SOIL STRENGTH AND FOREST OPERATIONS

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SOIL STRENGTH
AND
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Abstract

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The use of heavy machinery and transport vehicles is an integral part of modern forest operations. This use often causes damage to the standing trees and to the soil. In this study the effects of vehicle traffic on the soil are analysed and the possible consequences for forest management discussed. The study is largely restricted to sandy and loamy soils because of their importance for Dutch forestry.

Soil strength, defined as the resistance of soil structure against the impact of forces, can be described in terms of four basic strength factors: cohesion, friction, density, and structure. The experimental work was carried out in the laboratory, using three compaction tests: confined uniaxial compaction, hand compaction (newly developed), and Proctor. The results show the importance of moisture tension, soil structure, and loading type for soil strength. Soil strength is largely related to organic matter content for all sandy soils. The effects on soil structure of soil compaction and soil disturbance are measured as changes of soil water relations, density, and penetration strength. The results are represented in a so-called soil strength diagram. Soil strength is quantitatively modelled as a function of cohesion, density, and load factors. Moreover, a qualitative model of field soil strength and soil stability is presented.

The experimental results are interpreted in terms of effects on root growth and functioning, choice of vehicles and operation pattern, and possibilities for soil management. The possibilities for soil classification are explored, but it is concluded that the necessary soil data are poorly represented in standard soil surveys. Moreover, the practical use of such a classification is probably limited. Finally, some examples are described.

additional keywords: soil compaction, soil disturbance, soil survey, soil classification, site classification, terrain classification.

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Stellingen

1

Niet alleen de fysische maar ook de mechanische eigenschappen van een grond worden voornamelijk bepaald door zijn structuur. Metingen aan geroerde monsters geven daarom een beperkte, of zelfs onjuiste indruk van de eigenschappen van de bodem in het veld.

2

De fysische bodemeigenschappen kunnen, evengoed als de chemische, aan een boom beperkingen opleggen voordat uitgesproken gebreksverschijnselen optreden. Ook ten aanzien van deze eigenschappen is het werken met kritische waarden daarom weinig verhelderend voor de waardering van de bodemgesteldheid.

3

De bosbouw legt zichzelf onnodig beperkingen op wanneer de bodemgesteldheid als gegeven wordt beschouwd.

4

In de bosbouw denkt men nog teveel in termen van 'vakken' en 'wegen', terwijl de infrastructuur van het bos al begint met de onderlinge afstand van de bomen.

5

De enig zinvolle lange-termijn planning in de bosbouw is het streven naar maximale flexibiliteit. Het verleden leert, dat meer concrete doelstellingen worden achterhaald door de feitelijke ontwikkelingen.

6

In de huidige discussie over de vitaliteit van het bos wordt het effect van klimaatschommelingen ten onrechte gebagatelliseerd, hoewel het belang van kleine regionale klimaatverschillen in de bosbouw algemeen erkend is.

7

De ontwikkeling van de bosbouw in Nederland wordt geremd door een overheidsbeleid, dat subsidies relateert aan kosten in plaats van aan opbrengsten.

8

Het is merkwaardig, dat in natuurbeschermingskringen zoveel meer enthousiasme bestaat voor grootschalige monocultuur van Calluna vulgaris dan voor die van Pinus sylvestris.

9

Technisch vernuft wordt vaak gebruikt om gebrek aan inzicht en ervaring te verhullen; een goede vervanging is het echter vooralsnog niet.

10

De ineffectiviteit van ontwikkelingshulp zou tot herwaardering van koloniaal beheer moeten leiden.

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Ex nihilo nihil

voor Laura

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1 INTRODUCTION

1.1 Forestry

Forest products such as firewood and timber are almost as important to mankind as food, but the differences between the history of agriculture and that of forestry are enormous. The possibilities of using natural food sources are very much limited by the sparse, erratic, and often hidden occurrence of wild plants and animals, by the dangers of hunting, by seasonal production and lack of natural accumulation (with the exception of some animal species), and by limited possibilities for artificial storage. Because of all these reasons, gathering natural food has a low productivity, while the risks and losses are high. Dependence on natural food sources has proven to be an important obstacle to the development of mankind. With the beginning of agriculture some 10.000 years or more ago, mankind started to remove this obstacle and thus created the basis for the unprecedented growth of its population and power.

Obtaining essential forest products, on the contrary, is considerably facilitated by their conspicuous occurrence, and by the importance of natural accumulation processes which make the supply almost independent of current production. Thus, gathering wood has generally a high productivity, and shortages of wood are only noticed when the forests have dwindled to a fraction of the original. The history of forestry started only a few centuries ago in some areas, and still has to start in others. And, even today, world market wood prices are still largely set by the low-cost supply from natural forests in nordic and tropical regions.

Forestry, born out of the requirements of sudden shortages caused by decimated forest resources, immediately faces its most difficult task: building up stocks to a level which permits the regular use of the equivalent of the current production. This investment period, which may take between 10 and more than 100 years depending on growth rate and intended use, not only demands large amounts of capital and good organisation, but most of all a stable society in order to guarantee the investor his rights on the final products. If forestry has difficulty in getting off the ground in many countries, this has much more to do with the lack of firm property rights and of political stability than with technical inability, lack of knowledge, or financial profitability. And in many countries all over the world forestry is, or becomes, largely a (semi-)state activity, because of gradual breakdown or poor definition of private property rights, and increasing socio-political instability. This gradual monopolisation of forestry bears all the risks of other (state-)monopolies: sub-optimal allocation of resources, inefficiency and high costs, instability because of low diversity and changing priorities, and, finally, inadequate reaction to the wishes of the public and the market because of the character of the political decision system and the power of the organisation itself.

In fact, ownership rights usually are ultimately based on, and recognised because of, investments of individuals. So long as forest productivity depends on such investments, as it does in most cases, property rights are a necessity. However, many other elements of the forest system are not the result of private investment, and, therefore, not necessarily completely subject to private control. Therefore, we should understand legislative measures to protect the soil and the forest resource as such. On the same basis, many countries recognise a common right of access (e.g. Sweden, Federal Republic of Germany), a common right to wild flowers and berries, and other common rights.

1.2 Priorities in forestry

Commonly, the following forest functions are recognised:
- production (of wood and other materials, so-called minor forest products)
- protection (against avalanches and erosion, regulation of water run off, wind, etc.)
- conservation (nature, genes, ethical value, etc.)
- landscape and recreation.

These four functions, however, are not of the same nature and order. The last three functions can be performed by forests, but forests are not necessarily the most efficient or the best performers for these functions, as they are, usually, for the first function.

The reputation for erosion protection, for example, is founded largely on the fact that foresters don't work the soil as intensively as farmers, and that they protect the soil against (over-)grazing. But well-managed grassland offers, usually, a much better protection against erosion. Only on steep slopes can forests increase slope stability of the soil, and stabilise the snow cover, if present. The regulation of water run-off has more to do with the high evapotranspiration in forests, and the mismanagement of other landowners, than with any beneficial effect of the forest itself. Protection against wind is optimally provided by spaced and relatively open rows of trees, which have little resemblance to forests.

The same applies to the functions of recreation and landscape. Landscape and opportunities for recreation are largely determined by forest edges and by solitary trees, not by the forest as such (cf. the weeding of trees from Dutch heaths; the debate about the re-forestation of denuded British uplands; etc.). The popularity of forests by the public in search of recreation has more to do with the degradation of the landscape outside the forest and with the abundant use of no-entry signs and fences in the agricultural countryside.

Conservation, finally, is a highly doubtful function in itself. Nature itself is highly dynamic and even wasteful as is shown, for instance, by the tremendous loss of species and variability during the great ice-ages. There is no reason to believe that natural selection would be better or more purposeful than selection by man. Conservation of natural variability is important, especially variability of genes, because these genes may form the basis of future production. But this conservation may very well imply the use of exotic and selected plants. Conservation of natural vegetation as an entity may serve some purpose for scientific reasons, as the study of natural processes in such systems may aid our forest management. However, only a few reserves are needed for this purpose. Most other conservation efforts really serve the functions of landscape and recreation (cf. the intensive management of, for example, the Dutch nature reserves), or a fancy of the owner. An example is the recently presented development plan for the Dutch forest area: in this plan nature conservation is seen as the main function of a large part of the forest area. This conservation function is to be promoted by the use of so-called indigineous tree species (of usually unknown, but in any case not Dutch, genetic origin) and introduced animals (such as the Przewalski horse). Of course, this may be very attractive for recreational purposes, and for the odd biologist, but, strangely enough, recreation is to be limited, so as to cause no damage to the natural values.

In some western countries, there has recently been a shift of priorities in forest management from production to recreation and conservation. This is a dangerous development for the future of our forests. Not only are forests often sub-optimal for those functions (an honest choice might well involve getting rid of the forests altogether), but this insufficiently motivated change undermines the basis of all forestry activity: stability of rights. Foresters themselves invented the term multiple-use forestry to indicate that wood production leaves plenty of room for other forest functions, as should be the case with agriculture as well. The farmers, perhaps, realised the dangers and drove the public from their land, forgetting about multiple-use. The foresters risk being driven out of their own forests, because multiple-use is wrongly interpreted by the public as interchangeable use.

Even though I maintain that the primary forestry function is production, just as production is the primary function of agriculture, and that both forestry and agriculture should be multiple-use in the real sense of that word, forestry is not just another type of agricultural land use. However, most differences are of scale and intensity, and not of quality. The most important characteristic of forestry is the impossibility to harvest the current production annually, which, as stated before, necessitates investment in growing stock and complicated harvesting regulations. Because of this vague connection between production and harvest, forestry is, most of all, characterised by its concern about sustained yields. Many of the major issues in the debates between foresters are centered around this principle: for instance, the dispute about the supposed negative effects on the soil of conifers in comparison with broadleaved species, and the still open questions about the clear-felling management system and soil cultivation. Other questions have been solved almost unanimously (e.g. the negative effects of litter raking), but re-opened in a changed version (e.g. the use of full-tree harvesting systems). The long investment periods make forest production also very sensitive to catastrophes. Pre-occupation with stability is, therefore, another important characteristic of forestry. Finally, low prices of forest products, and remaining uncertainty about future developments, make foresters generally hesitate to invest. Thus extensiveness is another, usually conspicuous, characteristic of forestry. The principals of sustained yield and stability, but most of all of extensiveness, have prompted the forester to rely heavily on natural processes. Only in areas with rapid tree growth can more intensive forestry become feasible, relying less on natural processes by using soil preparation, fertilisation, and pest management. Generally, this has positive effects on the sustainability of yields, and only slight effects on stability.

Forestry is manipulating forests in order to optimise the usable output of the forest in terms of its different functions, under conditions set by the principles of sustained yield, stability, and the prevailing economic conditions. Much effort has been put into quantifying all forest functions in money-terms, which is bound to give unrealistic values because money derives its value from the market, whereas no market exists for most forest functions other than wood production. It is more rational to express the costs of other functions in terms of loss of capability of wood production, plus the direct expenditure for that function. For the forest owner, the value of the wood lost will be determined by the future market price; for the country as a whole, the wood-value may be much higher if domestic production has to remain at a given level. The question whether a given function is worth its costs demands a political answer. The forest owner must be compensated for his costs.

1.3 Methods in forestry

The forester has a number of methods available for manipulating the forest towards optimal functionallity. All methods have a biological, a technical, and an organisational component, which are interdependent. The biological component is concerned with the design of operations in terms of manipulation of natural processes and conditioning of environment, site, and stand. The technical component concerns the execution of these operations, and the organisational component concerns the planning of operations in time and space. The biological component of each method can be evaluated in terms of forest functions (e.g. wood production), the technical and organisational components in terms of financial costs. Usually, different methods can be used to achieve the same output for the main function. The method actually chosen will depend on the additional functions aimed at, on know-how and available resources, and on the prevailing socio-economic circumstances.

Because of the irregularities of natural processes, and our still incomplete knowledge, operations which conform very closely to natural processes may be the most demanding in technical and organisational terms. As regards costs, such operations may or may not be competitive. Unfortunately, biologists and technicians have grown apart in forestry, resulting in biologists designing operations impossible to execute economically by the technicians, or in technicians designing and executing operations without much regard for biological considerations. The results may be very damaging to the forest. This problem is illustrated by the classic question whether the forest should be adapted to the machine or the machine to the forest. Many people will opt for the second choice without hesitation, but they forget that forestry is nothing else than adapting forests to man, for his use and profit. Machines are just a tool of man to help him to achieve his aims. Both the design of forest operations and the design of machines should work together towards these aims.

Mechanisation of forest operations is a relatively recent development compared with other sectors of the economy. While farmers started a massive move towards the tractor, foresters followed at a distance; the subsequent move to harvesting machines in agriculture was not followed in forestry until recently. Today, forest work is still largely characterised by low labour-productivity and poor working conditions, with tractors and motor-manual tools as the most important equipment. The technical problems in coping with the heavy and irregular forest products and the often poor and irregular terrain conditions have long been a major obstacle for the mechanisation of forest work. However, these technical problems have now been overcome to an important degree as is illustrated by recent developments in Sweden. In that country, the share of motor-manual methods in thinning is expected to fall rapidly in the next few years. The already high degree of mechanisation in final felling is expected to show a further increase because of a shift to multi-function harvesting machines (Berggrund, 1984). Developments in other countries have been much slower due to different economic conditions, local forest conditions, organisational problems, and in some cases a strong sentimental opposition against mechanisation. In many situations the flexibility of motor-manual methods and of single-function machines will remain powerful arguments for some intermediate degree of mechanisation.

Mechanisation, of course, is not a goal in itself, but a number of factors has stimulated the use of machinery in forestry. The replacement of manpower, because of increasing labour costs or because of the unavailability of labour, is an important factor, but other factors may prove more important and more continuous in time. Examples of such factors are the execution of work which cannot be done by hand for technical (e.g. wood chipping) or social reasons (e.g. heavy and dangerous tasks, poor climatic conditions), the increase in work tempo enabling the forester to use certain periods optimally (e.g. salvage logging, tree planting, fertilisation, soil cultivation, etc.), and the constant quality of the work of machines (e.g. tree planting). Generally, the availability of machinery increases the options open to the forester and thus increases the chances of reaching optimal functionallity of the forest.

The use of machines has some drawbacks as well: high investment costs make good planning very important, and running costs are often not easily controllable. Machines are also less flexible, making, once again, higher demands on planning. The use of machines may have some side-effects on the forest and the environment: damage to vegetation and trees, with risk of subsequent disease development, damage to the soil structure, pollution, etcetera. Finally, working with machines may prove very strenuous for the labourers involved, due to high work tempo, monotony, vibrations, and other reasons.

If mechanisation, with all its inherent benefits, is to proceed, its drawbacks should be overcome by:

- adapting forest operations, machinery, and planning to the forest and the environment, principally through improvement of manoeuvrability of machinery and through increased flexibility
- adapting the forest to mechanised operations, principally through development of infrastructure, also within the stand, and through organisation of the establishment, development, and structure of stands in time, space, and scale
- adapting machinery to man
- lowering investment costs.

1.4 Aims of the present study

In this study I shall analyse the limitations which the soil may set to the use of terrain vehicles and self-moving machinery in forest operations. Such limitations may be based on the general principles of forestry, primarily the principle of sustained yields, and on the functions and priorities chosen for a given forest area. This analysis should provide basic information for the further development of forest operations and machinery and it should aid the forester, in any practical situation, with the planning and choice of methods for his particular operation on hand.

The environment in which the forestry vehicle operates is roughly defined by three strongly interacting elements: climate, terrain, and vegetation. These environmental elements not only largely determine the silvicultural possibilities, but they also determine the performance of working methods and machinery. The influence of forestry vehicles on the environment, however, is largely limited to the vegetation and to the soil. The other terrain factors and the climate are not much influenced, if at all. The influence on man and fauna, for example through noise or visual disturbance, will not be considered.

Any such influences of the forestry vehicle are to be recognised in a highly dynamic system with many internal and external influences and interactions. This system, furthermore, is subject to constant human interference at all levels. Only basic understanding and factual knowledge of these complex relations and processes will allow the forest manager to evaluate the impact of working methods and vehicle use on the environment, as well as the effects of other human interference. This complex system is illustrated and summarised in figure 1.

Figure 1 shows the strong interdependence of the three elements of the vehicle-soil-forest system. Thus, any direct effect on, and any development of, one of the elements will have some effect on the other elements and so, possibly, again on itself. This cyclic relation may result in progressive change or in stabilisation of the system. The forest manager, depicted in the middle of the figure, has the task to direct such processes, not only for his own purposes, but also for the long-term stability and development of the system.

The vehicle-element of the system is partly determined by technological developments, which, for the purpose of this study, can be considered to be autonomous (A_1 in figure 1). Further influence comes from the soil (B_{21}, e.g. bearing capacity of the soil may limit vehicle weight), and the vegetation (B_{31}, e.g. through stand-density or the dimension of the products to

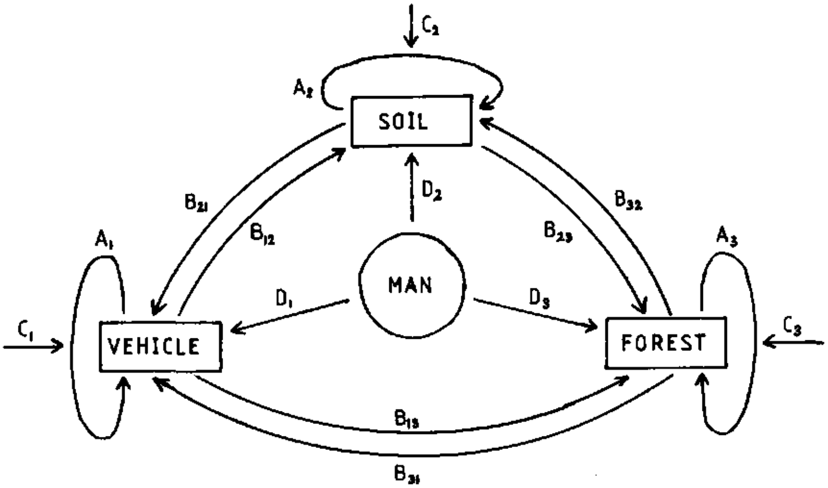

Figure 1: Internal and external relations of the vehicle-soil-forest system.
A = autonomous processes in each element
B = relations between elements within system
C = external influences on system (including passive human interference)
D = active human interference.

be handled). Within the limits to vehicle choice and performance set in this way, the choice is further limited by other terrain factors (slope, ground roughness, etc.), climate, the prevailing social and economic conditions, and by other restrictions outside the power of the forest manager (all depicted by C_1). Finally, the forest manager may alter his choice specifically because of the vehicle effects on soil and vegetation (D_1). This latter possibility will be discussed in more detail in this study (§ 6.2).

The soil-element of the system is in many cases dominated by pedological developments (A_2) such as podzolisation, laterisation, and the biological activity in the soil. These processes, in turn, are largely determined by external factors (C_2) such as the geology, the landform and associated hydrological processes, and the climate, including atmospheric deposition. Another important factor is the vegetation (B_{32}). The possible effects of vehicles (B_{12}) on the soil will be the main theme of this study. The possibilities for direct human interference (D_2, e.g. through soil cultivation or fertilisation) will also be considered in some detail (§ 6.3).

The forest-element, finally, is characterised by strong autonomous processes which express themselves in the regeneration, growth, and successional developments of the vegetation (A_3). The soil (B_{23}) and the climate (C_3) together set the limits for such developments and growth. The direct influence of vehicles (B_{13}) is generally much less, although damage to stems and roots may locally form a more important factor. Direct human interference (D_3) in forest composition and structure is, generally, the most powerful way in which man can direct forests to greater productivity. Such interference may profoundly influence the soil (B_{32}), for better or for worse, and the possibilities for vehicle use (B_{31}).

The aim of forestry is improvement of forest-productivity, be it for wood and fiber, or for other functions. The off-road vehicle is an important tool in forestry, but, at the same time, off-road vehicle activity may interfere with the aim of forestry, either directly (B_{13}) or indirectly, via the soil (B_{12} and B_{23}). Direct damage to trees is in many places an important problem which has been studied extensively and for which practical solutions exist (cf. Dimitri, 1983). The importance of indirect damage, via the soil, is only tentatively known, but probably much greater. The analysis of this problem is, so far, of an empirical nature, but the proposed solutions involve high costs and sometimes drastic changes in forest management. In this study, I shall try to give a fundamental description of vehicular effects on the soil (soil compaction and soil disturbance) and to interprete these effects in terms of forest management in relation to the total vehicle-soil-forest system. The accent of my study lies on soil compaction because of its long-term effects and hidden occurrence, which make it potentially more dangerous. However, soil disturbance, with its effects on the mineralisation rate of organic matter, is also discussed.

