0×10^{-6}

Figure A3.1 A piezometer tube used for the measurement of field hydraulic conductivity (after Dai & Sparling, 1973).



APPENDIX 4

Saturated hydraulic conductivity: Laboratory determinations using constant head permeameter apparatus.

Darcy's Law (Equation 2.2) states that hydraulic conductivity (k) is the discharge of water per unit area of the porous medium under a unit hydraulic gradient (Baird *et al.*, 1997). Using a formula derived from Darcy's Law, saturated hydraulic conductivity can be determined in the laboratory using constant head permeameter apparatus:

$$k = \frac{Q\,L}{t\,A\,(H_1 - H_2)}$$

(Klute, 1960) (A4.1)

where: k = Hydraulic conductivity coefficient (cm/s)

Q = Discharge (cm^3)

L = Length of sample (cm)

t = time (s)

A = Cross sectional area of sample (cm^2)

H_1-H_2 = Hydraulic head (cm)

Table A4.1 Components used in the laboratory determination of k_{sat} using samples collected from Cuilcagh Mountain.

SAMPLE	DEPTH OF SAMPLE (cm)	A (cm^2)	L (cm)	H_1-H_2 (cm)	t (s)	Q (cm^3)	k_{sat} (cm/s)
E2 (v)	40-45	17.4	5.0	20.5	3600	642	2.5×10^{-3}
E2 (v)	40-50	83.3	10.0	28.0	3600	497	5.9×10^{-4}
E2 (h)	40-50	83.3	10.0	28.0	3600	48	5.7×10^{-5}
E2 (h)	40-50	83.3	10.0	28.0	3600	113	1.4×10^{-4}
E2 (v)	80-90	83.3	10.0	28.0	3600	1573	1.9×10^{-3}
E2 (v)	80-90	83.3	10.0	27.4	3600	2177	2.7×10^{-3}
E2 (h)	80-90	83.3	10.0	28.0	3600	7	8.3×10^{-6}
E2 (h)	80-90	83.3	10.0	27.4	3600	0.13	1.5×10^{-7}
E6 (v)	40-50	83.3	10.0	28.0	3600	226	2.7×10^{-4}
E6 (v)	40-50	83.3	10.0	28.0	3600	268	3.2×10^{-4}
E6 (h)	40-50	83.3	10.0	28.0	3600	135	1.6×10^{-4}
E6 (h)	40-50	83.3	10.0	28.0	3600	62	7.4×10^{-5}
E6 (v)	80-90	83.3	10.0	28.0	3600	2120	2.5×10^{-3}

E6 (v)	80-90	83.3	10.0	27.4	3600	3203	3.9 x 10^{-3}
E6 (h)	80-90	83.3	10.0	28.0	3600	114	1.4 x 10^{-4}
E6 (h)	80-90	83.3	10.0	27.4	3600	20	2.5 x 10^{-5}
N4 (v)	30-40	83.3	10.0	27.4	3600	426	5.2 x 10^{-4}
N4 (v)	30-40	83.3	10.0	27.4	3600	193	2.4 x 10^{-4}
N4 (h)	30-40	83.3	10.0	27.4	3600	107	1.3 x 10^{-4}
N4 (h)	30-40	83.3	10.0	27.4	3600	235	2.9 x 10^{-4}
N4 (v)	70-80	83.3	10.0	27.4	3600	753	9.2 x 10^{-4}
N4 (h)	70-80	83.3	10.0	27.4	3600	195	2.4 x 10^{-4}
N4 (h)	70-80	83.3	10.0	27.4	3600	14	1.7 x 10^{-5}
NW5 (v)	50-60	83.3	10.0	27.4	3600	2014	2.5 x 10^{-3}
NW5 (v)	50-60	83.3	10.0	27.4	3600	4421	5.4 x 10^{-3}
NW5 (h)	50-60	83.3	10.0	27.4	3600	32	3.8 x 10^{-5}
NW5 (h)	50-60	83.3	10.0	27.4	3600	1.7	2.1 x 10^{-6}
NW5 (v)	115-125	83.3	10.0	27.4	3600	10	1.2 x 10^{-5}
NW5 (v)	115-125	83.3	10.0	27.4	3600	347	4.2 x 10^{-4}
NW5 (h)	115-125	83.3	10.0	27.4	3600	0.08	9.1 x 10^{-8}
NW5 (h)	115-125	83.3	10.0	28.0	3600	664	7.9 x 10^{-4}
E2 (h)	10-15	17.4	5.0	20.5	3600	2454	9.6 x 10^{-3}
E6 (h)	10-15	17.4	5.0	20.5	3600	522	2.0 x 10^{-3}
E7 (h)	10-15	17.4	5.0	20.5	3600	4572	1.8 x 10^{-2}
N1 (h)	10-15	17.4	5.0	20.5	3600	490	1.9 x 10^{-3}
NW4 (h)	10-15	17.4	5.0	20.5	3600	534	2.1 x 10^{-3}
NW5 (h)	10-15	17.4	5.0	20.5	3600	1812	7.1 x 10^{-3}

v = Vertical sample, h = Horizontal sample

APPENDIX 5

Horizontal displacement/shear stress curves: Shear strength determinations.

Figure A5.1 Horizontal displacement/shear stress curves for the acrotelm at site E2.