Although this study has a fundamental character, it is primarily aimed at the conditions prevailing in the Netherlands. The situation in the Netherlands will also be used as an example of the practical application of the results of this study.

1.5 Guide to this book

This book has been written by a forester, primarily for foresters. From the beginning, the aim has been to link theory and practice because I believe that both are closely related in forestry. Obviously, this approach has its limitations, scientifically as well as practically. So I refrained from using highly sophisticated measurement methodology, but chose for standard, easily repeatable measurements instead (chapter 3). On the other hand, I have included a fairly long discussion of the available theories and knowledge (chapters 2, 5, 6), primarily, but not exclusively, intended for non-specialist readers. The core of this book consists of the proposed model of soil strength (chapter 5) based on my experiments (chapter 4), and the application of this model and the theory to the forest situation in the Netherlands (chapter 8). A rather critical look at the many aspects of the vehicle-soil-forest system, and an attempt to integrate this system into one logical story about forestry, are found throughout this book.

For the reader who lacks the time or mind to read this book from beginning to end, I may suggest to start with chapters 4 and 5 if he is primarily interested in soil dynamics, consulting chapters 2 and 3 for my opinion on the theory and methodology. If he is primarily interested in the practical application, he should start with chapter 8, consulting chapters 6 and 7 for a broader discussion of the measures advocated. Of course, I hope that both groups of readers will finally decide to read the other chapters as well.

2 SOIL STRENGTH

2.1 Introduction

The soil is the uppermost layer of the earth crust which is subject to physical, chemical, and biological processes. Depending on the soil-forming factors (mainly parent material, topography, climate, vegetation, time, and man), different processes of weathering (e.g. fragmentation of rock, clay formation, etc.) and soil formation (e.g. oxidation, leaching, accumulation, etc.) are more or less active. Through these processes, the soil gradually changes and acquires properties which deviate from the parent material. At any given moment, the soil can be characterised by its composition and structure, and by the processes occurring in the soil. The latter give an indication of how the soil will develop in the course of time if the conditions remain constant. Composition and structure are not only changed by soil processes, but they also influence soil processes and, thus, each other as well.

Soil composition can be found by destructive analysis, which separates the soil into its elements, such as mineral particles and organic material, but also nutrients, soil fauna and flora, soil water, and soil air. Mineral particles change slowly in the course of time and may still reflect the original materials. Nutrients, organic material, and soil fauna and flora may change in the course of a period of a few years in response to soil processes, whereas soil water and air are subject to daily fluctuations. Analysis of the latter in terms of soil composition is, therefore, of little value.

Soil structure is the spatial arrangement of the elements of the soil, which can be found by direct or indirect measurement. Important aspects of soil structure are the aggregation of mineral and organic particles, and the size and distribution of the pores in between these particles. Soil structure may be quite variable in the course of a period of a few years or less in response to soil processes, although such changes remain within limits determined by soil composition.

Soil processes can be very diverse and are difficult to determine without extensive measurements. Usually their occurrence and intensity is deduced from the soil-forming factors or from soil structure and the morphology of the soil profile. However, one should always realize that soil morphology largely reflects past soil processes and not necessarily present processes. Soil processes may change relatively fast in response to changing soil-forming factors; especially temperature and moisture, which show daily fluctuations.

With the increasing demands man makes on the soil, he changes the soil not only indirectly via changes in soil-forming factors (e.g. vegetation, drainage), and, thus, of soil processes, but also directly via impact on soil composition and structure (e.g. fertilisation, soil cultivation, soil compaction). Such direct impacts may be seen as artificial soil processes, although they usually differ only in scale and intensity from natural processes. Of course, any such changes of soil composition or structure will have their impact on natural soil processes, which may counteract the original change (regeneration: e.g. leaching of fertilisers, loosening of compacted soil through earthworm activity) or fortify it positively (amelioration: e.g. improved nutrient cycling after application of deficient elements) or negatively (degradation: e.g. erosion of compacted soil).

The resistance of soil structure to the impact of forces is called soil strength. Soil strength relates forces on the soil to reaction of soil structure. Soil strength, or inertia of soil structure against forces, is just one measure of soil stability. The speed of regeneration to its former state after disturbance, and the sensitivity for amelioration and degradation are also measures of soil stability. Soil stability in itself, thus, has little meaning: a weak soil with a high regeneration potential may be more stable than a strong soil with a high sensitivity for degradation or a low regeneration potential. Also, stability is not always a positive feature: for example, strongly buffered soils, which have high chemical stability, may react poorly to fertilizers in case of deficiencies.

2.2 Causes of soil strength

Soil usually consists of a matrix of generally small particles, mostly of mineral nature and to a lesser degree of organic nature. The particles are locally in contact with each other but elsewhere voids, filled with water or air, exist between them. In the range of forces of interest, mineral soil particles may be assumed to be rigid (loam and sand) or slightly deformable (clay). Organic particles are deformable and compressible. Water and air are highly deformable through flow, and soil air is highly compressible as well.

Soils largely composed of rigid particles are the main subject of this study (sands and loams with low clay and organic matter content). Strain of the matrix of such soils has to be the effect of a change in position of the soil particles relative to each other. Such a change automatically alters the form, and possibly the volume, of the voids between the particles, which causes flow of water and air, or compression of air. Thus, part of the force acting on soil results in the displacement of particles relative to each other, and part of it results in flow or compression of water and air. Therefore, soil strength is not only determined by particle properties and soil structure, but also by water and air content, and by the possibilities of flow through the matrix.

Depending on the scale of the soil element studied, soil strength can be described in terms of four basic strength factors: cohesion, friction, density, and structure.

micro-level

At the most elementary level of scale (micro-level) soil strain involves the movement of one particle in relation to the other. Such movement involves two phases. The first phase requires a force to stretch or break the existing bonds (interparticle cohesion) between the two particles in the existing contact area. The second phase requires a force to slide the particles over each other. This force is proportional to the normal forces working on the contact area during the sliding process. The proportionality factor (interparticle friction angle) depends on the surface properties of the particles.

Cohesion (i.e., the bond between two particles) includes a wide variety of factors. The first group of factors is particle-dependent, the so-called true cohesion. Mass of particles, electric loading of the surface, chemical bonds, Madelung forces, and others may play a role. This group of factors is largely limited in its effects to clay particles because of the platy, layered structure and electrical loads of such particles. Comparable factors play a role in organic materials. Many of these binding forces are located on specific sites of the particle surface, and work over a very small distance. After disturbance, this cohesive strength is much lower because the bonds cannot re-establish at random.

A second element of cohesive strength is the binding force due to water tension. Because of the adhesion of water to the particle surface and the cohesion of water, the presence of water under negative pressure acts as a binding force. According to capillairs theory, this force increases with decreasing capillair diameter and, thus, with decreasing distance between particles. As with the first group, contact between the particles is not necessary. The capillary forces are not located on the surface and, therefore, remain active during particle movement, constituting one of the normal forces on the contact area which determines friction. The importance of the capillary forces increases with decreasing particle diameter, because in smaller particles a greater percentage of the surface is close to other particles. For the same reason, this force is most important in the plate-like clay particles. Positive water pressures work as a negative cohesive force and reduce cohesive strength.

The third group of cohesive factors can be indicated by the general term cementing. The active forces in cemented bonds are largely the same as in the other cohesive bonds, but scale and time are different. Cementing occurs where substances or small particles settle preferentially around existing contact areas, thus increasing the contact area surface and the forces per unit of contact area through adhesive or chemical bonds. Most cementing agents are suspended or dissolved in the soil water. When the soil dries, the soil water contracts more and more around the contact points between the particles, and so the preferential deposition occurs. Examples are: silt, clay, and small organic particles, dissolved organic material and iron or aluminum oxides, and others. Some bio-cementing may result from the adhesive properties of organic substances excreted by soil fauna or roots. Disturbance of cemented bonds usually completely destroys them and they only re-establish themselves in the same slow way with which they were formed originally, provided the same soil processes are still active. Firmly cemented soil layers are common in sandy and loamy soils. The physical activity of clays (swelling and shrinking) usually prevents their development. Bio-cementing may play an important role in the strength of loose topsoils, even though the forces involved are small.

Friction (i.e., the resistance against sliding over each other of two particles) is, generally, proportional to the normal force working on the friction surface. The proportionality factor (friction angle) is determined by the properties of the surface. The rougher the surface, the greater the friction angle. However, most mineral particles are coated with thin layers of organic or other substances. These coatings are often more stable on slightly rough particles, which, because of the coating, may exhibit lower friction than uncoated smooth particles. In clay, particles are almost completely separated by water and, thus, clay has very little frictional strength. The normal force on the friction surface is the sum of all normal components of the forces working between the particles. The most important are the weight of the particles, the applied forces, and those cohesive forces which remain active after disturbance, predominantly the water tension. The stress on the friction surface is called effective stress, to distinguish it from the externally applied stress. The effective stress, and thus friction, may be very low when the applied stress results in positive water pressures (e.g. some saturated soils, clays).

meso-level

The next level of scale (meso-level) is the homogeneous soil element. In such an element each particle is surrounded by other particles, and each particle has several contact areas. Strain of the soil element involves the breaking of many cohesional bonds, and friction over many differently loaded contact areas. We have no means of establishing forces and strains on the single particle in such a soil element, but in a homogeneous soil element we may assume homogeneous behaviour of the particles. Therefore, the strength of the element is not only a function of the cohesive strength and the frictional properties of each particle contact, but also of the number of particle contacts per unit surface or unit volume (soil density).

The density of a soil element (i.e., the volume fraction occupied by solids) depends on the form and dimensions of the particles and on the spatial arrangement, or packing state, of these particles. A soil composed of round particles with equal diameters can exist in several packing states ranging from approximately three to twelve contacts per particle. In such material, density is independent of particle size. Soils composed of a mixture of larger and smaller particles may reach much higher densities because the smaller particles can fill the holes left between the larger. Such mixtures may have high strength due to the combination of a high number of interparticle contacts and small pores as a result of the many small particles, and the high friction angle of soil element surfaces as a result of the larger particles. Addition of cementing agents may further increase the strength of such mixtures (cf. road and dam building, concrete, etc.).

The most simple strain mode of a soil element at meso-level is the strain in one plane (failure), with the parts on each side of this plane remaining rigid. The cohesive strength is the sum of all cohesive bonds over the plane of strain. Frictional strength, however, is not only determined by the surface properties of each particle, but also by the surface properties of the failure plane. This plane has its own surface roughness which is much greater than that of the single particles, depending on particle size and form. This high friction makes the occurrence of such a clear-cut failure plane unlikely: a smaller or larger zone around it will usually get disturbed as well, involving an unknown number of particles and bonds.

Strain of the soil element not only involves displacement of particles, but of soil water and air as well. Water and air are displaced under a pressure gradient. The flow resistance of the soil determines the pressure gradient needed. The buildup of pressure reduces cohesive and frictional strength. Thus, interparticle strength, while being a good measure for strain within the soil element, is much less determining for the strain of the soil element itself. The dependence of soil strain and strength on flow processes not only makes soil strain a time-dependent process, but also makes soil strength dependent on the dimensions of the soil-element. A larger soil element has longer flow paths and thus needs higher pressure differences, which may result in a great reduction of strength.

macro-level

When considering larger soil elements or natural soils, we often cannot assume homogeneity: cohesive bonds may be orientated or almost absent in some zones or planes, the density will show local variation, and secondary voids (i.e., those being not only determined by particle size and packing density) may be present. Soils consist typically of aggregates of particles which show greater cohesion and density within the aggregates than between them. This gives rise to a more complicated soil strength function, because the aggregates will, to some extent and under low stress, behave like separate soil particles with low cohesive strength and a large friction angle. The strength of the aggregates themselves is largely cohesive. Thus, soil strength is also a function of the arrangement of soil variability (soil structure). In fact, soil particles themselves are also a structural feature, being entities of more homogeneous material in the heterogeneous soil mass. But the strength of the particles is usually such that they may be considered rigid for our purposes. In soil engineering, however, a sub-micro level of soil strength is recognised: the strength of the single particle.

With the same overall density, an aggregated soil will be stronger than a homogeneous one. This is partly due to the combination of high cohesive strength within the aggregates and high frictional strength between them, but the distribution of water and air is equally important. Water is primarily concentrated in the smaller voids of the aggregates, whereas air occurs in the larger inter-aggregate voids. Strain of the soil elements will be concentrated in the weaker inter-aggregate areas where the flow resistance to air is very low. And where aggregates are strained, the flow distance for water to the nearest inter-aggregate void is relatively small, depending on aggregate size. Thus, the buildup of pressure in soil, water, and air, is less than in a homogeneous soil, and the consequent loss of strength is largely prevented.

The development of soil structure, or aggregation, is, to an important degree, the result of the activity of living organisms which not only determine the shape of soil structure but also its strength through the addition of organic compounds with cementing properties. One may distinguish between the active formation of aggregates, a process dominated by the activity of earthworms, and the formation of secondary pores, a process often dominated by root growth, although soil fauna may also be very important. Further strengthening of aggregates results from the growth of fine roots and fungal hyphae.

2.3 Theoretical models of soil strength

Theoretically, it should be possible to define soil strength fully by complete definition of forces and of soil reaction. As it is impossible to measure stress and strain of each single particle in a soil element, such measurements are usually made on the soil element as such, assuming complete homogeneity within that element (meso-level). Thus, soil strength is considered a function of cohesion, friction, and density, but soil structure is ignored. With structure, the particle-character of the soil is also ignored: the soil is considered a continuous material in which the properties are related to the particle composition. According to general stress theory, the state of stress on a soil element in the three dimensional space can be described with three independent stress vectors called the principal stresses σ_1, σ_2 and σ_3. When the principal stresses are not equal, the stress tensor can be divided into a mean normal stress $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$ and a deviatoric stress τ. The deviatoric stress follows from (Koolen and Kuipers, 1983):

$$\begin{array}{ccc} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{array} = \begin{array}{ccc} \sigma_m & 0 & 0 \\ 0 & \sigma_m & 0 \\ 0 & 0 & \sigma_m \end{array} + \begin{array}{ccc} \sigma_1 - \sigma_m & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_2-\sigma_m & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_3-\sigma_m \end{array} \qquad (1)$$

In a similar way we can describe the state of strain with 3 orthogonal principal strains which can be divided into isotropic strain (volume change) and deviatoric strain (deformation). The strength function linking stress and strain is unique for a given soil and, because of the strength effects of water, air, and soil structure, for a given soil condition. At a certain stress or strain soil elements will break or flow. This state is named a yield or failure condition.

The most complete theory of soil strength available at present is the model of critical state soil mechanics (Atkinson and Bransby, 1978). This model describes the state of stress by eight identical stress pairs on the sides of a regular octahedron. The stresses are given by:

$$\sigma_{oct} = (\sigma_1 + \sigma_2 + \sigma_3)/3 \qquad (2)$$

$$\tau_{oct} = [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{\frac{1}{2}}/3 \qquad (3)$$

with σ_1, σ_2, and σ_3 the principal stresses. This model relates the mean normal (*isotropic, spherical*) stress and the deviatoric stress to *soil* density and soil failure in a three dimensional space. Basic elements of the model are the virgin compression (normal consolidation) line (which relates spherical stress to density in the absence of deviatoric stress), and the critical state line (which gives the combination of spherical and deviatoric stress causing deformation at constant volume). This soil strength model is based on isotropic soil conditions and effective stresses. Because of the difficulties in measuring effective stresses, the model can only be applied to dry or drained saturated soils (Towner, 1983) in which effective stresses are equal to applied stresses. Nevertheless, it seems possible to extend the theory in an analogous way to non-saturated soils (Hettiaratchi and O'Callaghan, 1980, Leeson and Campbell, 1983). The more the soil contains large and irregular particles, and the more the soil is structured, the less it meets the conditions of isotropy. Anisotropy also causes soil strength to be sensitive to the loading axes and change of loading axes, and to the loading path. Furthermore, use on a routine basis is still far away because of the large number of measurements needed to define the model completely: for each moisture content and each structural condition, a full series of experiments would be necessary to get a complete picture of the strength of a given soil. As a conceptual framework which integrates much of the older, more limited, soil mechanics models, this model is very useful.

The strength function of most soils is very complex and difficult to determine experimentally. Many simple models of soil strength behaviour have been used as an approximation. Such models usually only apply to a very limited range of soils and soil conditions, and are often not very relevant to unsaturated structured field soils. The basic elements of such models are elasticity (i.e., strain proportional to stress and completely reversible upon relaxation; e.g. behaviour of some peats and dense clays under low stress), plasticity (i.e., strain by constant volume, proportional to stress, and permanent; e.g. wet clays), and viscosity (i.e., strain dependent on time). Many models with these and other elements are possible (Koolen and Kuipers, 1983).

Several models have been developed to describe relevant elements of the soil strength function. Most widely used is the Mohr-Coulomb failure theory, which describes soil shear strength in terms of cohesion and friction. This theory defines the principal stress combinations which lead to failure. The soil is represented as a rigid-plastic material, in which yield stress only depends on stress level, whereas in reality, mobilisation of shear strength of soils always involves volume changes. While this theory has proved useful for calculations of bearing capacity of dense materials which have little volume change, it is not very well suited for the more general study of soil strength phenomena which do not depend on well defined failure planes, such as soil compaction (Karafiath and Nowatzki, 1978).

Instead of the stress-strain relation, one may consider the energy-strain relation as the most relevant strength function. This has the advantage of being more directly related to the number of cohesive and frictional contacts actually activated in the process. Thus, it may give a better description of the strength and strain of soil structure. So far, this has been seldom used because of the theoretical and technical difficulties involved (e.g. Fattah et al., 1981, Yong et al., 1984).

In the field of soil engineering (in which non-structured, dense, and dry or saturated soils prevail) the available strength models have found wide application. In the field of terramechanics, the applicability of the available soil strength models is limited because the soils of interest are usually non-saturated, structured, and relatively loose. Even when it may be possible to define soil strength adequately in terms of change of volume and deformation of the soil element, the deformation of soil structure remains unknown. Moreover, the sensitivity to loading path and loading axis is not accounted for in any of these models. Another important problem is the fact that, in the field situation, stresses are usually applied on one surface of the soil element. The stresses on the other sides of such elements, and on other elements, result from the stress transmission through the soil. Such stresses are very difficult to measure and can only be estimated on the basis of the same false assumptions about soil homogeneity and effective stresses.

2.4 Stress transmission in soil

Whenever we consider the stress-strain relations of larger soil elements, we shall have to consider how the stresses applied to (part of) the surface of that element are transmitted. A non-uniform stress distribution results in a non-uniform strain distribution (a uniform stress distribution usually also results in a non-uniform strain distribution because of non-uniform strength).

When we load one particle of a granular material, this particle will transmit the force through all contact points with other particles. The direction and amount of transmitted forces depend on the orientation and number of the contact points relative to the applied load, and on the cohesive and frictional strength of the bonds between the particles. When the force on a particle exceeds the combined reaction force of all contact points, it will move in the direction of least resistance until the reaction force is sufficiently increased. This process results in soil failure whenever reaction forces do not increase upon particle movement, and in soil homogenisation and soil compaction when they do. Of course, it is impossible to describe the resulting pattern of forces on each particle in a soil with its large number of particles of irregular form and its structural features. Ignoring the particulate character will give poorer results the larger and more irregularly formed the particles are, or the stronger the soil is aggregated. Further complications arise from the transmission of forces via soil water and soil air, because of their effect on soil strength. Whenever one ignores the single particles and aggregates, one should consider the soil as a continuum and consider stresses instead of forces.

Direct measurement of stresses in the soil is extremely difficult because the measuring device has to have the same strength properties as the soil to be measured in order not to disturb the stress transfer process in the soil: if it is too strong, stress concentrates on the device; in the other case, stress concentrates on the soil around the device. Furthermore, it should be able to measure the direction of the stress. The water and air pressure have to be measured separately when the measured soil pressure values are to be transferred into effective stresses.

An exact measuring device can be the soil itself: strain of soil elements may be related to stresses, provided the strength function of the soil is adequately known. This is usually restricted to situations in which relatively homogeneous soils are stressed under conditions of small deviatoric stresses, in which case soil strain may be expressed in terms of soil density. In all other situations, artificial devices have to be used; for example: pressure cells (measure stress in one direction, but form a considerable discontinuity in the soil and are not very reliable), balloons (no directional measurement, but strength may be adjusted to soil condition by using different fluids in the balloon and adjusting the capacity of the measuring device; Bölling, 1984), or massive plastic materials (these may be used for directional measurements, but the material has to be adjusted to the soil properties and the practical use is restricted).

The most sophisticated method for predicting the stress distribution in soil is using finite element analysis. The soil continuum is represented as an assemblage of a finite number of elements or small segments which are interconnected at nodal points. The behaviour of the continuum is predicted by approximating the behaviour of the elements (Perumpral et al., 1971). This method makes it possible to account for some aspects of the particulate, aggregate, and heterogeneous properties of the soil, and is a major tool in the theoretical analysis of soil strength functions. However, the amount of work involved in such analysis is prohibitive for any routine application. Moreover, lack of knowledge of the behaviour of the elements may severely limit the accuracy of the analysis.

A basic stress distribution theory is the Boussinesq theory for elastic mediums, which has been modified with an empirical concentration factor by Fröhlich (Söhne, 1953). This has been used for the calculation of pressure distribution in different soils under tyres (Söhne, 1958; and many others after him). However, soil cannot generally be assumed to be an elastic material. In a plastic material, the effect of surface loading is decreased over a shorter distance from the loaded surface than in an elastic material (Karafiath and Nowatzki, 1978). In heterogeneous or layered soils, stress transfer may show considerable discrepancies with the above models (e.g. Taylor et al., 1980).

The transmission of stresses also influences the relation between spherical and deviatoric stresses. When a normal stress is applied on the surface, this will usually be the first principal stress if no shear stresses are applied. The second and third principal stresses depend on the transmission of this applied stress and on the strength of the surrounding soil. In a very loose soil with low strength, the second and third principal stresses will remain low and, therefore, deviatoric stress will be high (resulting in a condition which resembles unconfined compression). In denser and stronger soils, deviatoric stresses will be lower (resembling confined compression), but isotropic compression occurs only under influence of water tension in the absence of applied stresses. Soil failure occurs when shear stresses locally exceed shear strength. The stresses on a given soil element also depend on the position of the soil element in relation to the loaded surface and on the extent of the loaded surface.

A vehicle exerts stresses on the soil in the contact area with the wheels or tracks. Most important are the normal stresses caused by the static and dynamic weight of the vehicle, and the shear stresses caused by powered or braked wheels. Further stresses develop in the contact area due to the tread and flexibility of the tyres. Thus, a complicated pattern of normal compressive and tensile, and shear, stresses develops. The absolute value of the stresses depends not only on the vehicle, driving forces, and tyre characteristics, but also on soil properties: especially on soil strength, which determines the maximum reaction force of the soil, and thus the maximum stress on the soil.

Within the soil the stresses are transmitted according to the soil properties. With depth, normal stresses decrease more or less according to a quadratic function, shear stresses more or less logarithmically, the resulting first principal stress becoming more vertical with depth. Stresses spread in all other directions, too, depending on the soil properties. As a result, the axis of the principal stress, through a given point in the soil, rotates during the passage of a wheel.

Soil strain in reaction to the passing wheel depends on the changing stress field and soil strength. Typically, a soil particle near the surface first moves forward or sideward and upward as the wheel approaches (due to wheel sinkage, bulldozing effect), then downward and backward when it comes under the wheel (due to load and shear forces), and finally slightly upwards again (due to soil elasticity and soil adherence to the wheel). The end result of this path depends on wheel slip and soil properties. With increasing depth, horizontal displacement usually decreases considerably due to the sharp decrease in shear stresses. Clearly, the final displacement of the soil particle, and thus the final strain of a soil element, is always smaller than the maximum strain during the process. Usually, change of soil structure depends largely on the strain process, whereas soil density depends on the final strain. Soil structure features (e.g. infiltration rate) are, therefore, generally more sensitive to vehicle passage than soil density.

Shear stresses in the surface layer caused by wheel slip and tyre tread commonly exceed soil shear strength which causes failure, loss of cohesional soil strength and possibly soil dilatation (i.e., decrease of density). Such shear failure and strength losses limit the maximum pull a vehicle can develop on that soil. Wheel sinkage, another limitation to vehicle mobility, may result from compaction, displacement of soil (either as soil flow in wet circumstances or along failure planes in drier conditions: exceeding of bearing capacity), and from the digging action of slipping wheels.

A growing root exerts stresses on the soil at the root tip as it forces itself through the soil, and along the length of the root as it grows thicker. Because of the very low friction between root and soil, both processes are assumed to exert the same stress field of spherical expansion. The first principal stress is directed outward radially from the root surface in all directions. Because of the expanding circles around the root, tensile stresses will develop parallel to the root circumference and the soil will expand laterally as it is compressed: compression takes place under relatively high deviatoric stresses.

2.5 Empirical models of soil strength

In most cases in which loading of natural field soils is studied, the definition of the stress field proves very difficult and the formal definition of the soil strength function almost impossible. The obvious solution to this problem is the use of empirically defined strength functions in which the loading conditions of interest are simulated as closely as possible, and in which the strain can be measured in any terms which seem to be relevant. The resulting strength functions may be extrapolated to other soils or soil conditions, either by statistical correlation with elements of soil composition and soil structure, or by correlation with other, more simple, strength measurements, or by theoretical analysis of the results in terms of soil constants or soil strength factors which can be measured separately.

The possibilities for extrapolation and theoretical analysis of such empirically defined strength functions depend on the form of the measuring devices and the control over the variables during the measuring process. Thus, there is a conflict between exact simulation on the one hand, and the use of geometrically well-defined measuring devices on the other hand. Not surprisingly, this conflict has been the source of many long discussions in literature.

For reasons of standardisation, but especially because of the costs of full-scale experiments, measurements will usually be executed with down-scaled devices. Because of the particulate and aggregate nature of soil material, scaled devices can be expected to give different results whenever the device has the same dimensional order as the particles or aggregates, which is commonly the case. More rarely, up-scaling is necessary (e.g. the use of penetrometers to simulate soil resistance to rootgrowth), in which case the results may be highly unreliable because of the influence of particle and aggregate dimensions on that level. A further problem with scaling is the inclusion of non-structural soil variability. The smaller the device, the larger the variability it will experience. Especially in the case of measurements of the soil profile, which is seldom homogeneous in depth, the possibilities for scale measurements at the surface are limited. A third relevant aspect of scaled measurements is the time factor, which is too often neglected. To simulate a certain process at given speed with a down-scaled model, the speed of the model has to be increased in absolute terms. This can be illustrated by the strength decrease in loaded soil due to increasing water pressure, which depends on the transport distance and thus on the loaded area. To get the same pressure increase in a smaller loaded area, loading speed has to be increased. So far very little work has been done on the analysis and quantification of this time factor in model experiments (cf. Ehrlich, 1985).

The stress field under vehicle tyres shows a highly complicated pattern which depends on load, slip, tyre tread, and soil. The soil is generally highly variable, both in space and in time. Therefore, results of full-scale vehicle tests are difficult to measure in detail and to analyse, and thus not easy to extrapolate, whereas the costs of such tests usually make it impossible to cover all conditions and variability of interest. When high accuracy is needed, the use of a test vehicle or a single wheel tester may be warranted. In the field of mobility research and soil-tyre interaction, however, empirical methods are widespread. Any such method will have to cover the two basic stress processes in soil-vehicle interaction: normal stress due to loading factors and shear stress due to driving forces.

One of the most widely used methods is the plate sinkage and ring shear method developed by Bekker (1962, 1969) and modified by many others (e.g. Wong, 1980, Golob, 1982, Turner, 1984). Pressure-sinkage relations of the soil are measured with two different circular plates from which co-efficients are developed which can be used for extrapolation to other plate sizes. This is considered a model for the soil-tyre contact. A problem is the heterogeneity of the soil profile which influences the pressure-sinkage relation irregularly depending on scale, thus making extrapolation impossible. This is the more common situation in natural field soils. Shear strength of the soil is measured with a ring which is turned under different normal pressures. Scaling problems may exist with this method as well, and the penetration depth of the ring may be highly critical in non-uniform soil profiles. Also a serious problem is the effect of the grousers on the ring, because these make the analysis of the results very complicated and extrapolation difficult. The Bekker method has been widely used, often with great success, but it seems questionable if the relatively high costs of this method (because of the limitations to the scale of the devices) are justified by the results on natural field soils. This method is less suited for study of the change of soil properties as a result of the passage of a tyre. The loaded area is generally too small for adequate sampling, and the variability of the soil remains another problem.

Another approach to the mobility problem is the use of rigid wheels with well-defined geometry as a simulation of tyre-soil interaction (e.g. Arts et al., 1981). Such experiments allow for the expression of rolling resistance and sinkage as a function of wheel geometry, which can be extrapolated to tyres if the geometry of the loaded tyre is known (which is a difficult problem in itself). Because a long strip is loaded, sampling for soil analysis is possible. However, this method does not allow for shear strength measurements.

A further, drastic, abstraction from reality is the use of a penetrometer which measures the resistance of the soil to penetration of a standardised cone. The penetration resistance depends on friction and cohesion, but theoretical analysis of the process is so far impossible, except under some well-defined conditions. Nevertheless, the loading conditions appear to simulate tyre-soil interaction well enough to provide an indication of vehicle mobility (Wismer and Luth, 1974). The addition to the penetrometer of a vane allows for separate measurement of shear strength on soils with low friction, and thus increases its accuracy (Yong et al., 1975). The ease and low cost of penetrometer use have stimulated its application enormously, notwithstanding the sometimes fierce opposition by those who criticise its lack of theoretical foundation. Results are best in soils with low friction (Reece and Peca, 1981). Therefore, the value on structured or sandy soils is doubtful.

The penetrometer is also widely used to characterise the changes in soil condition caused by vehicular impact. The impossibility of differentiating between structural and density effects on soil strength, and the sensitivity to moisture content, limit its application for this purpose to reconnaissance studies.

It is probable that the accuracy of prediction by measurements without theoretical foundation, such as the penetrometer, could be greatly enhanced by simultaneously using a second measurement based on a different loading process. The more the two measurements are independent of each other, the better the results could be, as long as the loading processes involved also occur under tyres. Little research has been done along this line so far (e.g. Koolen and Vaandrager, 1984).

In the laboratory, a much more rigorous control of soil conditions is possible, thus removing the problem of soil variability and allowing for further reduction of scale of measuring devices. Thus, a more detailed theoretical analysis of soil-tyre interaction is possible, as well as a more complete coverage of different soil conditions (e.g. moisture content, initial density, etc.). Measurements take place either in a soil-bin or on soil samples. The soil-bin approach is very laborious and costly and, therefore, more useful for comparative study (e.g. of different tyres), and for theoretical analysis of soil-tyre interaction (e.g. Yong et al., 1980), than for routine simulation of soil strength properties and soil behaviour under tyres. The soil-sample approach is very versatile (Koolen, 1978) and a large number of standard tests are in use all over the world measuring compactibility and shear strength in simulation of soil-vehicle interaction.

The most important compactibility tests are:

- triaxial test: this test allows for continuous measurement of soil sample deformation under well-defined applied principal stresses. Effective stresses are not known, however, unless dry or saturated samples are used. Further problems may arise from sample geometry. This test is also very laborious if soil behaviour is to be described fully, and the results are not always directly applicable because the stress field in the soil is not accurately known.
- confined compression test: the soil sample is enclosed in a rigid cylinder and loaded vertically. This test is used in a slow saturated version as the

consolidation test in soil engineering and in a rapid unsaturated version as a simulation of tyre-soil interaction. The confined condition of the sample, which does not allow for lateral expansion during compression, is considered a reasonable simulation of the stress condition deeper in the soil or under a relatively large loaded surface. Measurements of soil-water relations or air permeability, before and after loading, provide a measure of soil structure. The friction between soil and cylinder is a problem in this test, but this may be reduced by choosing the right dimensions of the sample (Koolen and Kuipers, 1983).

- unconfined compression test: in this test the soil sample is not supported laterally, which causes the sample to fail under a load. The unconfined compressive strength plays a role in the compaction of loose, aggregated soils, because the single aggregates may be almost unconfined.
- Proctor test: this test is highly empirical, because the stresses in the soil are not theoretically defined, but which may be assumed to simulate compaction under conditions of relatively high shear stresses and rotating stress axes. Moreover, the compactive effort can be easily expressed in terms of energy in this test.
- other compactive tests with shear component: many other tests have been developed to evaluate the effect of shear stress on soil compaction (e.g. Raghavan and McKyes, 1977), but none of these tests is generally accepted as a standard. It is highly doubtful that they will, because they lack theoretical foundation and are also not clearly a good simulation of stress under tyres.

Some important shear tests include the direct shear test, torsional shear test, and vane shear test. Finally, the penetrometer can be used on soil samples as well, with the same restriction and possibilities as mentioned above for field use.

The penetrometer is also the most widely used instrument for simulation of root growth. The most important differences with a growing root are: size (the penetrometer is oversized and not flexible, causing important differences in structured soils with secondary pores large enough for roots), high penetration speed (for example, causing a buildup of water pressure, whereas the root lowers the water content around it), and friction (making penetrometer readings sensitive to tip-angle, material, and wear of the conus, and causing different stress fields in the soil). As long as these shortcomings are realised, the penetrometer proves a cheap, quick, and useful instrument. In soil engineering, the resistance against spherical expansion is also measured with a flexible pipe which can be pumped up with water. This much more laborious method is also hindered by the oversized dimensions and does not seem very useful for the study of rooting properties.

For the evaluation of soil structure, a great number of methods are available. The simple description of visual characteristics of aggregates and pores, including estimates of dimensions and numbers, form a standard routine in all soil surveys. Great progress has been made in the refinement of this description of soil samples with the aid of binocular microscopes and microscopic technics, and in the quantification of the pore system with the aid of image-analysers (micromorphology, e.g. Bullock and Murphy, 1985). Three dimensional analyses of pore systems can be made with scanning methods (e.g. röntgendifraction on stereoscopic photographs) or by filling the pores with a hardening material after which the soil is washed away (e.g. Rogaar, 1974).

Nevertheless, the most common and easiest method for quantification of the pore system still depends on indirect measurements: water retention and water flow or air flow in the soil under known conditions of pressure, tension, or gradient. This is the vast terrain of soil physics in which great progress has been made in recent years. Most widely used are infiltration rate, sorptivity, saturated and unsaturated conductivity, water retention with hysteresis effects, and air permeability. Usually one chooses those measurements which are most relevant to the problems experienced in the area of study: for example, infiltration rate where erosion is a problem, unsaturated conductivity where capillairy rise of water may cause problems with freezing or salt transport, etcetera. Extensive efforts have been made, with variable success, to link the different values to each other and to elements of soil composition such as texture, organic matter, and others.

3 METHODS

3.1 Choice of methods and areas

The aim of this study has been defined (§ 1.4) as the description of soil changes caused by off-road vehicle traffic in forest operations in such a way that prediction of impact is possible in any practical situation, at least in the Netherlands, as well as to facilitate interpretation of such predictions in terms of vegetation development, soil cultivation, road building, and vehicle performance. The final aim is to include soil management and forest operations as integral parts of all forest management. This wide field of study lies on the cross-section of soil pedology, soil physics, soil mechanics, vehicle mechanics, and forestry: all of them vast subjects of specialist scientific study with a long history of development. Clearly, my study will not aim primarily at the further theoretical development of any of these subjects as such, but at the integration of existing knowledge with the biological and technical aspects of forestry, and at the development of practical decision tools for the forest manager.

Integration, and not just summing up, of knowledge is only possible through the study of fundamental properties and the use of standardised methods. The necessary measurements have to be taken under controlled experimental conditions, excluding variability as much as possible. This virtually limits the possibilities to laboratory methods, since extremely laborious and costly methods are excluded in this study. Less rigorously controlled study conditions will make quantification difficult, while rapidly changing technical specifications of machinery and the variable views on forest road networks and management aims outdate any such study within a short time, making extrapolation in time or place almost impossible. The limited value of a large number of case-studies on this subject all over the world demonstrates this. Obviously this problem is strongly accentuated by our lack of theoretical understanding of the wheel-soil interaction in natural terrain and by the lack of adequate measurement techniques. This same lack of fundamental knowledge forces us to use more empirical methods in simulation of this interaction than we would like to do (§ 2.5). Simplicity, finally, is an important feature of methodology, if general use in the usually extensive forestry practice is wanted.

Even though the accent is on laboratory studies, nevertheless some field work is indispensable, not only to determine representative areas and to locate problem areas, but also as a control for the developed models. Somewhere along the way it is also necessary to re-introduce the field-variability, which has been disregarded so carefully when taking the problem to the laboratory. Finally, many of the most important factors determining soil properties and soil condition depend on the field situation: climate, topography, vegetation, and man. No forest survives on an office desk, and no forester will understand his forest fully from that desk. Fieldwork for my study was largely restricted to survey work and some additional experiments. Full-scale experiments were not executed in view of the limited resources available.

At an early stage, it was decided to limit this study largely to sandy and loamy soils. Such soils underlie 95 percent of the Dutch forest area (§ 8.1) and are important in many other parts of the world. Furthermore, inclusion of other soil types (clay, peat, or vulcanic) would require a completely different methodology and, therefore, a separate study (e.g. with respect to swelling and shrinkage). Finally, the latter soils are often somewhat protected against soil compaction by their low bearing capacity under wet conditions. Mobility is often a greater problem on these soils than compaction, and certainly a different problem.

According to the theory (§ 2.3, § 2.4), soil strain under vehicles is determined mainly by spherical stress, deviatoric stress, and change of stress axes. Forces are applied to the soil surface, and the resulting stress field depends on soil properties, changing as the soil changes, even when the applied force remains constant. The change of stress axes depends on soil properties and on the applied stresses, which may rapidly change depending on traction and vehicle speed.

To simulate this wide range of variable stress fields, three compaction tests were used. Firstly, the uniaxial confined compression test, which is characterised by a fixed principal stress axis and the lowest deviatoric stress which can theoretically occur in the field (e.g. under large static loads and in deeper soil layers). This test simulates one end of the range of possible stress fields, since isotropic compression does not occur in the field and would thus be less relevant. The second test is the standard Proctor test. In this test the sample is loaded sequentially on a small part of the surface, resulting in relatively high deviatoric stresses and important changes of the stress axes. This test simulates the other end of the range, even though possibly not the extreme end. The Proctor test was mainly used as a reference because it is one of the most widely used tests in soil engineering. However, stresses used in this test are much higher than occur in normal off-road traffic. Furthermore, the samples used in Proctor tests do not lend themselves to easy measurements of soil-water relations. To overcome these problems, a third test was developed, following a comparable loading principle as in the Proctor test, but using the same type and size of samples as in the uniaxial compression test, loading them by hand at much lower stress.

Penetration strength was used as a comparative value of soil strength, both in the field and on soil samples. This method was chosen because of its simplicity and its world-wide use for similar purposes. Measurements were used to monitor soil strength and soil change, to indicate root development possibilities in the soil, and to predict soil behaviour under loading. A small vane shear apparatus was also used as a comparison to penetrometer readings. No other shear measurements were taken, because their interpretation in terms of soil compaction is largely unknown and the methodology more complicated. This limits the results of this study as far as the prediction of vehicle performance is concerned, but such prediction was not a primary aim of this study.

The moisture relations of the soil were characterised by water retention (pF-curve) and (un-)saturated conductivity: both widely used and often available standard measurements. These measurements served to define moisture tension and content during experiments in the field and laboratory, to characterise soil structure and changes of soil structure, to indicate conditions for root development and root functioning in the soil, and to predict soil moisture condition in the field as a function of drainage, climate, and vegetation. For all these purposes a qualitative comparison of samples before and after loading was considered more important than accurate measurements of absolute values. No measurements on soil air were undertaken, even though the importance of soil aeration to root growth and functioning is undisputable. However, easy standardised methods are still lacking, and it is highly doubtful if measurements on relatively small soil samples are more reliable than predictions based on the interpretation of soil-water relations. Soil structure was also visually assessed to explain qualitatively the measured soil-water relations, but more sophisticated methods of structure assessment were not considered worthwhile for this study after some preliminary experiments.

The soil samples used in this study were analysed for pH, $CaCO_3$, texture, organic matter content, and specific density. No analyses were made of other chemical soil factors, as most samples represent poor sandy substrates with low pH in which no great effect of chemical soil factors is to be expected. Moreover, the studied areas and soil types are described in literature, giving generalised figures on chemical factors and on soil processes; these are considered adequate for this study (chapter 8).

The selection of areas for detailed study was based on a country-wide qualitative survey of forest and soil types, and forestry practices. This survey was based on available soil and plantation maps, inquiry of forest managers, and field observations with the aid of soil auger, penetrograph, and tensiometer. Field measurements were concentrated in areas identified by the local forest manager because of recent mechanised forest operations, the use of heavy off-road vehicles, or encountered mobility problems. The chosen study areas had to be representative of a certain landscape and soil type and, together, had to represent the majority of the sandy soil types in Dutch forestry. Preferably, study areas were chosen in medium-aged and recently thinned Douglas-fir forests. This choice was made to make the different study areas comparable, to have little ground vegetation, and to have recent tractor trails. Moreover, the Douglas-fir is one of the most productive and promising tree species for sandy soils in the Netherlands and much research has been devoted to this species in recent years. If representative stands were not present, other tree species (beech, poplar) were chosen.