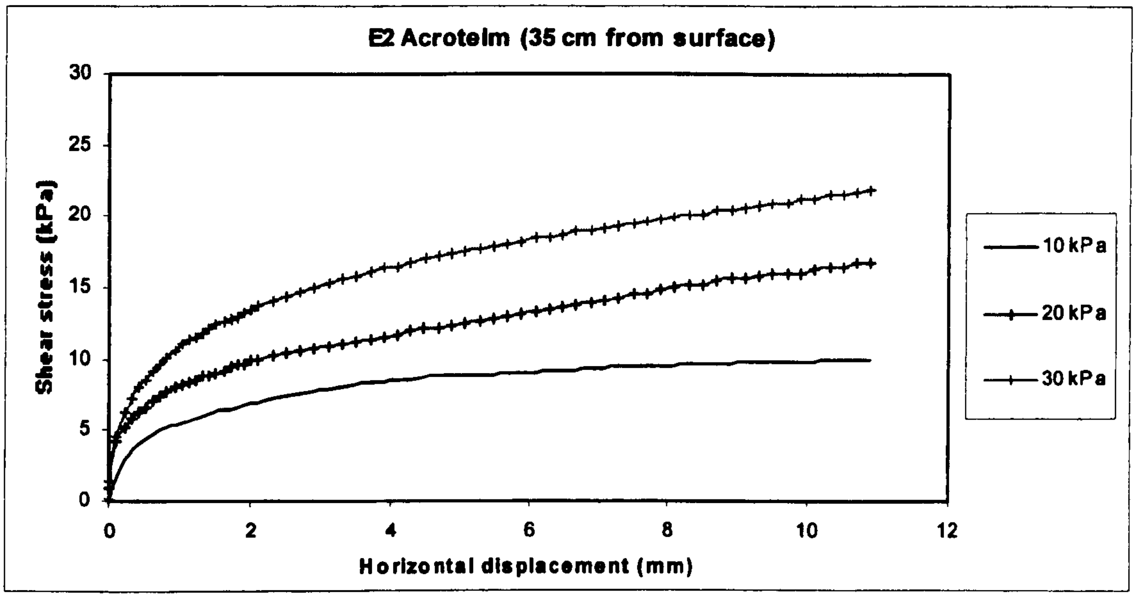


Figure A5.2 Horizontal displacement/shear stress curves for the upper catotelm at site E2.

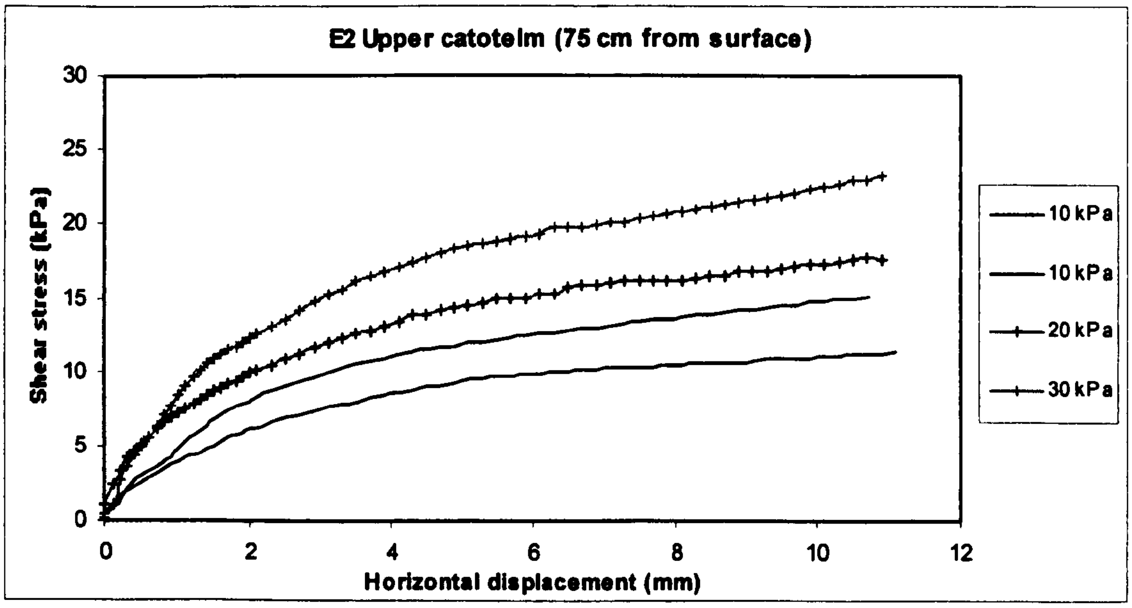


Figure A5.3 Horizontal displacement/shear stress curves for the basal catotelm at site E2.

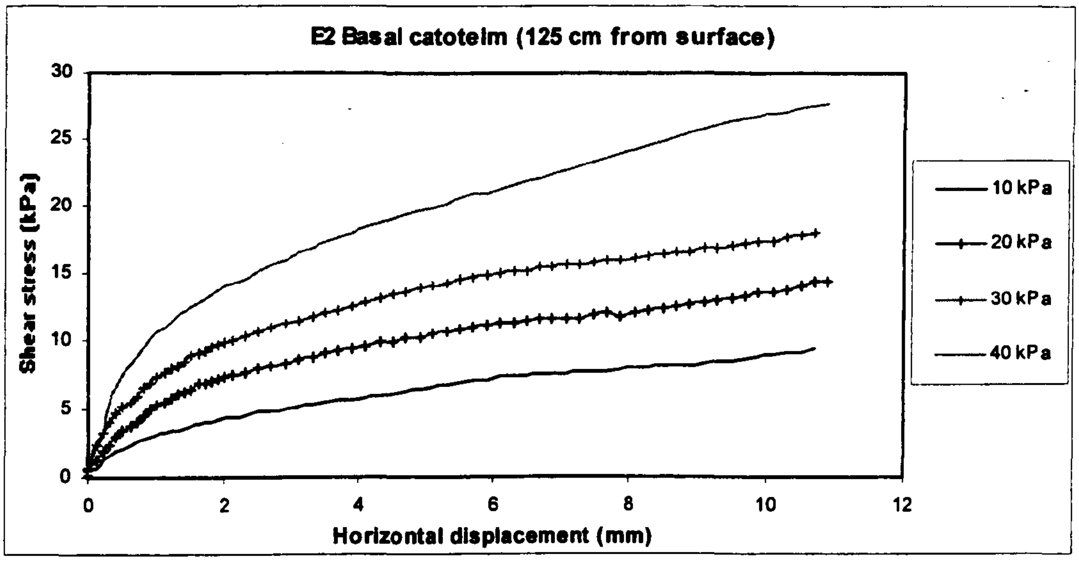


Figure A5.4 Horizontal displacement/shear stress curves for the acrotelm at site NW5.

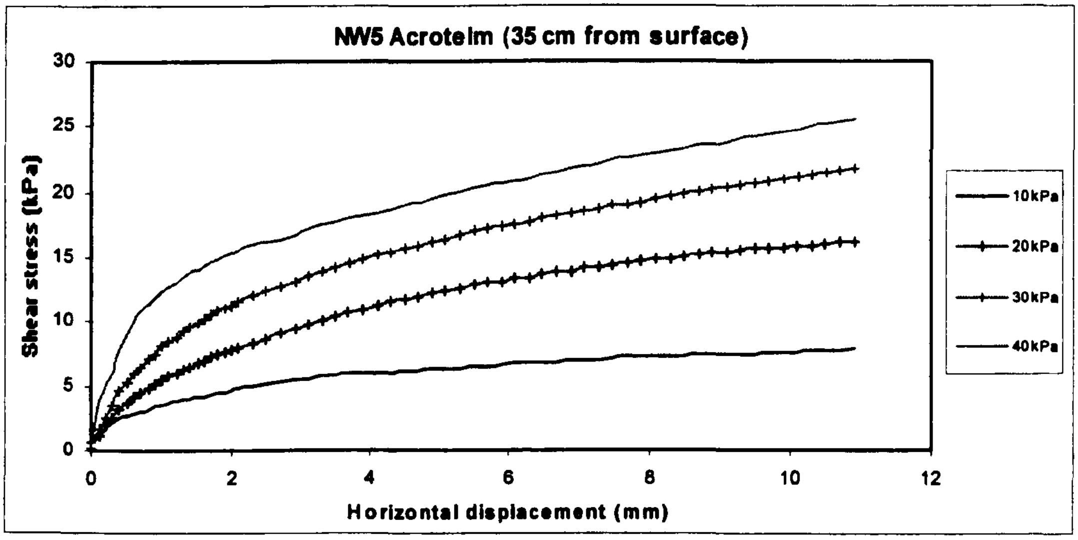


Figure A5.5 Horizontal displacement/shear stress curves *for the basal catotelm at site* NW5.

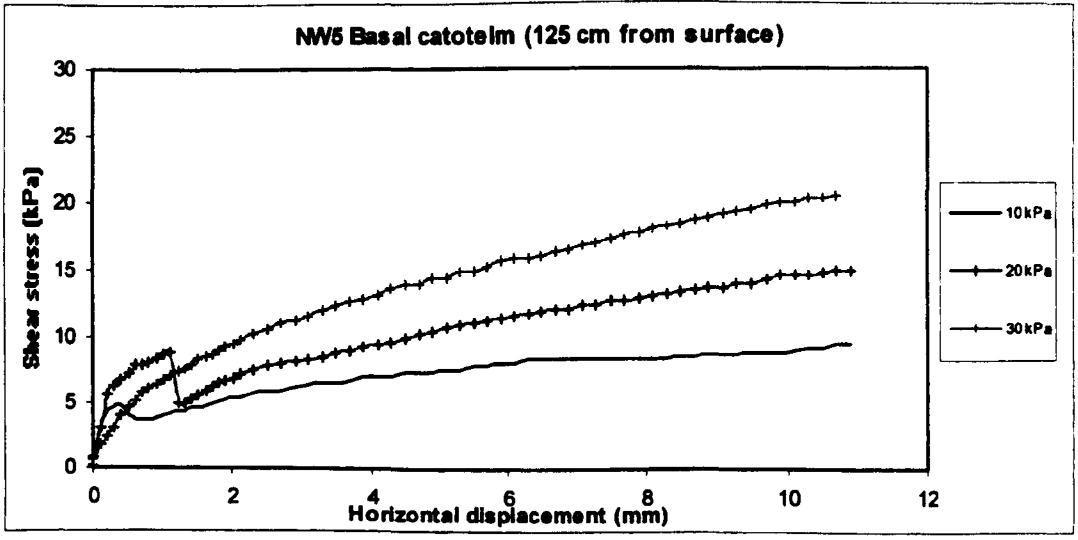


Figure A5.6 Horizontal displacement/shear stress curves for catotelm samples at site NW5.

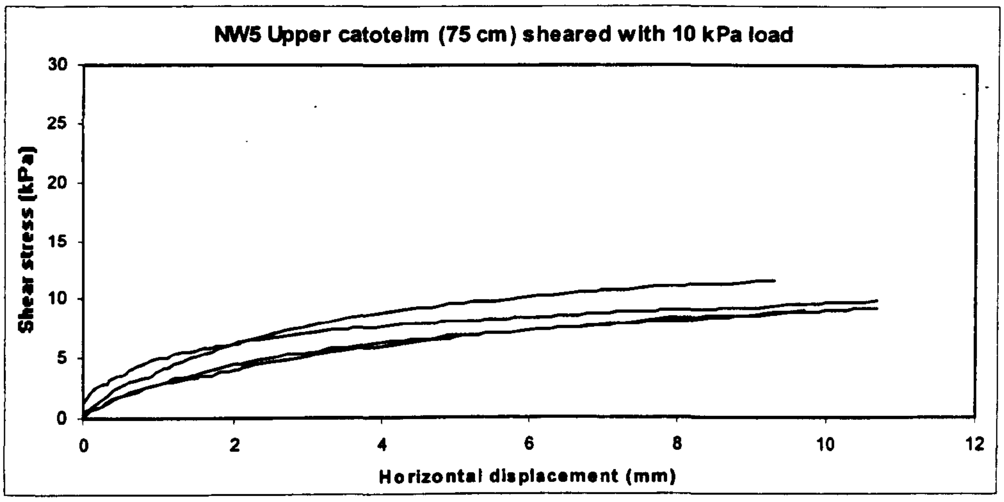


Figure A5.7 Horizontal displacement/shear stress curves for catotelm samples at site NW5.

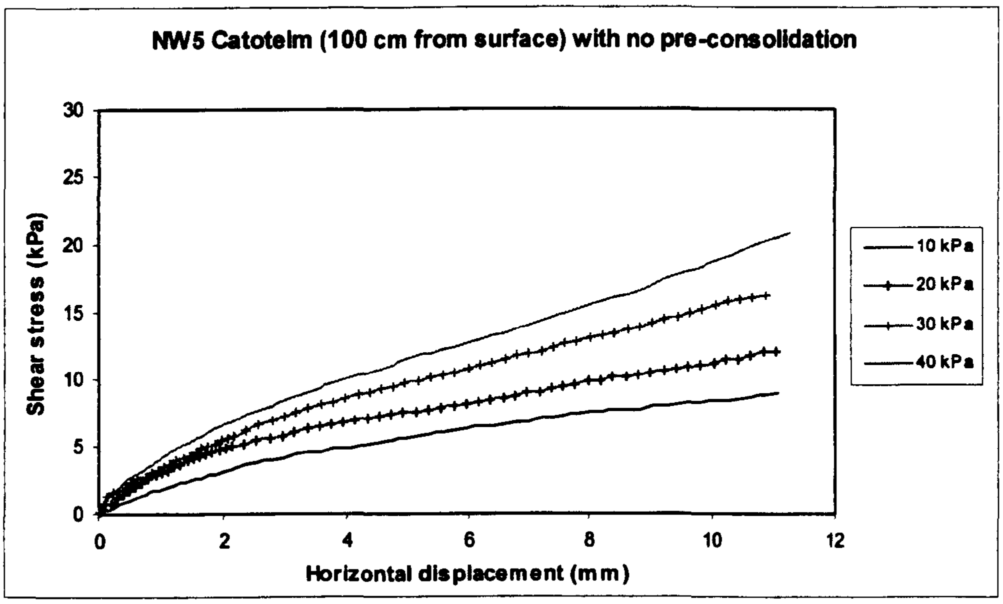


Figure A5.8 Horizontal displacement/shear stress curves for the clay samples at site NW10.