Field work was carried out from January to June, depending on weather conditions. Unfrozen soil, approximately at field capacity, was taken as the standard condition for field work.

3.2 Field procedures and sample preparation

Field work in the selected areas consisted of the following, usually in five replications some fifty metres apart:

- description of the soil profile: the litter layer and upper mineral layers were taken out with a spade, deeper layers (up to 1 meter) usually with an auger; classifications of soil colours (Munsell), texture and sand grade (sand ruler), and soil type (Dutch classification, Stiboka) were made, checking with soil maps for representativeness
- measurement of penetration resistance to 80 cm depth (3 or 5 replications of each measurement) and of soil moisture tension at 5-10 cm, 20 cm, and 40 cm depth.

From these measurements, one representative area which appeared largely undisturbed and not too close to major trees, was chosen for detailed study and sampling. This area was carefully cleared of all organic debris and litter, without soil disturbance, over a surface of 2-3 m^2, and the penetration resistance of the top soil was measured in a regular pattern with a pocket penetrometer. After these measurements, a series of soil samples was taken in the cleared area. Samples were taken at 2.5-7.5 cm or 5-10 cm depth and at 20-25 cm depth, the latter under the first after removal of excess earth. The following samples were taken:
- undisturbed 100 cc core samples (ø 50 mm, height 50 mm) for measurement of water relations (3-5 replications)
- undisturbed 250 cc core samples (ø 80 mm, height 50 mm) for compaction measurements (5-10 replications)
- bulk sample of approximately 15-20 kg fresh weight for soil analysis and for the preparation of samples for experiments, taken from the soil around and inbetween the core samples at the same sampling depth
- some additional core samples (100 cc and 250 cc), taken in adjacent areas with either relatively loose soil (e.g. near tree base) or dense soil (e.g. vehicle tracks) for comparison (3 replications).

All core samples were taken in metal sample rings (wall thickness 1.5 mm) which had a sharpened edge at the lower side. The rings were pushed in the soil manually with the aid of an extension rod. In some cases a rubber hammer was used. All samples which appeared disturbed, abnormal, or which contained large stones or roots were discarded. All core samples, retained in the metal rings, were trimmed to size with a small saw, covered underneath with 150 µm-mazed nylon cloth which was held in place with an elastic ring, and stored in a closed wooden box. All handling was done with great care to avoid shocks and disturbance. The bulk samples were stored in closed plastic bags.

The whole fieldwork procedure was devised to take series of core samples with as little variability as possible, to take bulk samples with a composition as close as possible to the mean of the core samples, and yet to ascertain the qualitative representativeness of the sampled area. Nevertheless, core samples usually showed a fair amount of variability in density, structure, and composition. This is due mainly to the fact that most sampled soils were tilled in the past, like most forest soils in the Netherlands. Therefore, experimental data on undisturbed cores are mostly interpreted qualitatively in relation to experimental data on prepared ring samples. The preparation method of the ring samples from the bulk soil samples aimed at removing all variability other than of the factor of interest, to facilitate deterministic interpretation while keeping the soil structure intact as much as possible.

In the laboratory, the bulk soil sample was thoroughly mixed by hand, removing only large roots (> ∿ 2 mm) and stones (> ∿ 1 cm), and crushing clods (> ∿ 1 cm). But otherwise, care was taken to exert little stress on the soil and to retain smaller roots and stones and the aggregated structure of the soil. The soil mass was then separated in portions and prepared for different experiments:

- 300 g samples (3 fold) for determination of moisture content (oven-dried at 105 °C for 24 hours)
- 3 kg for mineral analysis (air-dried for 1 week or longer)
- 5 kg for preparation of samples (field-moist enclosed until sample preparation)
- 4 kg for repeated Proctor test (air-dried to approximately 5% moisture)
- 4 kg for fresh Proctor test (field-moist enclosed until testing).

The accuracy of mixing was determined via the moisture content. Differences between samples taken from the bulk soil mass were usually below 0.2 weight percent moisture.

Metal rings of 250 cc were standardly filled with mixed field-moist soil material from the bulk sample (10 replications) and compressed uniaxially, by hand, in three layers with a pressure of 0.2 to 0.3 bar. The density thus obtained was usually slightly lower than the average bulk density of undisturbed field samples. All surplus soil was trimmed off with a small saw and the samples, retained in the metal rings, were covered underneath with

150 µm-mazed nylon cloth, like the undisturbed samples. Other filling procedures and different pressures were used when of interest, and for a series of 100 cc samples. The accuracy of this method was very high. The standard deviation of the bulk density of a series of ten samples was usually less than 0.01 g/ cm^3. Even cores filled one month later with the same soil (kept enclosed in plastic bags) and pressure, differed less than 0.03 g/cm^3, on average, with earlier filled cores; and this difference could often be explained by a slightly lower water content.

After this, both undisturbed and prepared samples were treated alike. The 100 cc samples were used for measurements of water relations. The 250 cc samples were equilibrated to different moisture contents, either on a standard sand-pF installation with low tension for moistening, or on dry filter paper for drying. Monitoring of water content was by weighing. After the samples had reached a particular water content (forming a series from relatively dry to relatively wet) they were enclosed for 1 or 2 weeks to assure homogeneous moisture distribution within the sample. Then testing started.

3.3 Description of measurement methods

The uniaxial confined compression test was executed on soil samples enclosed in metal rings (height 50 mm, internal diameter 80 mm, volume ∿ 250 cc) which were covered underneath with 150 µm-maze nylon cloth held in place with elastic rings. The samples were placed on a large flat metal plate and on top of the sample a loose metal plate with a diameter of 75 mm was placed to spread the applied forces evenly over the surface. Loading was done on a hydraulic test bank with a constant piston speed of 3 mm/s in simulation of loading rates in the field. The piston was stopped by hand at a given load, resulting in a constant load for a certain time (depending on soil settlement and slight piston creep), or abruptly moved upward with the same speed, resulting in almost simultaneous removal of the load (depending on soil elasticity). Thus any loading sequence was possible, within the limits of the reaction time of the operator and up to a maximum of 6 bar. Force and position were continuously recorded on a x-y plotter. Forces were occasionally checked with pressure transducers, piston position was checked for each measurement with a micrometer (reading accuracy 0.1 mm) mounted on the piston. Soil density for each force and loading sequence was determined from the sample height as recorded on the plotter, after adjustment for begin-and end-height as measured with the micrometer, and after adjustment for quick elastic rebound of the sample. Quick elastic rebound was determined from the sample height at which the piston (moving down again within 30 seconds after load removal) encountered resistance, as recorded on the plotter. Unless reloading was part of the loading sequence, the load was removed again at that point. Slower elastic rebound was measured with a micrometer, one hour after loading. Very low loads were applied by hand with a spring, calibrated up to 100 N (0.2 bar). This was used in most sample preparation work.

The uniaxial test gave highly reproducible results in terms of soil density, both for sample preparation and for compression tests. However, wall friction proved to limit compression of stronger samples, and at higher pressures, as can be expected theoretically (Koolen and Kuipers, 1983). Differences were small, however, as can be seen from the density reached by compressing samples of only 20 mm height in the same rings, which differed usually less than 0.03 g/cm^3 from the density reached in samples of 50 mm height. The full rings also show a slight decrease of density with depth, which was recorded with a micropenetrometer. Because these small differences were considered acceptable, full ring compression was used throughout this study (except in sample preparation, which was done in three layers).

Under moist to wet conditions, some water was pushed out of the sample at the bottom. Under very wet, and sometimes also under very dry conditions, soil was pushed out of the ring at the top, through the narrow space left open between the ring wall and loading plate. This latter phenomenon is called failure, and loading was stopped when it occurred. Quantitative interpretation of these phenomena is difficult because of the unknown flow resistance of the respective surface configurations.

A standard Proctor test was used, applying 25 blows with a hammer (mass 2.5 kg, diameter 51 mm) falling from 305 mm on each of 3 layers of soil enclosed in a metal ring screwed onto a footplate (ring height 116 mm, internal diameter 102 mm, volume 944 cc). The sample turned 58° automatically after each blow. Density was determined by weighing the total sample and correcting for moisture content, which was determined by oven-drying a small sample of soil taken at several places from the sample. Proctor densities were determined either repeatedly on one soil sample which was re-used at different moisture contents (repeated test), or singularly on fresh soil samples, each with different moisture content (fresh test).

A hand compaction test was used on prepared soil samples, both in 100 cc and 250 cc rings. The surface of the soil was loaded with a round flat metal plate (surface area 2 or 5 cm^2) mounted on a spring, calibrated to 100 N. Loading was done by hand to a certain pressure on each part of the sample surface in a sequential way (not unlike the Proctor test), going round along the side of the core and then to the middle, with little overlap, thus covering the surface approximately once (e.g. 10 times loading of 5 cm^2 or 25 times loading of 2 cm^2 on the 250 cc sample with a surface of 50 cm^2). Sample height was determined in half millimeters by taking the average of 4 readings of the surface, because of the slightly uneven surface resulting from this compression method. Height accuracy was within 1 mm (resulting in density differences of approximately 0.02 g/cm^3), and reproducibility was remarkably high. Wall friction played a minor role in this test, due to the localised loads, but one cannot assume homogeneous stresses under such small loaded surfaces to 5 cm depth. Nevertheless, the differences in density of a 2 cm- and a 5 cm-high sample loaded in this way were relatively small, although larger than in the uniaxial test, especially by higher soil strength (up to 0.06 g/cm^3). As in the uniaxial test, loading of full ring samples was used as a standard, while loading in three layers was used for reference and for special purposes. Unlike the uniaxial test, in this test the soil sometimes failed under the load in all moisture conditions. Such failure is considered a measure for the bearing capacity of the soil.

In the field, a hand-operated penetrograph was used (Stiboka/Eykelkamp), which graphically recorded penetration resistance (to a maximum of 500 N) against depth. A cone with a tip angle of 30° and a maximum diameter of 13 mm, screwed on a 0.8 m long shaft with a diameter of 10 mm, was used. If shaft friction occurred, some measurements in deeper layers were made after augering a hole down to the required depth. Care was taken to take the measurements in a constant way: all measurements were done by the author, and penetration speed was held approximately at 2 cm/s.

For small-scale measurements of topsoil in the field and of soil samples, a hand-operated pocket penetrometer (Eykelkamp/Soiltest) with a flat top with a diameter of 6.3 mm on a 50 mm long shaft of equal diameter (maximum load

100 N) was used. In spite of the rather different model, the resistance values per surface unit measured with this penetrometer proved to be almost exactly the same as those measured with a cone with a tip angle of 30° and a diameter of 5 mm on a shaft with a diameter of 2 mm. This latter cone was used in a motorised version with an automatic plotter to measure accurately penetration resistance against depth in soil samples. For all practical purposes, therefore, the pocket penetrometer could be used as a very easy and accurate tool. On denser or stronger soils the surface around the penetrometer point was loaded to prevent upheavel of the soil due to the penetration. This load was applied by hand over the full surface of the samples, using a wooden disk with holes for the point of the penetrometer. In the 250 cc samples, three measurements could be taken without interference, except in very strong soils. If soil disturbance was to be avoided because of further experiments with the sample, penetration resistance was measured to a depth of 6 mm. Although this resulted in slightly lower values, the differences were usually consistent.

Moisture tension in the field and on soil samples was measured with a quick-draw tensiometer (Soiltest, diameter of ceramic cup 5 mm, length of metal shaft 0.45 m, possibility for pre-setting of tension to reduce equilibration time). This tensiometer worked rapidly and accurately, up to 20 cbar on sandy, and 30-60 cbar on loamy and clayey soils, which covered most of my experimental conditions. Moisture content was determined gravimetrically by oven-drying for 24 hours at 105 °C.

The wet part of the pF-curve of soils was determined experimentally on the 100 cc ring samples. Both undisturbed field samples and prepared samples of different densities were used. The experimental set-up was along the lines described by Baker et al. (1974). The samples were placed in a no. 4 glass filter (pore ø 10-16 µm), which was connected to a 50 ml graded pipet through 2 m flexible tubing (outside diameter 6 mm, internal diameter 3 mm, with high volume stability). The whole system was filled with de-aerated water and covered to prevent evaporation. The sample was weighed before putting it on the glass filter, and any in- or outflow of water could be seen directly on the pipet without any disturbance of the filter-sample contact. The maximum tension measured routinely was 150 mbar, because higher tensions took a very long time before equilibrium was reached (because of the loss of filter-sample contact) and caused problems of air-entry through the filter.

Usually, differences between samples of different densities were already small at 100 mbar tension, and within accuracy limits at 150 mbar. Samples of different density and structure of the same soil were measured concurrently to ascertain comparable conditions. At the end of the measurements (after 1 to 3 weeks), the samples were weighed, oven-dried, and weighed again. Usually, unexplained water losses amounted to less than 1 cc per sample and were probably caused by evaporation. To complement the pF-curves for drier soil conditions, moisture tension of samples dried to different water contents was estimated by using the filterpaper method (Hamblin, 1981). Water content of the filterpaper (Whatman no. 42 paper), after an equilibrium time of up to 1 week in contact with the soil, was translated in tension values using the graph provided by Hamblin. No attempt was made to detect differences caused by soil structure with this method, because differences measured at 150 mbar tension were usually already negligible.

The same set-up and samples as used for the wet part of the pF curve were also used for the measurement of unsaturated conductivity. Two methods were employed: firstly, the outflow of water was measured in the pipet directly following the installation of a given tension value after the sample was in equilibrium at the last tension value (Gardner, 1956), and secondly, by measurement of the outflow of water from the sample directly after the application of 2 cc water on top of the sample in equilibrium with a given tension. Both methods gave highly comparable and consistent results, suitable for comparison of samples, though perhaps not very accurate in absolute terms. Saturated conductivity was measured on 100 cc and 250 cc samples by the constant head method (5 mm head). The samples had free outflow underneath, or they were placed on a suction table at a low suction. A thirty minute minute equilibrium time was given.

Soil analyses were done in a professional laboratory (Oosterbeek, Netherlands), and standard laboratory methods were used (Black, 1965).

3.4 Presentation and analysis

This study has primarily a qualitative fundamental character but is nevertheless aimed at a public with a predominantly practical attitude. Therefore, I have chosen for the use of mostly traditional units and dimensions (such as g/cm^3 for density, (c)bar for tension and pressure, cm for soil depth, et cetera), which will be readily understood by most readers.

The whole sampling and sample preparation procedure resulted in very homogeneous samples. Consequently, I took most measurements singularly, on one sample in each condition. Because all samples were prepared in series with gradually changing conditions (primarily of moisture content or of density), it was still possible to detect abnormal values for a single sample. Such values, however, occurred only once or twice. Thus, the soil properties of each sampling area are accurately described but, of course, representativeness for the particular compartment or soil type is not guaranteed, even though the sampling areas were chosen carefully. The description of the variability of soil properties is based on causal relations between soil composition and soil structure on the one hand, and soil strength on the other hand. These causal relations are determined from the analysis of detailed measurements on soil samples of different sampling areas. The analysis is based on theoretical interpretation of measurements, aided by graphical correlation. Virtually no use was made of statistical techniques because of the low variability of the samples from one sampling area, and the qualitative character of the analyses made.

4 EXPERIMENTAL RESULTS

4.1 Soil factors in uniaxial compression

In § 2.2 soil strength is described in terms of four basic strength factors: cohesion, friction, density, and structure. Soil compressive strength is derived here from the density reached at a given compressive force or pressure. This density is a function of cohesion, friction, and structure. In natural, structured soils these factors are interdependent and they change continuously during soil compression. Study of soil compressive strength in terms of these strength factors, therefore, is problematic. To overcome this problem, I shall describe the compressive strength of the investigated soils in terms of soil composition, moisture content, and structure. These three factors, although they are not completely independent, may be varied independently from each other and they can be held constant, within limits, during compression. For each of these factors I shall analyse how the measurements on each soil can be related to those on the other soils, and how this can be explained in terms of the basic soil strength factors.

4.1.1 Soil composition

Ten soil types were used for experiments; their composition is given in table 1 and illustrated in figures 2 and 3. The soils are tabled in order of increasing coarseness. The experimental soils can be divided into four groups: one silty clay loam (no. 1), two silt loams (nos. 2 and 3, which differ only in organic matter and structure), one loam (no. 4) and 6 sands (nos. 5-10, which range from loamy fine to medium sand, with variable organic matter and loam content). Further details of the soils and their classification are given in chapter 8.

Standard, prepared ring samples of the ten soil types were dried or moistened to 15 weight percent moisture, equilibrated for up to two weeks, and compressed uniaxially with 4 bar. The results are given in table 2. In order to correct for different values of specific density, density is also expressed in terms of pore volume (percentage of total volume).

Table 1: Composition of the investigated soils.

	soil type (no.)									
	1	2	3	4	5	6	7	8	9	10
sampling depth (cm)	25	5	25	5	5	10	25	5	5	5
pH (KCl)	7.3	3.7	4.0	7.5	3.5	4.1	4.3	3.3	4.3	3.5
$CaCO_3$ (%)	9.5	-	-	8.0	-	-	-	-	-	-
organic matter (%)	2.0	3.5	2.6	1.8	7.8	0.2	0.9	4.5	1.6	2.3
specific density (g/cm^3)	2.70	2.60	2.62	2.65	2.52	2.65	2.64	2.57	2.63	2.61
Particle-size distribution (%)										
0-2 µm	37.5	7.4	6.8	13.7	7.2	2.2	6.3	8.4	7.5	6.4
2-16	19.5	7.4	7.6	6.6						
16-50	33.5	69.4	69.6	33.5	14.0	2.7	7.7	6.9	7.8	3.4
50-105	4.9	11.8	12.0	44.5	18.1	19.0	14.7	9.1	8.6	4.9
105-150	1.6	0.8	0.8	0.7	17.9	29.1	14.9	11.3	8.6	8.3
150-210	1.8	0.9	0.9	0.6	20.2	26.7	21.8	19.7	17.6	13.8
210-300					11.2	11.4	13.6	16.5	16.3	18.7
300-420	1.2	2.3	2.3	0.4	6.6	4.9	9.9	13.3	17.3	23.2
420-2000					4.8	4.0	11.1	15.1	16.3	21.3

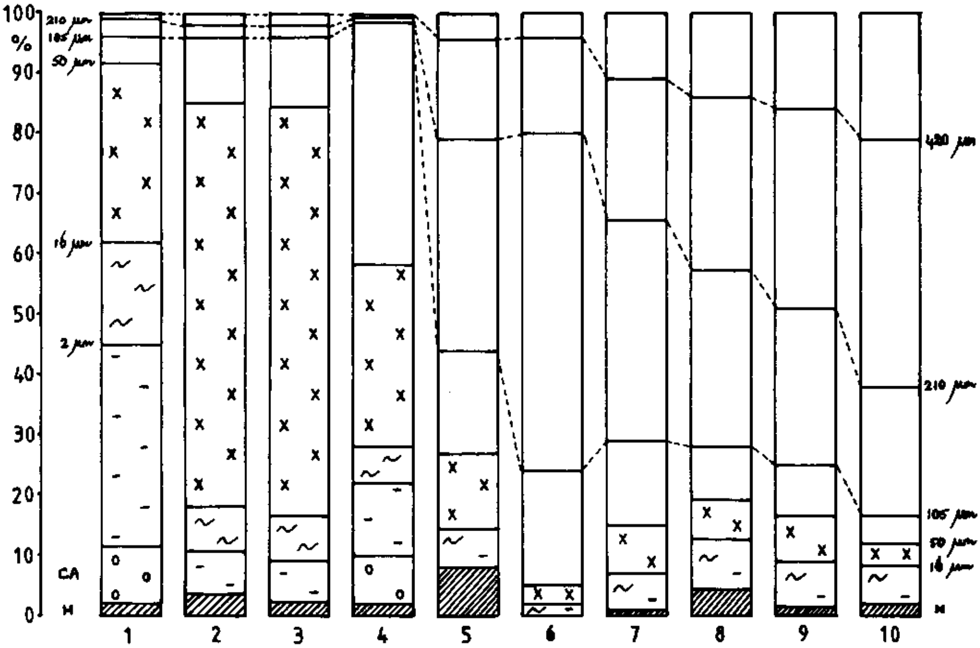

Figure 2: Composition of the investigated soils (1 = no. soil type).
H = organic matter, Ca/o = $CaCO_3$, - = 0-2 µm, ~ = 2-16 µm, x = 16-50 µm.