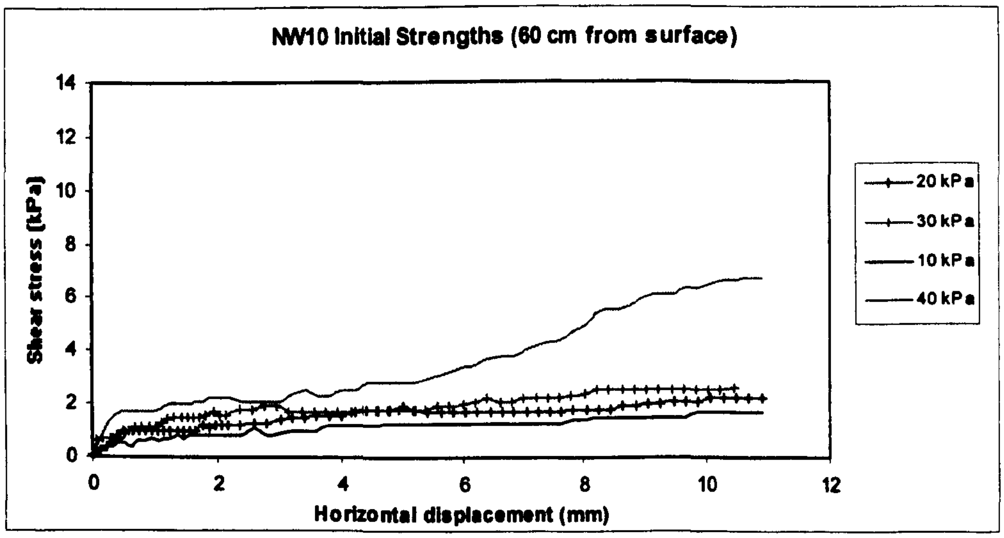
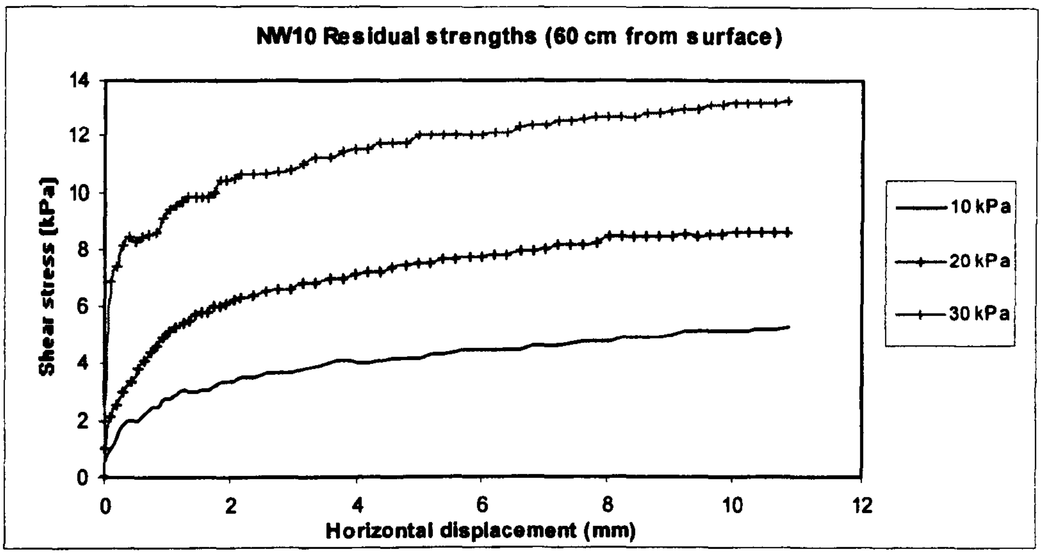


Figure A5.9 Horizontal displacement/shear stress curves for the clay samples at site NW10 (Residual strength determinations).



APPENDIX 6

SEEP/W Model formulation

The three components which form the physical basis for the SEEP/W model are: Darcy's Law; a single governing equation based on continuity for the changing volumetric water content of each elemental volume (in terms of total head and hydraulic conductivity in the x and y directions); and for transient analyses a 'soil moisture characteristic' curve for each material in the problem. Each of these are outlined here from the SEEP/W *User's Guide* (GEO-SLOPE, 1995a).

Darcy's Law is given by equation 2.2 in chapter 2. Under conditions of unsaturated flow, hydraulic conductivity varies with changes in water content and pore water pressures (GEO-SLOPE, 1995a). As the SEEP/W model calculates flow for both saturated and unsaturated conditions, Darcian velocity (v) is preferred to specific discharge (q):

$$v = \mathbf{k}\, i \tag{A6.1}$$

where **k** is the hydraulic conductivity and i is the hydraulic gradient. Therefore, the actual average velocity of flow through a given soil is calculated as the Darcian velocity divided by the porosity of the soil (GEO-SLOPE, 1995a).

The governing differential equation used in the formation of SEEP/W for slopes under steady state conditions is:

$$0 = \frac{\delta}{\delta x}\left[k_x \frac{\delta H}{\delta x}\right] + \frac{\delta}{\delta y}\left[k_y \frac{\delta H}{\delta y}\right] + Q \tag{A6.2}$$

Where:

H = Total head

k_x = Hydraulic conductivity in the x-direction

k_y = Hydraulic conductivity in the y-direction

Q = Applied boundary flux

This equation states that the flow (flux) entering and leaving an elemental volume must be equal at all times. For transient conditions, the flux at any point in time (t) is equal to the change in the volumetric moisture content (θ). Therefore, the equation is given as:

$$\frac{\delta \theta}{\delta t} = \frac{\delta}{\delta x}\left[k_x \frac{\delta H}{\delta x}\right] + \frac{\delta}{\delta y}\left[k_y \frac{\delta H}{\delta y}\right] + Q \tag{A6.3}$$

The finite element formulation uses hydraulic gradient (i) as its key parameter. The hydraulic gradient and therefore Darcian velocity (v) are obtained by calculating the total head (H) for each element and at each time step (for a transient analysis). The stress state variables used for calculating saturated and unsaturated flow are (σ - u_a) and ($u_a - u_w$), where σ is the total stress, u_a is the pore air pressure and u_w is the pore water pressure.

The storage, or 'soil moisture characteristic' curve is the relationship between the volumetric moisture content (θ) and the pore water pressure (u_w). To perform a transient analysis, the soil moisture characteristic curve for each material in the problem must be specified. The hydraulic conductivity function for unsaturated conditions can also be obtained from this relationship (see GEO-SLOPE, 1995a).

APPENDIX 7

Hydraulic conductivity functions and soil moisture characteristic curves used in the hydrological modelling (SEEP/W)

Figure A7.1 The k-function for the acrotelm used in the hydrological modelling of the Cuilcagh peat slopes (SEEP/W).

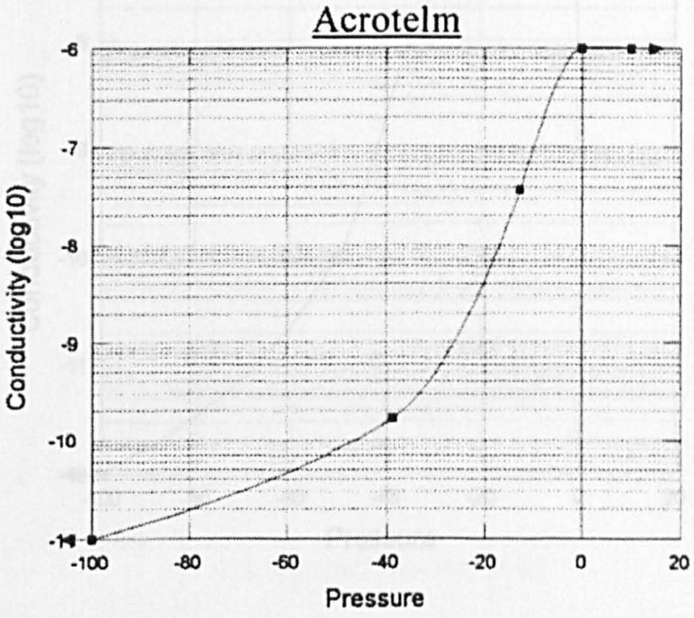


Figure A7.2 The k-function for the catotelm used in the hydrological modelling of the Cuilcagh peat slopes (SEEP/W).

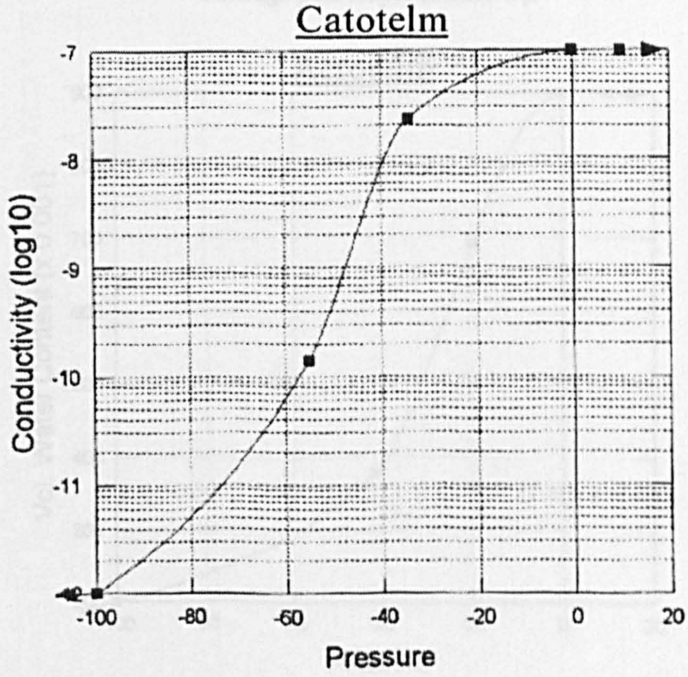


Figure A7.3The k-function for the clay used in the hydrological modelling of the Cuilcagh peat slopes (SEEP/W).

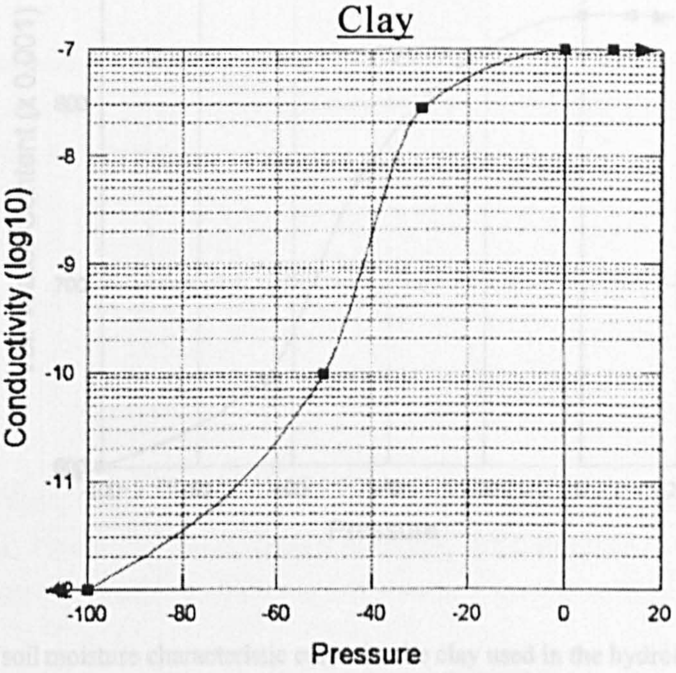


Figure A7.4 The soil moisture characteristic curve for the acrotelm used in the hydrological modelling of the Cuilcagh peat slopes (SEEP/W).