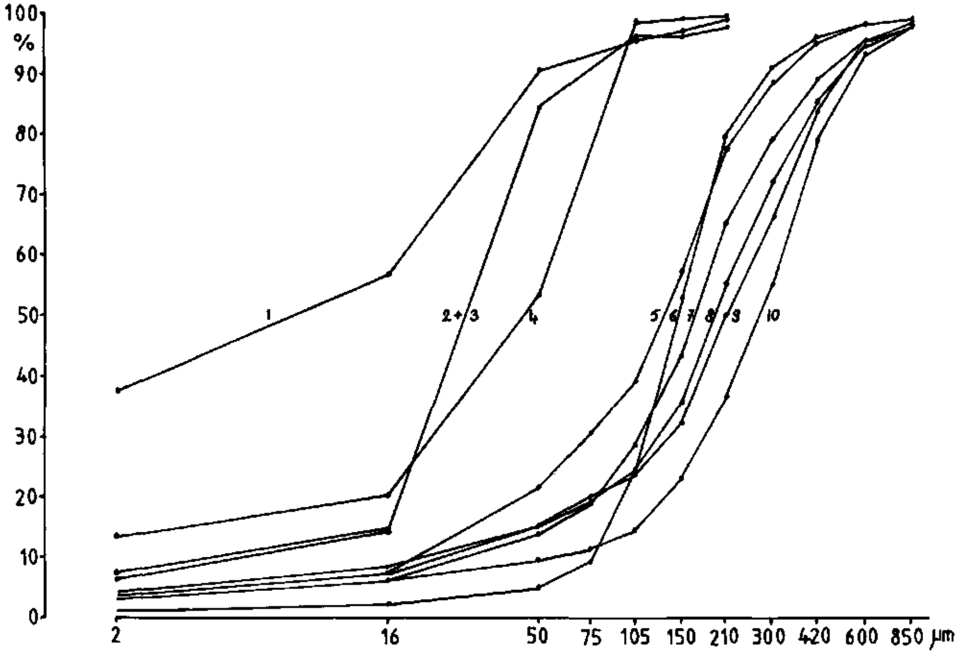

Figure 3: Particle-size distribution of the mineral fraction (1 = no. soil type).

The ten experimental soils reach the same compressive strength at very different densities or pore volumes, in this case ranging from 37 to 59 % pore volume. Apparently, there is a different relation between strength and density for each soil type. The differences found must be caused by different values of cohesional, frictional, or structural strength parameters. Some obvious candidates, in terms of soil composition, for correlation with soil strength will be discussed below.

Table 2: Density of experimental soils after 4 bar uniaxial compression at 15 % moisture.

	soil type (no.)									
	1	2	3	4	5	6	7	8	9	10
bulk density (g/cm^3)	~1.10	1.15	1.24	1.34	1.15	1.67	1.61	1.27	1.54	1.41
pore volume (%)	~ 59	56	53	49	54	37	39	51	41	46

pH

In my experiments the two most clayey soils (nos. 1 and 4) are slightly alkaline because of a high $CaCO_3$ content, whereas all other soils are strongly acidic, with most variation in pH explained by a negative correlation with organic matter content. Any pH effect on strength, therefore, is masked by textural differences and my results do not permit conclusions on the pH effects. As most loams and sands are acidic in many important forest regions, and as pH effects on such soils are probably small in any case, this is not a serious drawback. This is otherwise for soils with an important clay content, as pH is known to influence true cohesion and structure of clays quite considerably. Acidic clays, therefore, might react differently from the investigated clays.

Organic matter content

In figure 4a the relation between pore volume and organic matter content is shown. On the basis of this relation, three soil groups can be distinguished: the silty clay loam (no. 1) on its own, the silt loams and loam together (nos. 2, 3, and 4), and finally the sands (nos. 5-10). In figures 2 and 3 and in table 1 we can easily recognise these groups on the basis of: average (or median) particle size, percentage of particles < 16 µm or percentage of particles > 210 µm (the latter does not separate the silty clay loam from the silt loams, however), which, of course, are all closely related characteristics. Within both groups which contain more samples, a linear relation exists between pore volume and organic matter content up to 2.5 (for the sands) respectively 3.5 (for the loams) percent organic matter. At higher organic matter content, the relation levels off, for the sands at least.

The strength effect of organic matter is based on several processes. In the first place, it increases true cohesion in the soil at the contact points between particles. This explains why strength increases are less when the organic matter content exceeds a certain percentage. That happens when most contact points are 'saturated' with organic material. In finer soils, such as loams, more contact points exist, and, therefore, a higher percentage organic matter is needed to 'saturate' them. Whether such relations also exist between clay particles is doubtful because the platy clay particles form very different structures compared with the more or less rounded loam and sand particles. In the second place, organic matter increases apparent cohesion because of its hygroscopic properties. A higher organic matter content

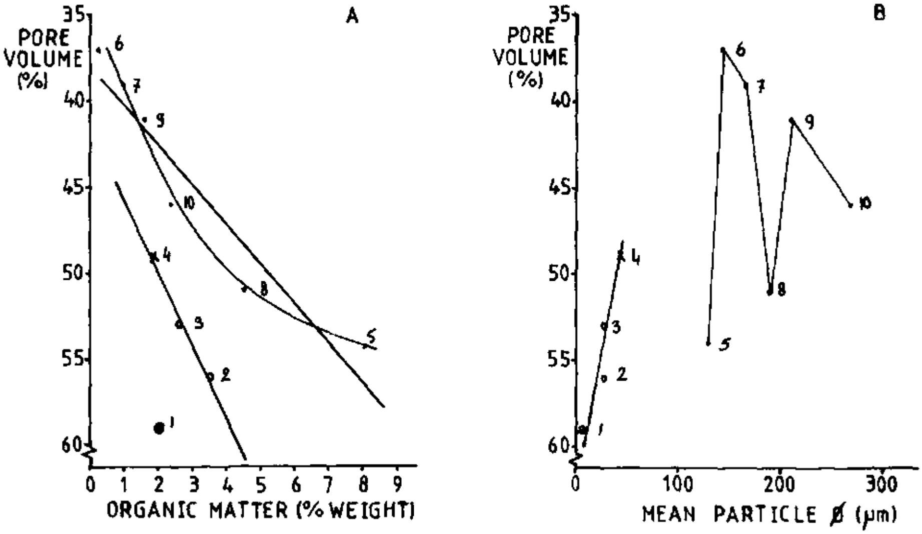

Figure 4: Soil density after 4 bar uniaxial confined compression at 15 % moisture, as a function of organic matter content (4a) or coarseness (4b) (1 = no. soil type).

causes a higher water tension at the same water content, or a higher water content at the same tension (§ 4.1.2). This effect is expected to be more or less proportional to the organic matter content. Finally, organic matter has some effect on friction, as the surface of the mineral particles is changed when it is coated with organic matter. This effect is probably not very important in the range of forces of interest because the increased true cohesion promotes aggregation of the soil, thus making the frictional properties of single particles less important.

Coarseness

In figure 4b the relation between pore volume and coarseness of the mineral fraction is shown. Coarseness is expressed as the particle size which separates the mineral fraction into two equal halves (by weight) of smaller respectively larger particles (figure 3). Coarseness shows an approximately linear relation with pore volume for the fine textured soils (nos. 1-4). This may be explained by the effect of small particles on apparent cohesion, in analogy with the effect of organic matter described above. However, the increase in coarseness coincides with a decrease of organic matter content for the soils 2 to 4, and with striking differences in texture. The linear relation with coarseness, therefore, might well be accidental. True cohesion caused by clay particles plays, apparently, a minor role, as can be seen from the relatively low strength of the loam (no. 4) which has the second highest percentage of clay. As discussed above, this might be different at lower pH values. In the sands, no consistent relation exists, which is no surprise because apparent cohesion depends mostly on the fine particles which show relatively little variation between the different sands. Most variation in apparent cohesion is, therefore, due to differences in organic matter (see above) and these differences largely mask the effect of the fine particles.

The larger particles also tend to have a somewhat more irregular surface and form, which should increase friction. However, in the range of forces of interest, micro-aggregation is very important. Therefore, cohesion, which determines aggregate-strength, seems to be a more important factor than interparticle friction. Small variations in frictional properties of single particles do not, apparently, have much influence.

Heterogeneity

Theoretically, heterogeneous soil material can be packed to greater density than homogeneous material because, in the former, smaller particles may fill the voids between the larger. The experimental results do not support this idea: relatively homogeneous soils such as nos. 2, 3, and 6 (figures 2 and 3) are found on both ends of the scale and so are the more heterogeneous types (e.g. nos. 4 and 9, but cf. figure 6). However, the differences in homogeneity are not very large, and in the range of forces of interest most differences are probably masked by structural effects. This means that we are really looking at the compaction of a mixture of (micro-)aggregates and not of loose particles.

4.1.2 Soil moisture content

The same procedure, as described above under 'soil composition', was repeated at different moisture contents. The results are plotted in figure 5. As water content increases, all soil types show basically the same behaviour: at first, pore volume decreases almost linearly, then the decrease levels off until a more or less distinct peak density is reached, after which porosity increases again.

Soil strength increases with increasing density. This causes some flattening

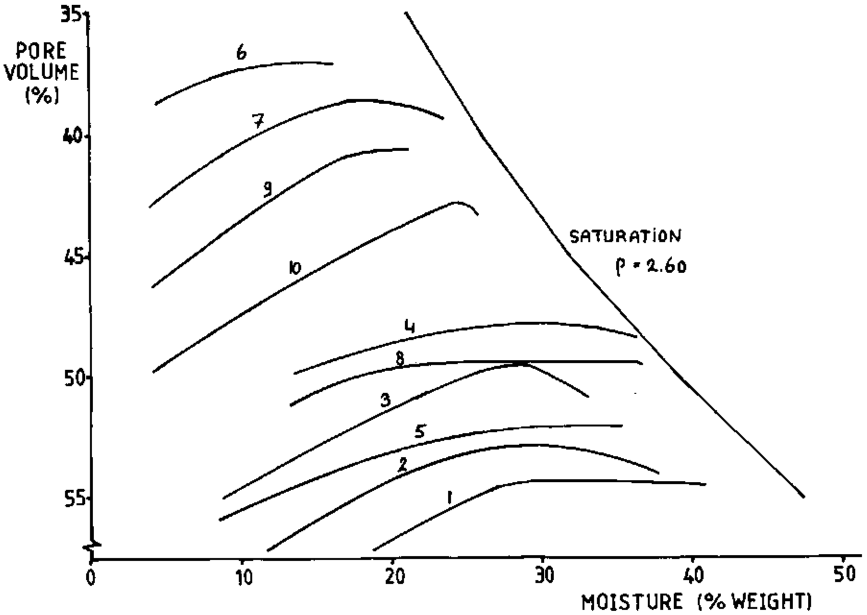

Figure 5: Soil density after 4 bar uniaxial confined compression as a function of moisture content and soil type (1 = no. soil type).

of the curves, because the same decrease of cohesive strength results in a smaller increase of density when the density is higher. The effect of density is discussed in more detail in the next paragraph. The effect of soil moisture on soil strength is important but complicated. The most important aspects of this effect will be discussed below.

Water tension

In a given soil, a higher moisture content means a lower water tension but a larger surface over which the tension acts. The resulting apparent cohesion (tension x surface) is usually lower. Depending on the pF-curve of the soil, this decrease of cohesion usually becomes less steep in the wetter part of the curve where relatively large changes in water content correspond with small changes in water tension. For pF values smaller than 2.0, apparent cohesion may remain almost constant. In soils with relatively high true cohesion, the changes in apparent cohesion in the wetter part of the curve may be irrelevant. This offers one explanation for the much flatter curves of soils 5 and 8 compared with the other sands and loams.

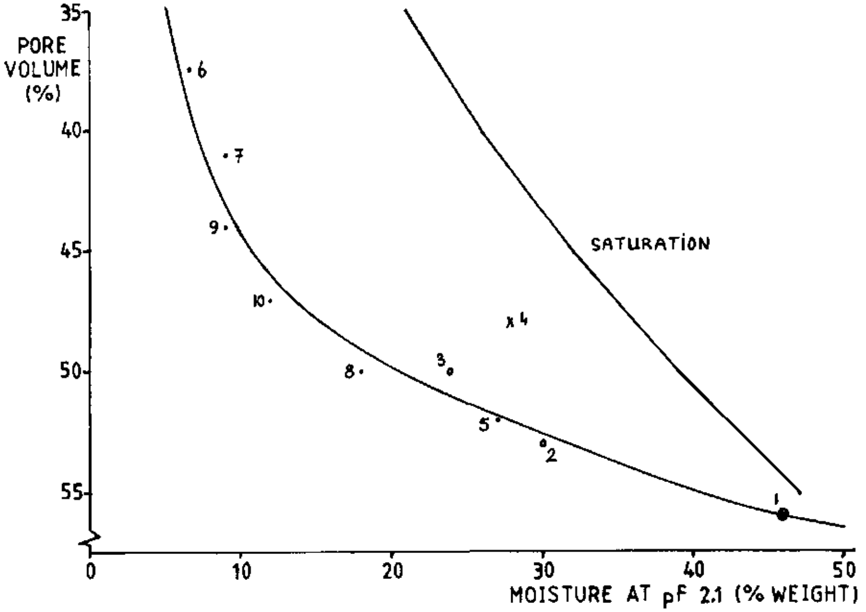

Figure 6: Soil density after 4 bar uniaxial confined compression at pF 2.1 as a function of moisture content (1 = no. soil type).

At a given pF-value, apparent cohesion (and thus soil strength) is positively related to the corresponding moisture content. In figure 6, the relation between pore volume after 4 bar compression and moisture content at pF 2.1 is shown for all investigated soils. The position of soil 1 is uncertain because it reached saturation during compaction. If we assume that pore volume is linearly related to total cohesion, and moisture percentage to apparent cohesion, then the aberations from a linear relation between pore volume and moisture content at pF 2.1 must be caused by true cohesion. This picture coincides well with the description of the effect of organic matter content on soil strength (§ 4.1.1). As the organic matter percentage increases in the sands, true cohesion increases rapidly at first (soils 6, 7, 9, and 10) and remains almost constant at higher percentages (soils 8 and 5). The true cohesion of the silt loams (soils 3 and 2) is comparable to that of the sands. The apparently low value of the loam (soil 4) probably points to a greater compactibility of this soil due to its heterogeneity. Even though other effects related to soil composition make exact linear relations unlikely, this description seems to have much qualitative value.

Water distribution

In structured soils, the moisture content is not evenly distributed throughout the soil. The picture of the effect of water tension, therefore, needs refinement. At a given water tension, the soil consists of denser parts with small pores (the aggregates) with relatively high water content and high apparent cohesion, which are separated by looser parts and larger pores, with relatively low water content and low cohesion. As the tension decreases, water content increases only a little in the aggregates because they were already relatively wet. Therefore, aggregate-strength decreases almost equally with the decrease of tension. Between the aggregates the increase in moisture content compensates more or less for the decrease in tension. Consequently, cohesional soil strength becomes more homogeneous with increasing water content, and the aggregate character becomes less influential, which changes the frictional properties of the soil. This causes a greater strength loss by aggregated soils with increasing moisture content than one would expect from the effect on apparent cohesion alone.

Water permeability

Compaction causes a decrease of pore volume and thus necessitates both the compression of air in the pores and the transport of air and water from the compacted areas. When the soil is wetter, the amount of water and the distance over which it is to be transported increases, depending on the structure of the soil. As soon as pressures build up in the pore water, the effective load on the mineral particles decreases and thus compression as well, even though this process may cause a pronounced decrease in aggregate strength. Obviously, the soils with lower water permeability are the first to show this relative decrease in compressibility (figure 5, e.g.: clayey soils, nos. 1 and 4; soils with high organic matter, nos. 5 and 8; very homogeneous soils with little aggregate development, no. 6). When the water content is even higher, compressibility decreases absolutely, notwithstanding the almost complete loss of cohesional strength. This whole process largely explains the flattening and subsequent decrease of the compaction curves in this experiment. The loading-rate dependency will be discussed in chapter 4.2.2.

4.1.3 Soil structure

To study the effect of structure on uniaxial compressive strength, the compressibility of standard samples of six soil types was compared with that of undisturbed field samples on the one hand and with that of completely pulverised or puddled samples on the other hand. The results are shown in figure 7.

The compressive strength of the field samples is almost the same as that of the standard samples, although typically slightly higher. This alikeness was the aim of the standard preparation method and is not surprising in the case of more or less crumbly topsoils (soils 4, 5, and 9) and in the case of loose

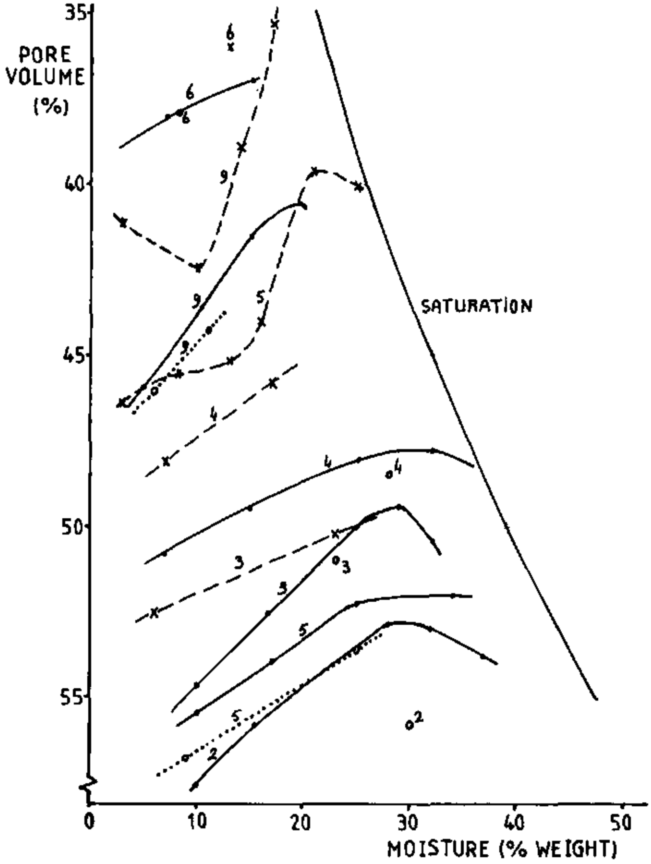

Figure 7: Soil density after 4 bar uniaxial confined compression as a function of moisture content and soil structure (2 = no. soil type).
• —— = standard samples
0 ··· = undisturbed field samples
x - - = pulverised samples.

soil layers with very little macrostructure (soils 3 and 6). Soil 2 is the only exception, which can be explained by its dense and cemented field structure, which had to be loosened for the preparation of standard samples. The differences in the other samples can also be explained in terms of disruption of a lightly developed macrostructure during sample preparation. However, the measured values on field samples were rather variable because of local differences in soil composition and structure, and the difference between field and standard samples is only statistically significant for soil 2.

The more rigorous sample treatment produces rather different effects. Soil strength decreases in all cases, slightly in soils 3 and 6, more pronounced in soils 4 and 9, and strikingly in soil 5 (no measurements on soil 2 available). The decrease of strength, as compared with standard samples, shows a minimum value at some intermediate moisture content. At low moisture content, cohesive bonds due to water tension do not re-establish completely after disturbance, resulting in important strength loss (soils 3, 5, and 9, at moisture < 10%). This process is most pronounced in the coarsest soil (9) and does not occur in soil 4, due to its high clay content. At intermediate moisture contents, these cohesive bonds are less sensitive to disturbance, and strength loss depends mostly on the loss of structural strength due to disruption of true cohesional bonds and the fragmentation of aggregates. This strength loss is small in soils 3, 6, and 9, higher in soil 4 and very high in soil 5. This corresponds with the less developed aggregate structure in soils 3, 6, and 9 as compared with soil 5. Two explanations seem possible for the intermediate strength loss of soil 4. In the first place, the clay fraction may behave quite differently from the particles in other soils. Puddling of clay soils is known to cause structural collapse and this may also occur in this loam. In the second place, and this plays a role in the other soils as well, the homogenisation of the soil causes the soil to have a lower water tension at a given water content than it would have in a more structured condition, especially at higher water contents. This effect is most pronounced in soils with a high percentage of fine mineral (soil 4) or organic (soil 5) particles. This may also partly explain the great strength loss at high water content of soils 5 and 9. Aggregate destruction is more complete in the wetter samples as well, which causes additional strength loss.

In figure 8 the results of the measurements on standard and pulverised samples are compared on the basis of organic matter content (cf. figure 4a).