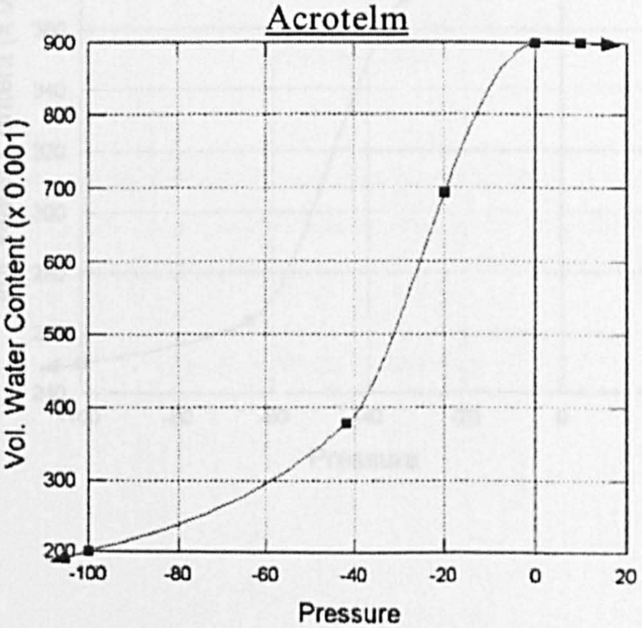


Figure A7.5 The soil moisture characteristic curve for the catotelm used in the hydrological modelling of the Cuilcagh peat slopes (SEEP/W).

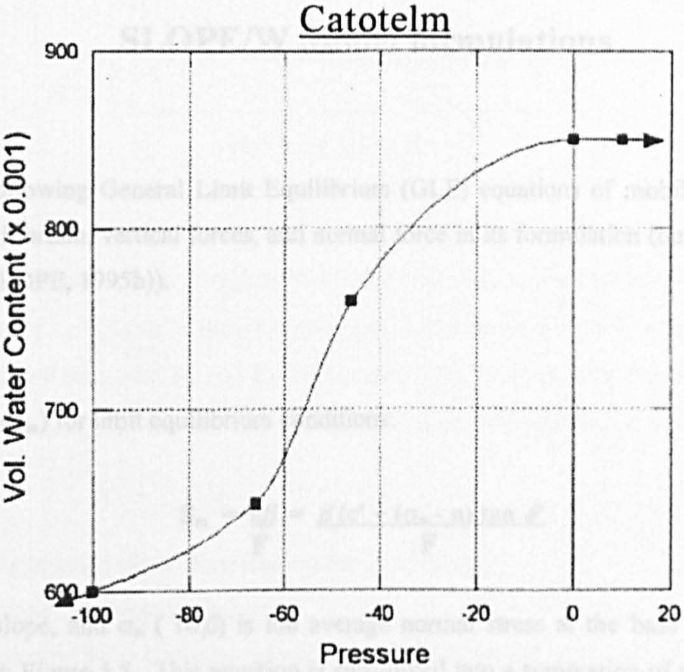
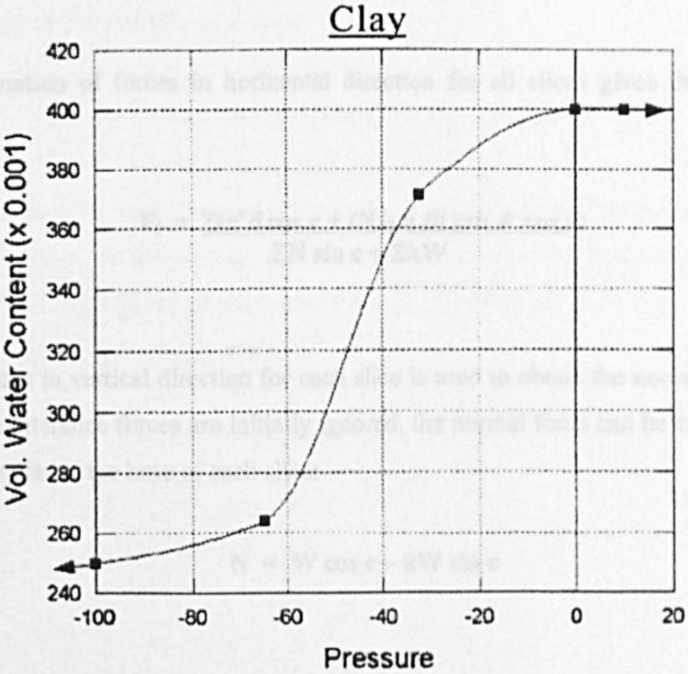


Figure A7.6 The soil moisture characteristic curve for the clay used in the hydrological modelling of the Cuilcagh peat slopes (SEEP/W).



APPENDIX 8

SLOPE/W Model formulations

SLOPE/W uses the following General Limit Equilibrium (GLE) equations of mobilised shear force, moment equilibrium, force equilibrium, vertical forces, and normal force in its formulation (outlined from the SLOPE/W *User's Guide* (GEO-SLOPE, 1995b)).

Mobilised shear force (S_m) for limit equilibrium conditions:

$$S_m = \frac{s\beta}{F} = \frac{\beta(c' + (\sigma_n - u)\tan\phi'}{F}$$

(A8.1)

where β = angle of slope, and σ_n (N/β) is the average normal stress at the base of each slice. All other parameters are given in Figure 5.5. This equation is substituted into a summation of moments about a common point for all slices, to give an equation for Factor of Safety moment equilibrium (F_m):

$$F_m = \frac{\Sigma(c'\beta R + (N - u\beta) R \tan\phi'}{\Sigma Wx - \Sigma Nf + \Sigma kWe}$$

(A8.2)

In addition, the summation of forces in horizontal direction for all slices gives the Factor of Safety force equilibrium (F_f):

$$F_f = \frac{\Sigma(c'\beta \cos c + (N - u\beta)\tan\phi' \cos c)}{\Sigma N \sin c + \Sigma kW}$$

(A8.3)

The summation of forces in vertical direction for each slice is used to obtain the normal force at the base of the given slice (N). If the interslice forces are initially ignored, the normal force can be calculated by summing the forces acting perpendicular to the base of each slice:

$$N = W \cos c - kW \sin c$$

(A8.4)

Equation A8.4 can then be substituted into A8.2 to give the Factor of Safety using the Ordinary Method of Slices. As this method assumes interslice shear forces are zero, normal force is calculated as:

$$N = \frac{W - \dfrac{c'\beta \sin c + u\,\beta \sin c \tan \phi'}{F}}{\cos \alpha + \dfrac{\sin c \tan \phi'}{F}}$$

(A8.5)

If the interslice force is required (e.g. Morgernstern-Price method), the interslice normal force (E) is obtained from the interslice shear force (λ), as E is a percentage of λ, determined by a functional distribution, f(x). The Morgernstern-Price method uses both F_m and F_f and equates them by calculating the necessary ratio of normal to shearing interslice forces (λ), f(x) can then be defined as constant throughout the slip surface (GEO-SLOPE, 1995b).

There are four main stages in the model formulation for computing F:

1. Interslice forces ignored (Ordinary Method);
2. Interslice forces assumed to be zero, and non-linear F_m and F_f are solved;
3. Calculation of λ to make $F_m = F_f$;
4. F_m and F_f plotted against λ to determine F which satisfies F_m and F_f.

SLOPE/W uses Fredlund's (1987) modification of the Mohr-Coulomb shear strength equation to incorporate the effect of unsaturated soil on the stability of a slope.

$$s = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b$$

(A8.6)

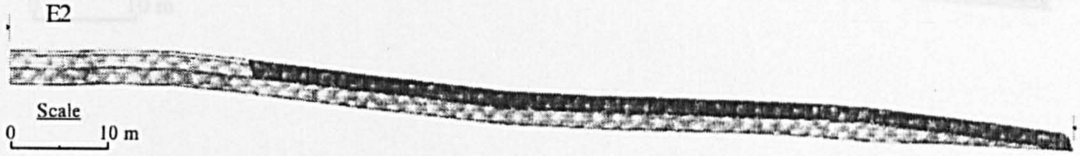
where u_a is the pore air pressure, u_w is the pore water pressure, and ϕ^b can be interpreted as an angle of additional friction as a result of suction. In most cases, this equation can be used for both saturated and unsaturated soil conditions as u_a is usually zero (atmospheric pressure) and ϕ^b can be set to ϕ' (i.e. effective angle of internal friction) in saturated conditions (Fredlund, 1987).

APPENDIX 9

Profiles of the modelled slopes illustrating the vertical slices used in the calculation of F

Site: E2 **Depth of acrotelm:** 0.5 m
Slope length: 105 m **Depth of catotelm:** 1.5 m
Gradient: 7.5 - 2.5° **Depth of clay:** 2.0 m
Calculated F (using assumed position of the failure surface): 1.6

Figure A9.1 Slope profile of E2 used in the slope stability modelling (SLOPE/W).

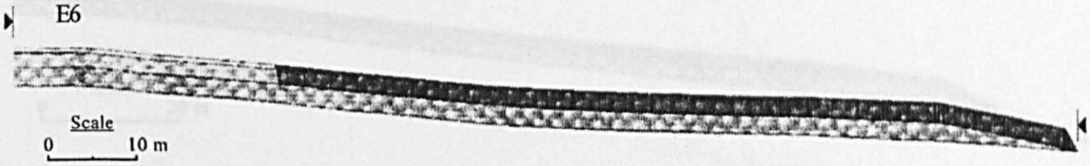


Site: E3 **Depth of acrotelm:** 0.5 m
Slope length: 425 m **Depth of catotelm:** 1.5 m
Gradient: 3.5 - 3.0° **Depth of clay:** 2.0 m
Calculated F (using assumed position of the failure surface): 2.0

Figure A9.2 Slope profile of E3 used in the slope stability modelling (SLOPE/W).

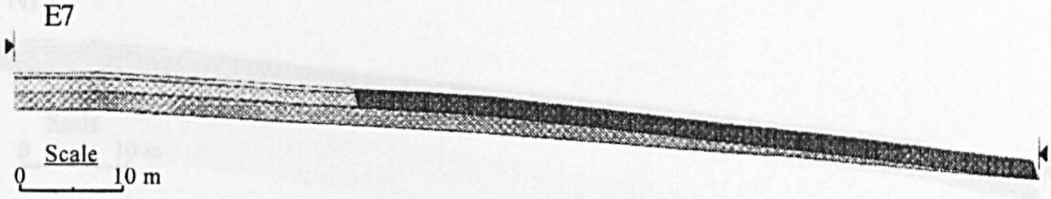
Site: E6 **Depth of acrotelm:** 0.5 m
Slope length: 110 m **Depth of catotelm:** 1.5 m
Gradient: 5.5 - 1.5° **Depth of clay:** 2.0 m
Calculated F (using assumed position of the failure surface): 1.9

Figure A9.3 Slope profile of E6 used in the slope stability modelling (SLOPE/W).



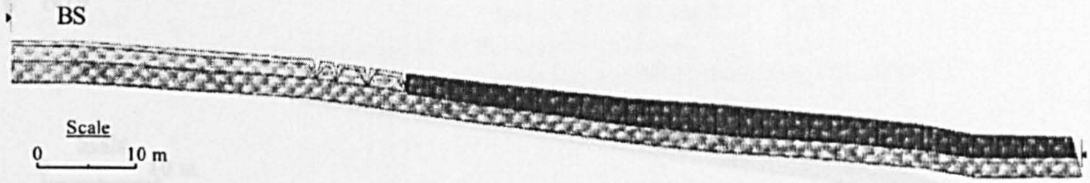
Site: E7 **Depth of acrotelm:** 0.5 m
Slope length: 105 m **Depth of catotelm:** 1.5 m
Gradient: 4.5 - 5.0° **Depth of clay:** 2.0 m
Calculated F (using assumed position of the failure surface): 1.3

Figure A9.4 Slope profile of E7 used in the slope stability modelling (SLOPE/W).



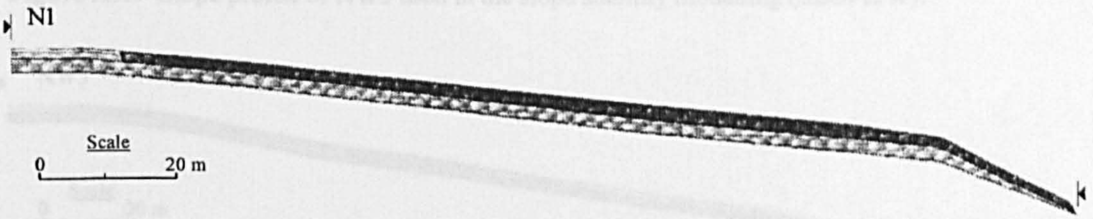
Site: BS (Bulging slope) **Depth of acrotelm:** 0.5 m
Slope length: 90 m **Depth of catotelm:** 1.0 -2.2 m
Gradient: 4.5 - 8.0 - 5.5° **Depth of clay:** 2.0 m
Calculated F (using assumed position of the failure surface): 1.3

Figure A9.5 Slope profile of the bulging slope used in the slope stability modelling (SLOPE/W).