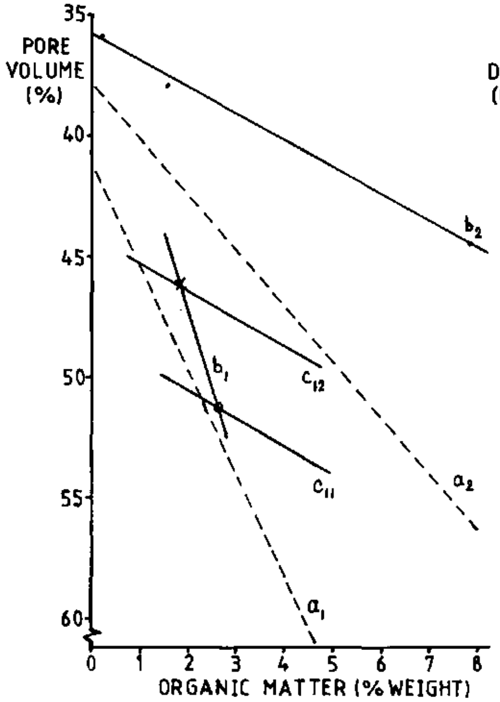

Figure 8: Regression lines of 4 bar uniaxial density at 15% moisture against organic matter content.
a = standard samples
b = pulverised samples
1 = silt loam and loam
11 = silt loam
12 = loam
2 = sand.

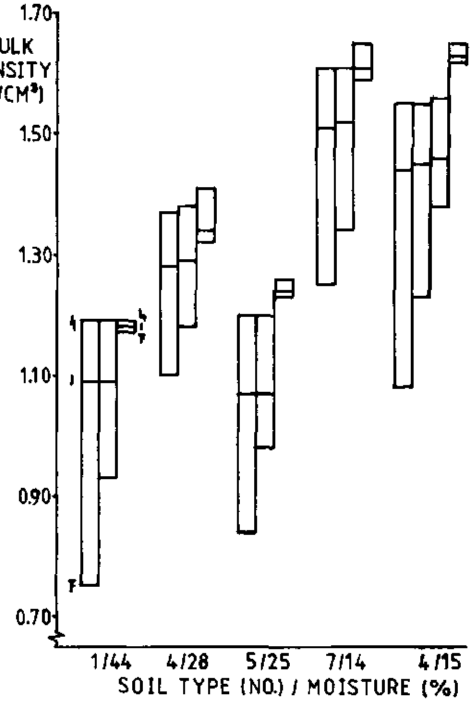

Figure 9: Soil density after 1 and 4 bar compression as a function of initial density of standard samples.
F = initial density at filling
1 = 1 bar compression
4 = 4 bar compression.

The influence of the organic matter percentage on soil strength in the sands is considerably lower for the pulverised samples, corresponding with the destruction of at least an important part of the true cohesional bonds and aggregate structure. The remaining effect may largely be based on the water retention capacity of the organic matter (§ 4.1.2). In the finer textured soils, on the contrary, the influence of organic matter on strength apparently increased. As this is theoretically unlikely, we may assume that the linear relation found in figure 4a is accidental and that the loam (no. 4) forms a category of its own.

Usually, structural differences are accompanied by density differences. This might prompt us to question if the above-described strength differences are partly due to differences in initial density. Figure 9 shows the results of an experiment in which compressive strength of 5 soil types in standard structural condition, but precompacted to different densities, was measured. One and 4 bar densities are almost independent of initial density, as long as they are clearly higher. However, the density increases slightly when the initial density approaches the normal compacted level. This effect is most obvious in the loam (no. 4) and absent in the silty clay loam (no. 1). I shall discuss this phenomenon further in paragraph 4.2.3 (load repetition). For the present discussion, we may assume independence of initial and 4 bar density because all samples were much looser than the 4 bar density (except some undisturbed field samples, which have been left out of figure 7 for this reason).

4.2 Load factors in uniaxial compression

Uniaxial compression is an empirical soil strength test. The results not only depend on soil properties (§ 4.1), but also on the loading process. I have already discussed the influence of wall friction and sample form in paragraph 2.5; in this paragraph I shall discuss two other important loading variables: pressure (§ 4.2.1) and time (§ 4.2.2). Finally, I shall describe the effect of repeated loading as a load factor (§ 4.2.3). Repeated loading could have been treated as loading of precompacted samples, thus as a soil factor (§ 4.1.3). All samples are precompacted to some degree, but repeated loading with the same load presents a special case which is best understood in relation to other loading processes described in § 4.3.

The standard loading procedure for the study of load factors was as follows. At pressure levels of 1, 3, and 6 bar the load was removed, re-applied and again removed before applying the next pressure level. Relaxation time was about 30-60 seconds. After the second 6 bar loading, the pressure was held at approximately 5 to 6 bar during 30 seconds. Sinkage for each higher pressure level was considered to be independent of that for the lower because of the great pressure differences (effect of precompaction, § 4.1.3). The sinkage for intermediate pressure levels was graphically interpolated. The procedure and analysis is illustrated in figure 10.

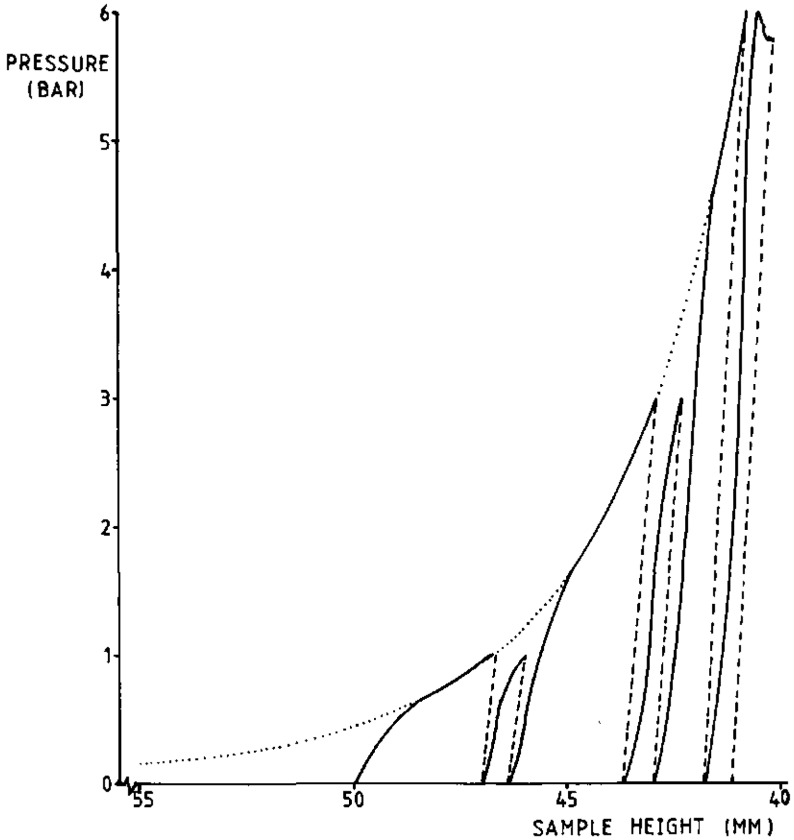

Figure 10: Example of loading procedure and sample compression.
—— = actual load-sinkage measurements
---- = load removal
.... = idealised compression line.

4.2.1 Pressure

Figure 11 shows the relation between pressure and density for standard samples of 8 soil types at 15 percent moisture content and of 1 soil type at 35 percent moisture (no values for soil type 6 available) and for pulverised samples of 4 soil types at 15 percent moisture content.

All soils show a rather similar behaviour. As the load increases, density increases become smaller. Because soil strength increases with increasing density, if all other factors are equal, a smaller density increase at higher density causes the same strength increase as a greater density increase at lower

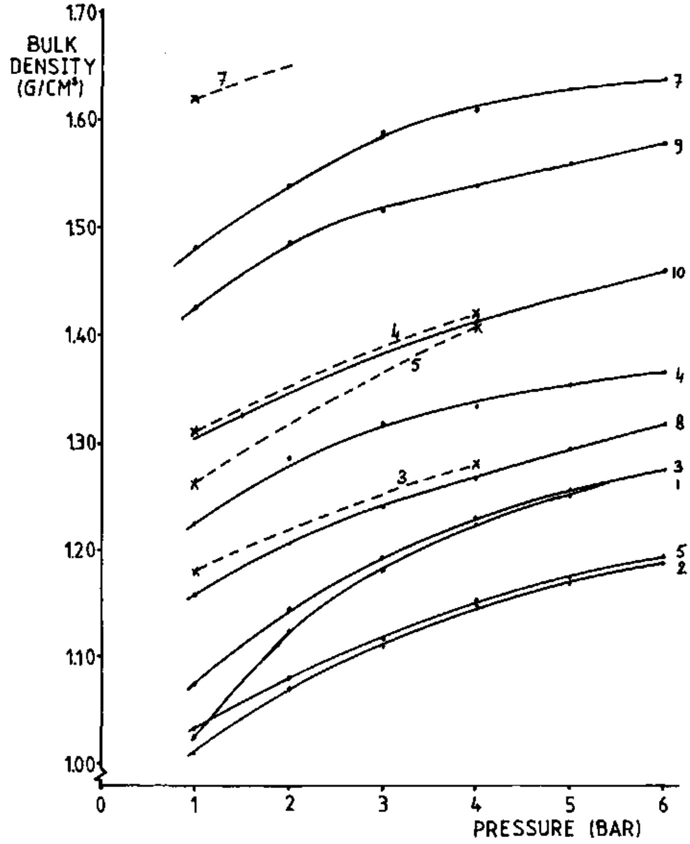

Figure 11: Soil density as a function of pressure at 15 % moisture content (35 % in case of soil type no. 1) (2 = no. soil type).
•—— = standard samples
x---- = pulverised samples.

density. This effect is somewhat accentuated by the friction between soil and cylinder wall, which also increases with increasing compaction.

The absolute density increase of the standard samples from 1 to 6 bar is remarkably similar for the 5 sands (soils 7, 9, 10, 8, and 5), only slightly lower for the loam (4), and slightly higher for the silt loam topsoil (2). The silt loam subsoil (3) and the silty clay loam (1) show the greatest density increases. Thirty (5, 8, 10) to forty (1, 7, 9) percent of this increase occurs from 1 to 2 bar, around eighty percent from 1 to 4 bar. The absolute density increase of the pulverised samples, as compared to the standard samples, remains the same for soils 4 and 7, increases for soil 5, and decreases for soil 3. The relatively large density increase of some samples (soils 1 and 3 standard, soil 5 pulverised) is apparently related to a soil structure consisting of large aggregates in which water tension is the dominating strength factor. The relatively large density increase of soils 7 and 9 at low pressure may be caused by a similar process. The flattening of the curves at higher pressure is also influenced by a change of aggregate properties and by the lowering of effective pressure caused by changes in water tension during compression.

Figures 12a and b show the influence of water content on the pressure-density relation for soil 5 (loamy fine sand) respectively soil 3 (silt loam subsoil) in two structural conditions (standard and pulverised). Large strength decreases with increasing water content point to the relative importance of water tension as a strength factor; smaller strength-decreases point to the relative importance of other strength factors (§ 4.1.2). At high water contents and at high pressures the curves flatten because of the saturation effect (§ 4.1.2).

The strength of the standard samples of soil 5 is clearly dominated by aggregation due to true cohesion as is shown by the small influence of water content and the large effect of pulverisation. At higher pressure the water content has slightly more influence, possibly because of compaction-induced decreases of water tension at higher moisture contents and because of some disturbance of true cohesive bonds. Destruction of macro-aggregates in the pulverised samples causes an important strength loss and remaining strength depends largely on water tension. At 15 percent moisture, relatively large aggregates are formed which support 1 bar pressure better than either wetter (because of lower tension) or drier (because of smaller aggregates) soils. But 4 bar pressure crushes these same aggregates to larger density than the stronger drier aggregates. The sample with 20 percent moisture shows most clearly the critical strength of these aggregates which collapse almost completely at higher pressure. At 25 percent moisture, water tension is too low to support even 1 bar pressure, and pressure increases have little effect because of the saturated condition.

The strength of the standard samples of soil 3 is apparently dominated by water tension, as is shown by the large influence of water content and the relatively small effect of pulverisation, especially at low pressure. At higher

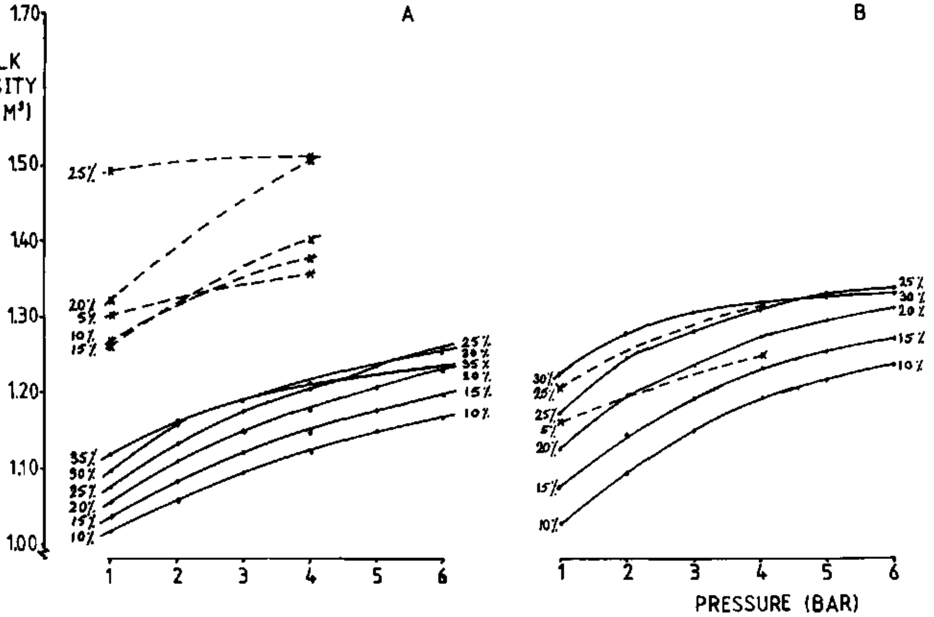

Figure 12: Soil density as a function of pressure, moisture content, and structure, for soil 5 (12a) and 3 (12b).
•—— = standard samples
x---- = pulverised samples.

pressure, as the soil gets denser, some of the larger aggregates become crushed and the properties of particles or stable micro-aggregates become more important and the moisture effect decreases slightly. This is shown more clearly by the pulverised samples in which strength is largely determined by the properties of the micro-aggregates because the water tension is very small, not only in the wetter, but also in the drier sample, as the bonds between the aggregates did not re-establish after disturbance. Samples of intermediate moisture content would probably show the same behaviour as the pulverised samples of soil 5, but much less pronounced. The very small strength loss of the 25 percent pulverised sample compared with the 25 percent standard sample shows the minor importance of macro-aggregation in this soil (§ 4.1.3, figure 7).

The pressure-density relations of all not-too-wet standard samples can be accurately described by a logarithmic model of the following form:

$$\hat{\gamma}(p) = \gamma(1) + a \ln p \qquad (4)$$

with: $\hat{\gamma}(p)$ = density at given pressure (g/cm^3)

$\gamma(1)$ = density at 1 bar (g/cm^3)

a = constant (depending on soil type, structure, and moisture)

p = applied pressure (bar).

The variation of the constant a (table 3) appears to remain within fairly narrow limits, around 0.10 for standard samples, leaving $\gamma(1)$ as the main variable in explaining density differences between soil types or moisture conditions (chapter 5).

Table 3: Examples of the use of a logarithmic model of the pressure-density relation for two soil types.

	soil type (no.)/moisture content (% weight)			
	no. 3/11%	no. 3/25%	no. 5/11%	no. 5/25%
$\gamma(1)$ (g/cm^3)	1.03	1.17	1.01	1.07
a	0.12	0.10	0.09	0.10
correlation (r^2)	0.995	0.997	0.986	0.990

4.2.2 Loading rate and loading time

The uniaxial compression test used in my experiments involved a constant compression rate of approximately 3 mm per second of samples originally 50 mm high. The pressure in this test is a function of soil resistance against this loading (table 4).

Usually, the compression time from 1 to 6 bar is less than a few seconds, but the time before 1 bar is reached can be somewhat longer in the case of very loose samples. Especially at higher pressure, we may therefore expect some time-dependency in the compression. This was tested on samples of soil types 1, 4, and 8, at different moisture contents. These samples were loaded with 5 to 6 bar during 30 seconds, after precompaction with 6 bar (figure 10). This loading always resulted in some additional sinkage, usually some 0.2 mm, corresponding to a density increase of less than 0.01 g/cm^3. More significant even, additional sinkage was completely independent of moisture content in each soil type. No failure (§ 3.3) occurred in samples which did not fail at 6 bar pressure, but samples which failed already at the

6 bar pressure continued to do so.

Table 4: Example of time-pressure relations in the uniaxial compression test with a loading rate of 3 mm/sec (soil type 4 at 17% moisture).

Pressure (bar)	Time (sec)	Δ Time (sec)
0	0	-
1	1.10	1.10
2	1.90	0.80
3	2.37	0.47
4	2.67	0.30
5	2.90	0.23
6	3.07	0.17

Apparently, the loading rate used in the experiment is sufficiently low not to influence to an important degree the compaction of all samples which are not too wet. We may, therefore, consider the dry part of the compaction curve up to the maximum density reached as almost independent of the loading rate, within fairly wide limits. Only a much faster loading rate would probably decrease compaction, but such a loading rate would be unrealistic in the field. The wet part of the compaction curve beyond the maximum density cannot be independent of the loading rate because of the transport processes involved. This has not been studied experimentally because of the difficulties in translating any results, thus obtained, to field circumstances. The relatively small sample size facilitates the removal of excess water as compared with the field. Therefore, a relatively fast loading rate on the sample simulates a slower loading rate in the field, but quantification of this process is very difficult (§ 2.5). The maximum density obtained under a low loading rate of wet samples and well-drained conditions would probably not much surpass the maximum density of the compaction curve because the latter is also reached under conditions of a very low water tension, leaving density, true cohesion, and friction as main determinants for soil strength.

4.2.3 Load repetition

Repeated loading with the same pressure and within short time-intervals is a very common process in the field. The passage of one vehicle already involves 2 to 4 wheel passages, and often the same vehicle passes several times over the same path. The simulation of this process in the uniaxial compression test is described above (§ 4.2, figure 10). The effect of repeated loading on soil density is expressed as the equivalent pressure, that is: the pressure needed to reach the same density on that soil sample without load repetition. The equivalent pressure divided by the applied pressure is called the efficiency of repeated loading (table 5).

Table 5: Efficiency of repeated loading in soil type 4 (loam) on standard samples (see text for explanation).

	moisture content (% weight)					
	17	23	26	28	32	34
1 bar first loading	1.00	1.00	1.00	1.00	1.00	1.00
second loading	1.15	1.17	1.17	1.19	1.24	1.34
third loading	1.22	1.29	1.32	1.34	1.44	1.51
3 bar first loading	1.00	1.00	1.00	1.00	1.00	-
second loading	1.15	1.20	1.20	1.24	1.27	-
third loading	1.23	1.33	-	1.33	1.37	-

In table 5 some trends are visible:

- repeated loading has an important compactive effect which, however, decreases with each following repetition
- the efficiency is remarkably alike at both pressures
- the efficiency increases regularly with increasing moisture content, more rapidly at high moisture content (32% and 34% in this case), and somewhat more rapidly for the third than for the second loading.

These trends prove correct for all other soil types, for different structural conditions, and also for the 6 bar pressure level, although the 6 bar values are less accurate because of the extrapolation of the pressure-density curve involved. Quantitative differences exist between the different soils, however. The silty clay loam, loams, and loamy fine sand have slightly lower efficiency values (approx. 1.10-1.15 for the second loading and 1.15-1.25 for the third, at intermediate moisture content), the other sands approximately the same as the loam. Undisturbed field samples have almost the same efficiency values as the standard samples, pulverised samples slightly higher. The increase in efficiency with increasing moisture content is lower for the silt loams and very low for the loamy fine sand, but higher for the other sands as compared with the loam.

The efficiency of repeated loading correlates negatively with cohesion. This may be partly explained in terms of loading time, especially at very high moisture content. But the effect is much larger than one would expect on basis of the results of the loading time experiments (§ 4.2.2) in view of the very short loading times involved with reloading. Another explanation runs as follows. Upon load removal some particle re-arrangements in the soil occur, due to elastic rebound and uneven stress distribution in the soil (uneven, because of wall friction and soil structure). The next load, therefore, causes a slightly different stress field in the soil, and thus some additional compaction (§ 2.3). Particle re-arrangements during elastic rebound are most likely in soils with low cohesion and will decrease with increasing density under the same pressure. Thus, the negative correlation with cohesion, and the decreasing compactive effect of further load repetition, are qualitatively explained.