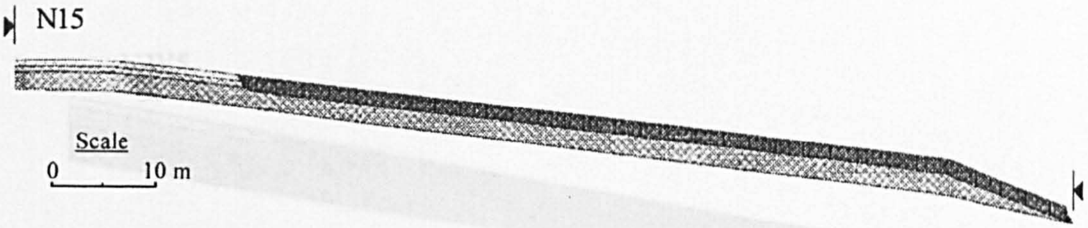
Site: N1 **Depth of acrotelm:** 0.5 m
Slope length: 155 m **Depth of catotelm:** 1.0 m
Gradient: 7.0 - 6.0 - 17.0° **Depth of clay:** 2.0 m
Calculated F (using assumed position of the failure surface): 1.5

Figure A9.6 Slope profile of N1 used in the slope stability modelling (SLOPE/W).



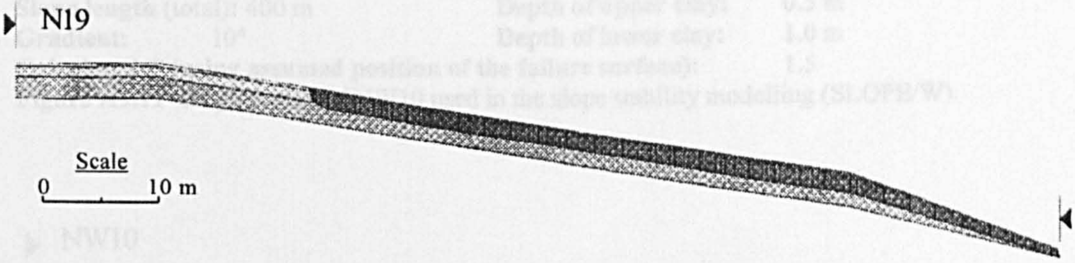
Site: **N15** **Depth of acrotelm:** 0.5 m
Failure length: 90 m **Depth of catotelm:** 0.5 m
Gradient: 7.0 - 8.0° **Depth of clay:** 1.5 m
Calculated F (using assumed position of the failure surface): 1.5

Figure A9.7 Slope profile of N15 used in the slope stability modelling (SLOPE/W).



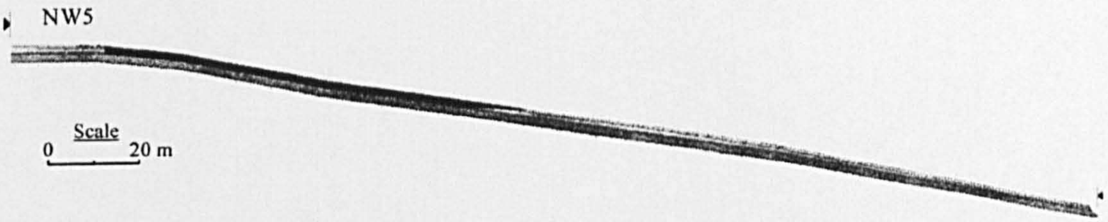
Site: **N19** **Depth of acrotelm:** 0.5 m
Failure length: 65 m **Depth of catotelm:** 0.5 m
Gradient: 9.0 - 16.0° **Depth of clay:** 1.5 m
Calculated F (using assumed position of the failure surface): 1.4

Figure A9.8 Slope profile of N19 used in the slope stability modelling (SLOPE/W).



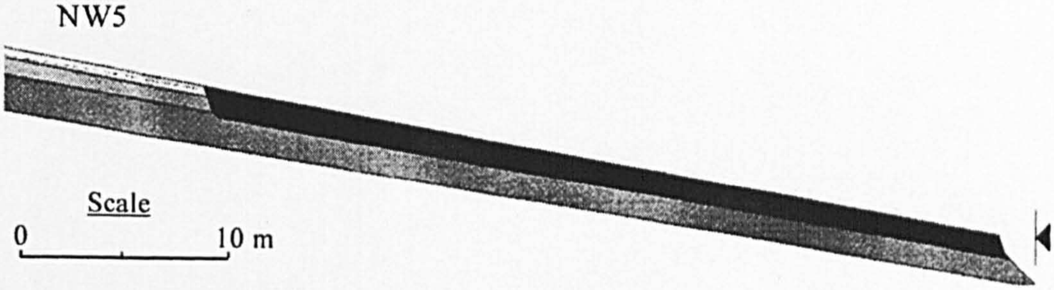
Site: **NW5** **Depth of acrotelm:** 0.5 m
Slope length: 230 m **Depth of catotelm:** 1.0 m
Gradient: 6.0 - 12.0° **Depth of clay:** 2.0 m
Calculated F (using assumed position of the failure surface): 1.5

Figure A9.9 Slope profile of NW5 used in the slope stability modelling (SLOPE/W).



Site: **NW6** **Depth of acrotelm:** 0.5 m
Failure length: 40 m **Depth of catotelm:** 1.0 m
Gradient: 10° **Depth of clay:** 2.0 m
Calculated F (using assumed position of the failure surface): 1.4

Figure A9.10 Slope profile of NW6 used in the slope stability modelling (SLOPE/W).



Site: **NW10** **Depth of peat:** 0.7 m
Slope length (total): 400 m **Depth of upper clay:** 0.5 m
Gradient: 10° **Depth of lower clay:** 1.0 m
Calculated F (using assumed position of the failure surface): 1.5

Figure A9.11 Slope profile of NW10 used in the slope stability modelling (SLOPE/W).