Table 6: Examples of values for the efficiency of repeated loading, depending on the constant b and variable n in the model $\hat{p}(n) = (1 + b \ln n)p$.

	b			
	0.20	0.30	0.40	0.50
n = 1	1.00	1.00	1.00	1.00
2	1.14	1.21	1.28	1.35
3	1.22	1.33	1.44	1.55
10	1.46	1.69	1.92	2.15

The effect of load repetition can be reasonably described by a model of the following form (table 6):

$$\hat{p}(n) = (1 + b \ln n)\, p \qquad (5)$$

with: $\hat{p}(n)$ = equivalent pressure (bar)

b = constant (depending on moisture content)

n = number of load repetitions

p = applied pressure (bar)

$1 + b \ln n$ = efficiency of repeated loading.

4.3 Load type and soil strength

Uniaxial compression is just one method for measuring compressive strength of soils, characterised by a relatively uniform and stable stress field in the soil. In paragraph 4.2.3 the efficiency of repeated uniaxial loading was discussed in terms of minor changes of the stress field in the sample. In this paragraph, I shall describe two loading types which cause more pronounced changes of the stress field and compare them with the uniaxial test (§ 4.3.1 and § 4.3.2). Loading of soil does not necessarily cause compaction. Soil flow was already discussed for uniaxial loading. In paragraphs 4.3.1 and 4.3.2 soil failure becomes more prominent. In paragraph 4.3.3, I shall describe some soil strength measurements in which compaction plays a subordinate role.

4.3.1 Proctor compaction test

Five soil types (nos. 2, 3, 4, 5, and 9) were compacted in a standard Proctor test using air-dried mixed soil material and re-using the same soil material (after addition of water and thoroughly mixing and loosening) for measurements at successively increasing water content. Besides that, samples of fresh soil material (except for soil type no. 4) were compacted in the Proctor test at field moisture content. The results are shown in figure 13.

The Proctor curves have, basically, the same form as the uniaxial compression curves, but density increases much faster with increasing moisture content. Moreover, in three soils the curve has a minimum value next to the driest measurement. Both phenomena are closely related. The hammer in the Proctor test exerts large forces on a small surface. This has not only a compactive effect but also a loosening effect when failure occurs. Compaction depends strongly on cohesion within the aggregates, aggregate size, and soil density (§ 4.2.1), whereas failure depends more on the cohesion between the aggregates, together with aggregate size and soil density which determine the friction angle. Failure occurs in the plane with the lowest strength wich is usually between aggregates, while compaction almost always depends on deformation of the aggregates themselves.

The first Proctor measurement of each series is executed on relatively dry soil which still has partly its natural structure, and thus consists of rela-

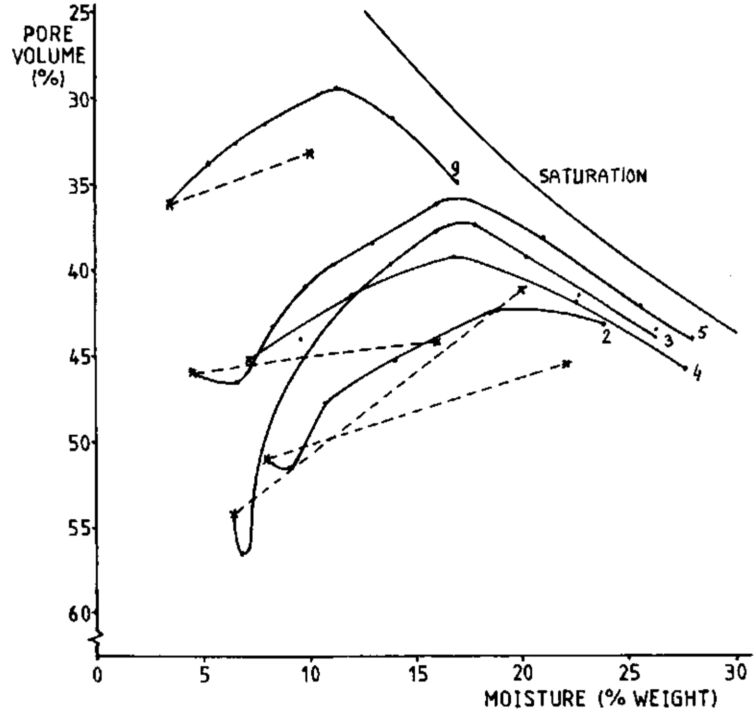

Figure 13: Soil density after Proctor-compaction as a function of moisture content (2 = no. soil type).
•—— = repeatedly used material
x---- = fresh material.

tively large and strong aggregates with little cohesion between them. The compactive effect is largely offset by the loosening effect and the resulting density is relatively low. This is most pronounced in the soil with the lowest friction angle and cohesion, in this case soil 3, which has little structure, fine particles, and which is dry. Nevertheless, some of the aggregate structure of the samples is broken down during this first measurement, and the second measurement is executed on smaller, but about equally strong, or even stronger, aggregates. The soil will thus have a lower friction angle and still little cohesion between the aggregates. Through this change of soil condition, the loosening process of soil failure during the second measurement may be more enhanced than the compactive process, in which case the resulting density is lower than in the first measurement (soils no. 2, 3, and 5). In soil 9 this process is not observed, probably because of the high friction angle of the coarse sand fraction, independent of aggregation, and because of the high density due to low compactive strength. In soil 4 the absence of a minimum value may be due to the relatively high moisture content of the second measurement, leading to a relatively high cohesion between the aggregates. In subsequent measurements soil structure is increasingly broken down and the cohesive strength of the aggregates decreases with the increasing moisture content, while the cohesion between the aggregates increases. Thus, failure is prevented and the density increases with each measurement, up to the point that high moisture content limits further compaction.

The relative importance of structure for the Proctor strength can be determined from the density reached on the fresh soil material as compared to the standard curve at the same moisture content (figure 13, table 7). The influence of structure is largest in soil type 5, as might be expected from paragraph 4.1.3, but, contrary to expectations, it is somewhat larger in soil 3 than in 2. However, the maximum density reached in the standard curve is a function of the number of Proctor-measurements taken on the same sample, and this number is also higher in soil 3 than in 2. The absolute value of the maximum, therefore, has limited meaning.

Table 7: Comparison of Proctor and uniaxial compressive strength.

soil type (no.)	moisture (% weight)	max. Proctor density (% pore volume)	fresh Proctor density * (% pore volume)	4 bar uniaxial density (% pore volume)
2	21	42	46	54
3	18	37	42	52
4	17	39	42**	49
5	17	36	44	54
9	11	29	33	43

* The fresh Proctor densities have been measured by slightly different moisture contents, the tabled values have been adjusted to account for this.
** Estimated value.

The Proctor density of fresh soil samples is well above the corresponding uniaxial values (tabel 7) with relatively little variation between the soil types. In absolute terms, the difference is smallest in soils 2 and 4. We may also interprete these Proctor values in terms of equivalent uniaxial pressure, using the logarithmic relations of paragraph 4.2.1 (table 8).

Table 8: Equivalent uniaxial pressure of Proctor values for fresh soil using a logarithmic pressure(p)-density(γ) relation.

soil type (no.)	moisture (% weight)	logarithmic pressure-density relation for confined uniaxial compression	r^2	fresh Proctor density (g/cm^3)	equivalent uniaxial pressure (bar)
2	21	$\gamma = 1.05+0.10 \ln p$	1.00	1.41	36
3	18	$\gamma = 1.10+0.11 \ln p$	1.00	1.52	48
4	17	$\gamma = 1.24+0.08 \ln p$	1.00	1.54*	50
5	17	$\gamma = 1.03+0.10 \ln p$	0.99	1.41	54
9	11	$\gamma = 1.43+0.09 \ln p$	1.00	1.76	48

* Estimated value.

The equivalent pressure is lowest in soil 2, but on the whole remarkably constant for all soils. Neither real pressure nor loading time are known in the Proctor test, as they depend on soil reaction. The increased compaction is the result of higher pressure (counteracted by some failure), higher deviatoric stresses, changing stress fields in the soil (related to loading sequence and repeated loading), some break-down of structure because of this loading process, and less wall friction. When the same soil material is reused time and again, break-down of structure becomes more and more important.

It is possible to compare the Proctor and uniaxial test in energy terms. Compactive energy of the uniaxial test is derived from the pressure-sinkage diagram (figure 10), multiplied by the surface area on which the pressure is applied, and divided by dry sample weight, to make the results comparable to the Proctor values. The energy input of the Proctor test is derived from the mass and the fall-height of the hammer and the number of blows, divided by dry sample weight. Sample weight is chosen as reference instead of sample volume, because the latter changes during the compaction process. In formula:

$$E\ (\text{uniaxial}) = \int p \cdot dh \cdot s / M_s \ (J/kg) \qquad (6)$$

with: p = applied pressure (N/m^2)
h = sample height (m)
s = sample surface (m^2)
M_s = dry mass of sample (kg).

$$E\ (\text{Proctor}) = M_h \cdot g \cdot h \cdot L \cdot N_B / M_s \quad (J/kg) \tag{7}$$

with: M_h = mass of hammer (kg)
g = acceleration due to gravity ($9.81\ m/s^2$)
h = height of fall (m)
L = number of layers
N_B = number of blows/layer
M_s = dry mass of sample (kg).

Table 9: Energy input of the uniaxial and Proctor test on fresh soil samples (see text for explanation).

soil type (no)	moisture (% weight)	E(6 bar uniaxial) (J/kg)	E(Proctor) (J/kg)	E(Proctor)/ E(uniaxial)
2	23	51	420	8
3	21	40	390	10
4	17	29	385	13
5	16	49	420	9
9	10	28	337	12

The compactive energy of uniaxial 6 bar compaction of a few standard samples at field capacity ranges from 30 to 50 J/kg. The corresponding energy input of the Proctor test on these samples ranges from 340 to 420 J/kg, or 8 to 13 times as much (table 9). The equivalent pressure of the Proctor compaction was estimated to be 6 to 8 times the 6 bar uniaxial compression (table 8). This may actually be an underestimation, because the logarithmic pressure-density model is not valid for very high pressures (chapter 5). The energy input, therefore, may be fairly well related to compaction. Soils 4 and 9 show a low energy input at uniaxial compression because of the relatively limited additional compaction at higher pressure (figure 11), expressed in a low value for constant a in formula 4 (§ 4.2.1 and table 8). Because the energy input of the Proctor test is relatively constant, the ratio E(Proctor)/E(uniaxial) is much higher for these two soils. Nevertheless, the equivalent uniaxial pressure of the Proctor test did not differ much from the average for these two soils (table 8). This may be due to the inaccurateness of the logarithmic model for high pressures.

In figure 14 the standard Proctor curve of soil type no. 5 is compared with the results of uniaxial compression of samples with the same disturbed structure as the Proctor sample (with corresponding moisture content). After each Proctor measurement the soil material was loosened and moistened. Some material was used for filling a ring sample for uniaxial compression while the rest was re-used for the next Proctor measurement, with the addition of some new material to make up for the losses. Thus, with increasing moisture content, the original structure is more and more broken-down. Nevertheless, at 1 bar uniaxial pressure the soil has optimum strength at about 13% moisture. At that moisture content cohesion between the small remaining aggregates is maximal. This inter-aggregate strength is lower than the intra-aggregate strength and, at higher pressures, strength is increasingly determined by the latter, causing the optimum strength to shift to drier values. Both at the dry and the wet end, the influence of pressure is relatively small. At the dry end the soil consists of very strong small aggregates with little cohesion between them; at the wet end compaction is limited by the saturated condition.

The equivalent uniaxial pressure of the Proctor values is remarkably constant, except for the driest measurement (table 10). If we assume that the compactive effect of the Proctor test is independent of moisture content, then we may quantify the loosening effect. In figure 14, the 24 bar equivalent pressure line is indicated, based on the relations of table 10. The deviation of the Proctor curve from this line is the effect of soil failure. Soil failure, apparently, has little influence above 10% moisture in this soil. This is confirmed by the visual observations during testing.

The equivalent pressure of the Proctor test on fresh soil of soil type no. 5 is 54 bar (table 8) whereas that of the Proctor test on disturbed samples is only 24 bar (table 10). This may be explained by the break-down of structure which is most pronounced at the first Proctor measurement on a given soil. Thus, a Proctor measurement on fresh soil material is much more effective in terms of equivalent pressure than Proctor measurements on al-

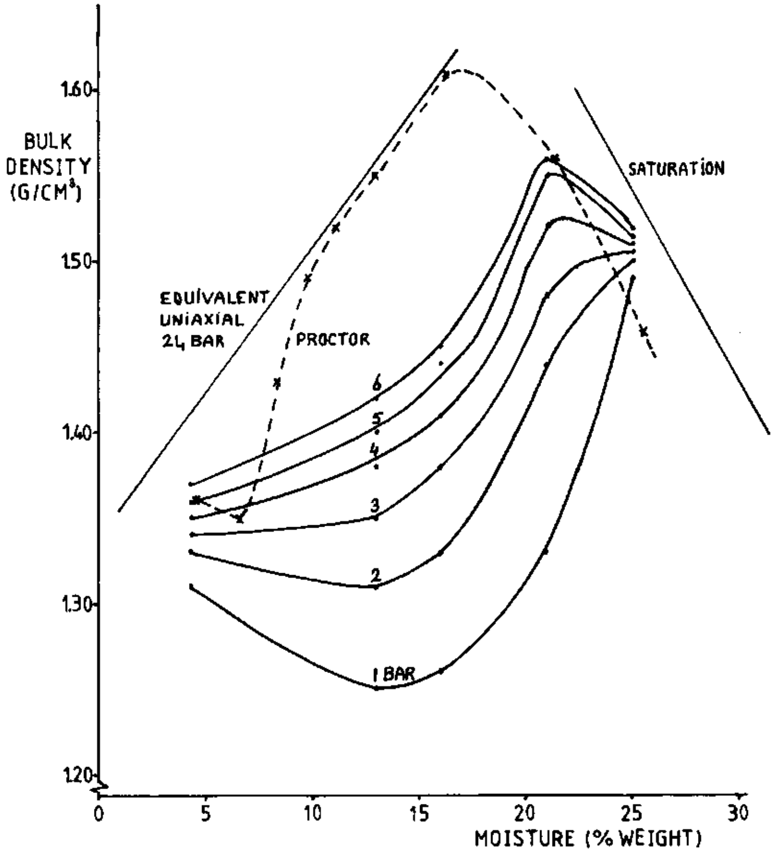

Figure 14: Soil density after confined uniaxial and Proctor compaction of disturbed samples of soil type no. 5, as a function of moisture content. Equivalent uniaxial density at 24 bar is extrapolated from measured values, using a logarithmic model.
•—— = uniaxial
x--- = Proctor.

ready highly disturbed soil material. For the same reason, the equivalent pressure on dry samples will be higher than on moist samples because in the first, cohesive bonds are more sensitive to disturbance. This is illustrated by the driest Proctor measurement on soil 5. This is a first measurement on relatively undisturbed soil, but the equivalent pressure compared to the standard uniaxial compression on undisturbed samples is around 90 bar, even though the density is lowered through failure. This is in sharp contrast to the equivalent pressure of only 5 bar compared to the uniaxial compression on disturbed samples (table 10).

Table 10: Equivalent uniaxial pressure of standard Proctor values using a logarithmic pressure(p)-density(γ) relation for uniaxial compression on disturbed samples of soil type no. 5.

moisture (% weight)	logarithmic pressure-density relation for confined uniaxial compression	r^2	standard Proctor density (g/cm^3)	equivalent uni-uniaxial pressure (bar)
4.3	$\gamma = 1.30+0.03 \ln p$	0.98	1.36	5
9.5	$\gamma = 1.27+0.07 \ln p$	1.00	1.49	20
12.8	$\gamma = 1.25+0.10 \ln p$	1.00	1.55	24
16.2	$\gamma = 1.26+0.11 \ln p$	1.00	1.61	25

4.3.2 Hand compaction test

The hand compaction test has been used on two soil types (nos. 5 and 10). Except for very low pressure, the densities reached in the hand test are higher than in the standard uniaxial test at the same pressure (table 11).

Table 11: Comparison of standard uniaxial confined compaction and hand compaction of samples of soils nos. 5 and 10, approximately at field capacity.

	soil density (g/cm^3)			
	soil type no. 5/20% moisture		soil type no. 10/15% moisture	
pressure (bar)	uniaxial test	hand test	uniaxial test	hand test
0.2	0.90	0.90	1.19	1.20
1.0	1.05	1.08	1.31	-
2.0	1.11	1.17	1.37	1.43
4.0	1.18	1.23	1.42	1.53
6.0	1.23	-	1.46	-

The efficiency of the hand test is defined as the equivalent uniaxial pressure needed to reach the same density, divided by the applied pressure in the hand test. This efficiency value is approximately 1 at 0.2 bar, rising to 2 at 2 bar, and even higher at 4 bar for soil 10, but only 1.5 at 4 bar for soil 5. The relatively high and increasing efficiency may be explained by the higher deviatoric stresses, the changing stress axes, and the lower wall friction of the hand test compared with the standard uniaxial test. These loading factors play a very small role in loose soils under low stress, but become increasingly important at higher stress and in denser soil. However, when the applied stresses are relatively high compared to soil strength, soil failure occurs, which reduces the efficiency of compaction and even may loosen the soil. The smaller the loaded area, the lower the stress at which failure occurs. The decrease of the efficiency of the 4 bar loading of soil 5, therefore, may be related to the use of a loading surface of 2 cm², whereas lower stresses were applied on 5 cm². Thus, the compactive effect of this hand test depends also on loaded area and on initial soil strength, like the Proctor test (§ 4.3.1). The effect of soil moisture is illustrated in figure 15.

The slope of the compaction curves of the hand test is steeper than that of the uniaxial test, except at very low pressure (soil 10). Under very dry conditions, soil strength of soil 10 depends largely on orientated cohesional bonds. These bonds are less resistant to hand compaction than to uniaxial compaction, because of the higher deviatoric stresses and changing stress

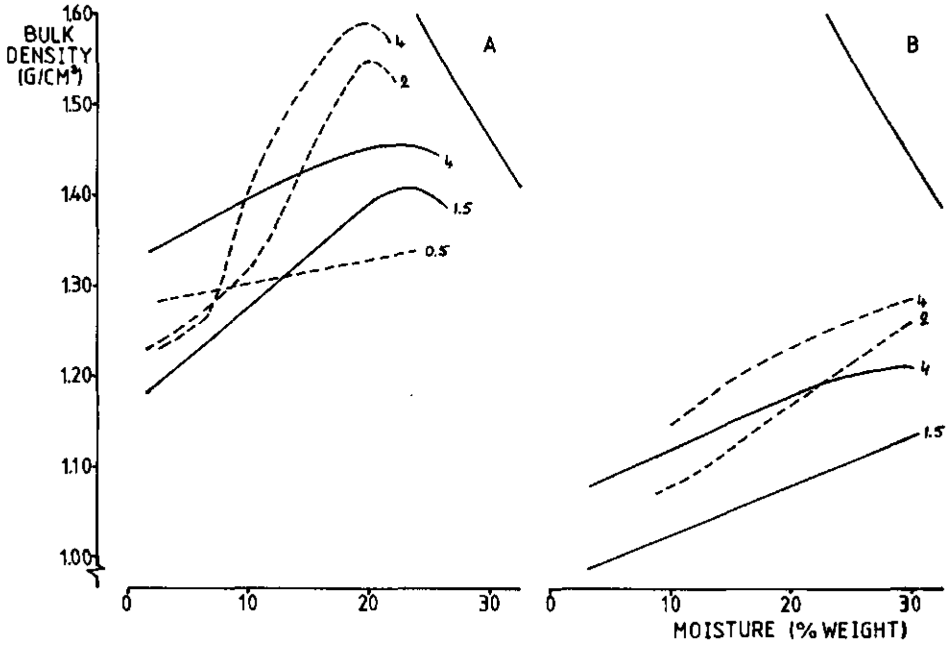

Figure 15: Comparison of standard uniaxial confined compaction and hand compaction of samples of soils nos. 10 (15a) and 5 (15b), as a function of moisture content.
——— = uniaxial test (bar)
----- = hand test (bar).

fields in the former. However, as the stress increases and the loaded surface decreases, failure becomes the dominant process, reducing final density. When soil strength increases, due to higher water content (and thus higher inter-aggregate cohesion) or higher density, the loading type of the hand test becomes rapidly more effective than that of the uniaxial test. Under wet conditions, much higher densities can also be reached because of the localised compactive effect, which facilitates water transport. The difference between uniaxial and hand compaction test is larger for soil 10 than for soil 5. The loading type of the hand test is apparently less effective in cohesive than in frictional soils. The efficiency of repeated loading is also higher in the hand test due to more pronounced changes of the stress axes (cf. § 4.2.3).

4.3.3 Penetration strength

Penetration strength of most soil samples was measured with the pocket penetrometer before and after compression. Penetration strength was also measured in the field. Thus a large amount of data was obtained. Penetration strength proved to be more variable than compaction strength. This is to be expected because the soil volume influenced by the measurement is much smaller and, therefore, more variable. In figure 16 penetration strength of soil type no. 4 is plotted against soil density and moisture content. The curves are based on intrapolation of the measured values. Two curves of standard uniaxial compression and the standard Proctor curve are also plotted for reference.

The curve of 15 bar penetration strength is almost the mirror image of the curve of 4 bar uniaxial compression. At low to medium moisture content both are almost parallel, showing a gradual decrease of strength with increasing moisture content. At the moisture content which starts to limit further compaction, the penetration curve begins to rise more steeply. Near saturation, the penetration and compaction curves become parallel with the saturation line, but in opposite directions. The correlation between both measurements comes as no surprise because the penetration process also depends on soil compaction around the penetrating point. Soil failure is not very relevant in most of my penetration measurements because of the generally low to medium density of the samples. In all denser samples, failure was prevented by loading of the sample surface (§ 3.3). However, because only a small soil

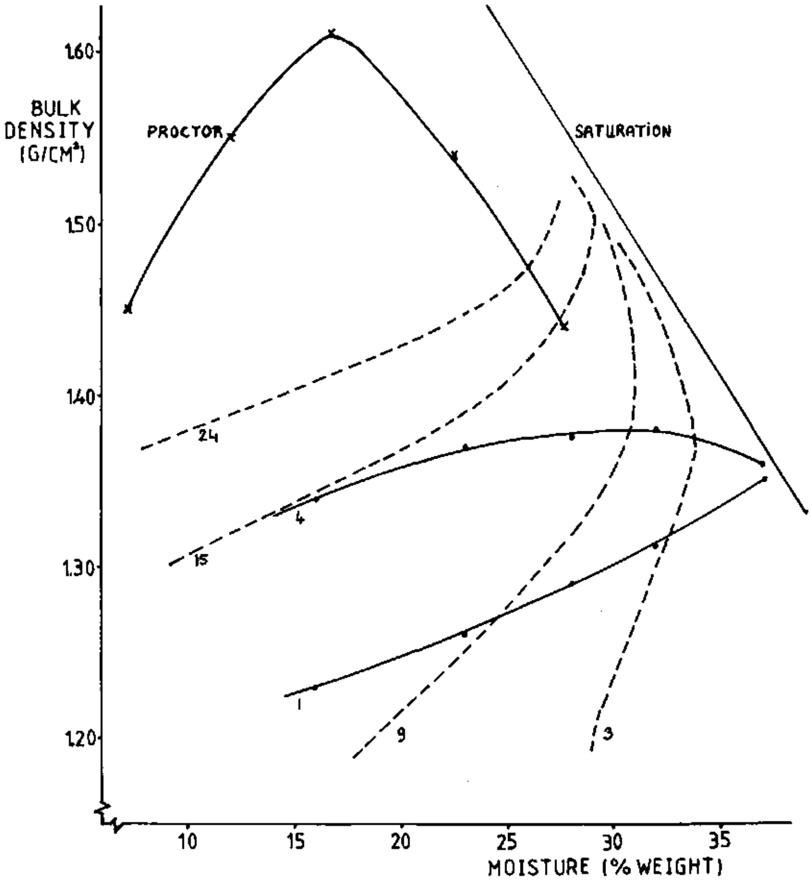

Figure 16: Penetration strength as a function of soil density and moisture content for soil type no. 4. Uniaxial and Proctor compaction curves shown for reference.
•—— = uniaxial (bar)
x—— = Proctor
---- = penetration (bar).

zone is influenced by the penetrating point, water transport becomes not limiting and the low strength at very high moisture content is fully expressed in penetration strength.

The compaction curves for different pressure levels are almost parallel to each other, as are the penetration curves at higher density. At lower density and higher moisture content, the penetration curves are much steeper. This can be partly explained by the high pressure exerted by the penetrometer. If we assume that compaction under the penetrometer point reaches the uniaxial values, then the 3 bar penetration measurements in the 28-32% moisture range in figure 16 would compact the soil locally close to saturation. The corresponding strength loss around the penetrometer point explains the great influence of moisture content on penetration strength in this range, even though the sample as a whole is a long way from saturation. According to this theory the 3 bar penetration curve should become more horizontal at lower moisture content, but no measurements are available for this soil to prove it. In other soil types, however, such behaviour was observed.

In loose soils the first principal stress during penetration is high, relative to the other principal stresses. Penetration in such soils thus resembles unconfined compression and is largely dependent on cohesion. This is another explanation for the great influence of soil moisture on penetration strength at low density. With increasing density, penetration increasingly resembles confined compression.

The absolute strength values are different for compaction and penetration. The penetration measurement loads a small surface, but the soil surface actually influenced is much larger. Consequently, penetration pressure is higher than the corresponding uniaxial pressure. With increasing density the relative difference decreases, but the absolute difference increases slightly: in soil 4 at 15 percent moisture, 9 bar penetration strength corresponds to 0.5 bar compaction strength (18 times, 8.5 bar difference), 15 bar to 4 bar (4 times, 11 bar difference) and 24 bar to approximately 10 bar (2.4 times, 14 bar difference).

In the other soils, penetration strength shows basically the same behaviour. In the silty clay loam (soil type no. 1), penetration strength is very much dominated by cohesion, and even the 15 bar penetration curve is almost independent of soil density at approximately 35 percent moisture. In the silt loams (nos. 2 and 3) even the 3 bar penetration curve runs parallel to the compaction curves at lower moisture content as was predicted above, corresponding with approximately 0.5 bar compactive strength. In the silt loams (2 and 3), the loam (4), and the loamy fine sand (5), the quantitative relation between compaction and penetration strength is much alike, but in the other sands a given penetration strength (e.g. 9 bar) corresponds to a much higher compaction strength (i.e. 5 à 6 bar) because of the lower cohesion in these soils.

In the field and in field samples, penetration strength is somewhat higher than in standard samples, which corresponds to higher cohesion associated with a more developed macrostructure. In the pulverised samples, on the contrary, it is lower, just as the compaction strength.

A number of vane shear measurements were taken on the surface of soil samples and in the field. The measured values proved to be correlated with those measured with the penetrometer. The vane shear measurements have no theoretical advantage over the penetrometer on frictional soils because it is impossible to distinguish the frictional and cohesive components of the measured soil strength. Moreover, they disturb the relatively small soil samples much more than the measurements with the penetrometer. For these reasons, I discontinued the measurements and I shall not discuss them further.

4.4 Loading effects on soil structure

So far I have discussed the strength of the investigated soils in terms of load-density relations, even though I defined soil strength as the resistance of soil structure to the impact of forces (§ 2.1). Measurements of soil density are easily performed, standardised, and reproducible. Therefore, they are widely used for the monitoring of soil changes under loading, as a substitute for measurements of soil structure. As long as soil structure is primarily determined by stable properties of rigid particles and by soil density, such an approach will yield very good results. However, in structured and aggregated soils this is quite different. In fact, changes of soil structure have already been mentioned several times in order to explain the changes in density under loading which have been observed (e.g. § 4.3.1). In this paragraph, I shall describe in more detail the effects of loading on soil structure, using soil-water relations to characterise soil structure (§ 3.1).

4.4.1 Water retention

In 100 cc metal rings, soil samples were prepared at different densities with standard soil material at field moisture content. Water retention of these samples was measured at tensions ranging from 0-15 cbar and compared with the water retention of undisturbed field samples (§ 3.3). The results for soil type no. 5 are shown in figure 17a. Water retention is expressed as a percentage of soil weight (and not of sample volume) in order to eliminate the

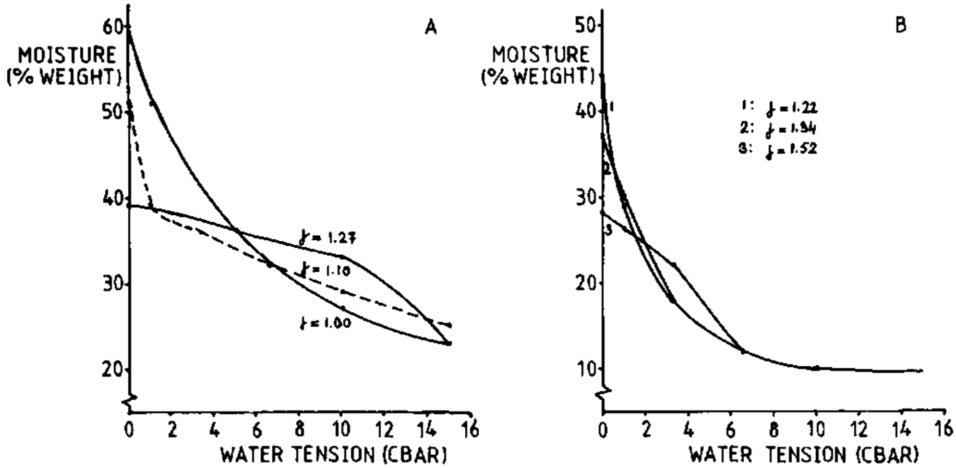

Figure 17: Water retention of soil types no. 5 (17a) and no. 9 (17b) as a function of water tension and soil density (γ).
—— = standard samples
---- = undisturbed field sample.

effect of compaction on the numerical value of soil moisture. As the field samples may have a slightly different soil composition, the shape of the curves in figure 17a is more important than the absolute values.

At zero tension the samples are saturated and the percentage of water held depends on the total pore space (being lowest in the densest sample). As the tension increases, water flows out of the sample. The field samples show a relatively high outflow from 0-1 cbar, the looser standard samples from 1-5 cbar, and the denser standard samples from 10-15 cbar. Apparently, the field samples, though intermediate in density, have a different structure compared to the standard samples. In undisturbed field soils, the cavities are not a function of the random organisation of given aggregates, as in the standard samples, but for a large part the result of tunneling agents such as roots and soil fauna. Therefore, the pores in field soils tend to be more continuous and regularly formed than in the standard samples, which results in a regular outflow-pattern with increasing tension, and a high outflow at very low tension due to a few large pores. The structure of the standard samples is, basically, determined by the more or less rounded aggregates. This causes the water to be held in cavities which have relatively small connections with other cavities. Since cavities are only emptied when the tension rises to the level corresponding to the diameter of the connections, the sudden rise of outflow after a certain tension is reached is typical (c.f. the densest sample in figure 17a when tension rises above 10 cbar). As the density increases, the diameter of the connections decreases more than the total pore volume. Therefore, compaction usually increases the water retention at intermediate tension (in this case at 10 cbar), but the differences decrease rapidly at higher tensions (in this case already at 15 cbar). This effect of compaction is further illustrated in figure 17b for soil type no. 9.

The more intensely the structure of the soil is disturbed, the higher will be the moisture retention at low or medium tension due to the increasing homogenisation of the pore system. This can be illustrated by the effect of the moisture content during compaction on the water retention of the compacted sample (table 12).

Table 12: Water retention (% weight) at 10 cbar tension (pF=2) as a function of moisture content during compaction.

moisture content during compaction	water retention at 10 cbar tension					
	soil 3		soil 4		soil 5	
	field samples	standard samples	field samples	standard samples	field samples	standard samples
15	29	36	27	30	30	40
20	30	-	30	31	32	-
25	32	34	30	-	34	-
30	35	-	29	30	35	36
35	35	37	-	32	35	35

As the moisture content during compaction increases, the water retention at pF 2 increases, especially in the field samples, although the differences in density are small. This may be explained by the variability of strength within the soil due to soil structure. As has been explained in paragraph 4.1.2 under 'water distribution', aggregate strength decreases, relative to overall soil strength, with increasing moisture content. Compaction of a drier aggregated soil may leave the aggregates almost intact, as the aggregates are packed in a denser configuration, primarily at the expense of the largest cavities. This causes a change in moisture retention at very low tensions only. Compaction of a wetter soil, on the other hand, causes a more general restructuring of the soil material, which may even involve some loosening of the aggregates themselves because of dilatation in the densest parts. This causes a more pronounced homogenisation of the soil structure, an increase of water retention at low and medium tensions, and, possibly, some decrease of water retention at higher tensions. Not surprisingly, this effect is most pronounced in soil types with well-developed structure (soils 3 and 5, as compared with soil 4, table 12). In the standard samples, there is much less effect of moisture content during compaction on water retention at pF 2. In these samples the water retention is high in all cases, due to the effect of sample preparation on soil structure. Differences due to moisture content during compaction would probably be more pronounced at higher tensions, but this has not been measured.

4.4.2 Water conductivity

Saturated water conductivity is largely determined by the widest continuous pores available, according to the general flow rule. Obviously, this parameter is highly sensitive to disturbance of soil structure (§ 4.4.1). This is illustrated by results of measurements on soil type no. 5 (figure 18), which show that the moisture content during compaction is a much more important variable than density in explaining differences in saturated water conductivity. Comparable results have been found for other soils (table 13). The coarser soils have a much higher saturated conductivity, but the relative effect of the moisture content during compaction is largely independent of soil type. The increase in conductivity for the wettest measurement in soil 4 coincides with a much lower density.

The results of the measurements of saturated water conductivity on these standard samples show remarkably regular tendencies, due to the random soil packing and the relatively small aggregate size in all soil types (except soil type no. 1, which has been left out of these experiments because of the erratic results). In field soils the results are more variable, due to the importance of large pores which are highly sensitive to disturbance and difficult to measure in soil samples. Nevertheless, field measurements are widely used because of their relevance for erosion and irrigation studies, but they are difficult to interpret in terms of soil structure. This may be different for measurements on prepared soil samples, as is shown by these results.

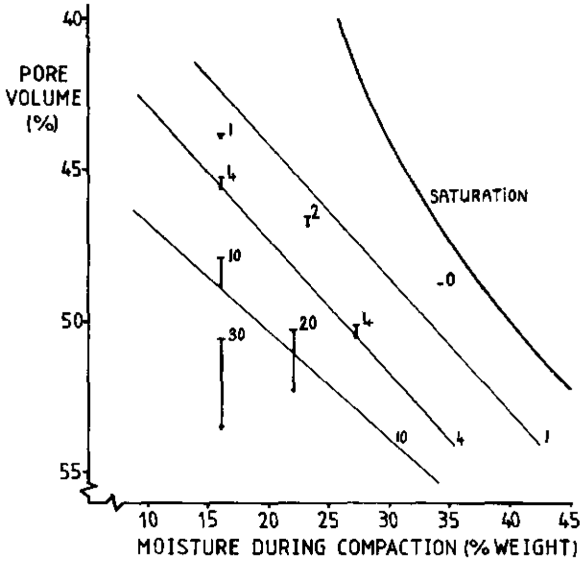

Figure 18: Saturated conductivity of hand compacted standard samples of soil type no. 5, as a function of soil density and moisture content during compaction.
vertical bar = saturated conductivity of soil sample (mm/hour)
sloping line = estimated soil condition with equal saturated conductivity (mm/hour).

Table 13: Saturated water conductivity of standard soil samples, compacted uniaxially with 6 bar, in relation to moisture content during compaction.

moisture content during compaction (% weight)	saturated water conductivity (mm/hr)					
	soil 3	soil 4	soil 5	soil 7	soil 8	soil 9
5	-	-	-	-	-	900
10	100	90	190	300	-	300
15	-	60	150	-	-	120
20	-	20	-	60	170	80
25	30	-	80	-	70	-
30	-	5	20	-	-	-
35	10	10	-	-	70	-

Unsaturated conductivity is, in many cases, a more interesting parameter. Most flow processes in soil water are unsaturated (e.g. percolation of rain, water-flow to the roots, capillary water rise above the phreatic level, etc.).

In figure 19 the unsaturated conductivity of standard samples of soil type no. 4 is shown in relation to the water content, expressed in volume percentage and weight percentage, and in relation to the water tension. When the water content is expressed as a volume percentage, an increasing density correlates with a decreasing conductivity. Because of the higher density, the same volume of water is spread over more contact points and, therefore, the average diameter of water-filled pores is smaller, the tension higher, and the conductivity lower. When the water content is expressed as a weight-percentage, an increasing density correlates with an increasing conductivity. Because of the higher density, the contact points are closer to each other and, therefore, more water-filled pores occur on a surface-unit base (that is: the volume-percentage is higher). Finally, when the conductivity is correlated to the water tension, a mixed relation arises because of the effects of

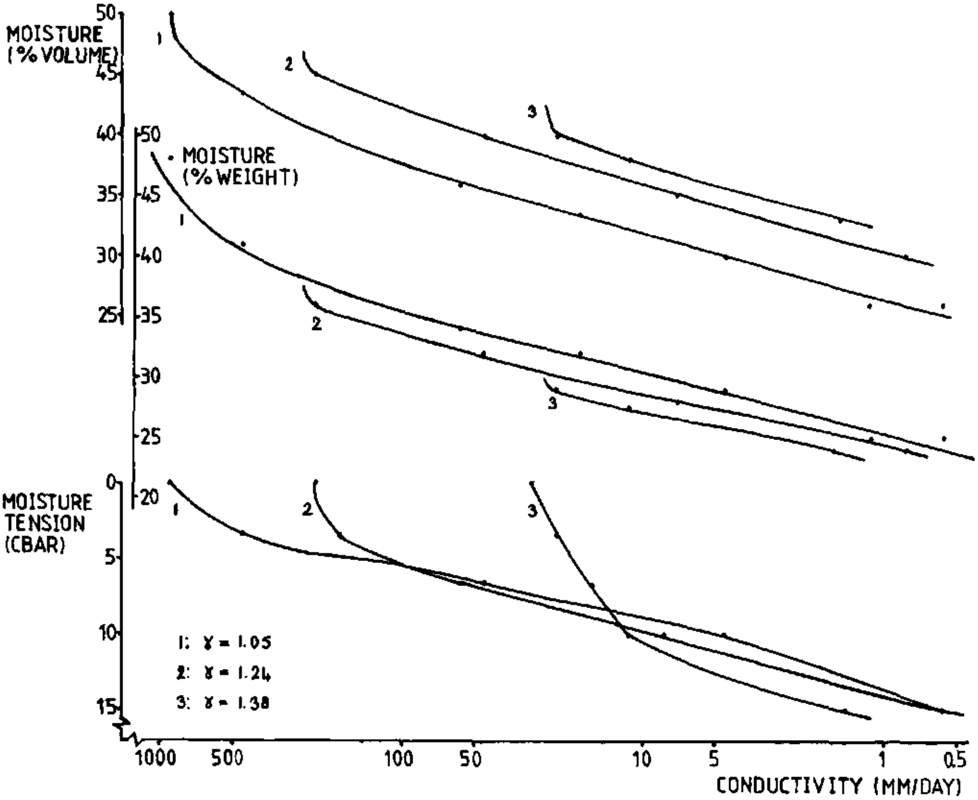

Figure 19: Conductivity for water of standard samples of soil type no. 3, as a function of water content (by volume and by weight), water tension, and soil density (γ).

compaction on water retention. At low tension, the conductivity decreases with increasing density because of the lower water retention. At high tension, the conductivity increases with increasing density, due to the better contacts at the same weight-percentage, or the higher volume-percentage. At intermediate tension, the increased water retention due to compaction increases conductivity even more.

4.5 Soil strength diagram

The results of the measurements on each soil type can be graphically represented and summarised in a figure which I shall call the soil strength diagram. Such a diagram shows the effect of different stresses, applied under different conditions, on the structure of a certain soil material.

The soil material is defined by its composition (e.g. particle-size distribution, organic matter content, specific density, and pH) and by its initial structure (e.g. undisturbed field structure or pulverised; usually described qualitatively). The applied stresses are defined by pressure level, by rate, duration, and sequence of loading, and by loading type (the latter usually described qualitatively; e.g. confined uniaxial or Proctor). The conditions of stress application are defined by the moisture content during loading, and by the moisture tension before loading. The structure of the soil, finally, is defined by moisture retention, (un-)saturated conductivity, and bulk density. Different factors may be used to define and describe the elements of the strength diagram, depending on their relevance and the availability of data.

Figure 20 shows an example of a soil strength diagram for a hypothetical soil, which is based on the relations and tendencies found in my experiments, and which is qualitatively representative for the behaviour of most of the experimental soils. The strength diagrams of some of the experimental soils are given and interpreted in chapter 8.

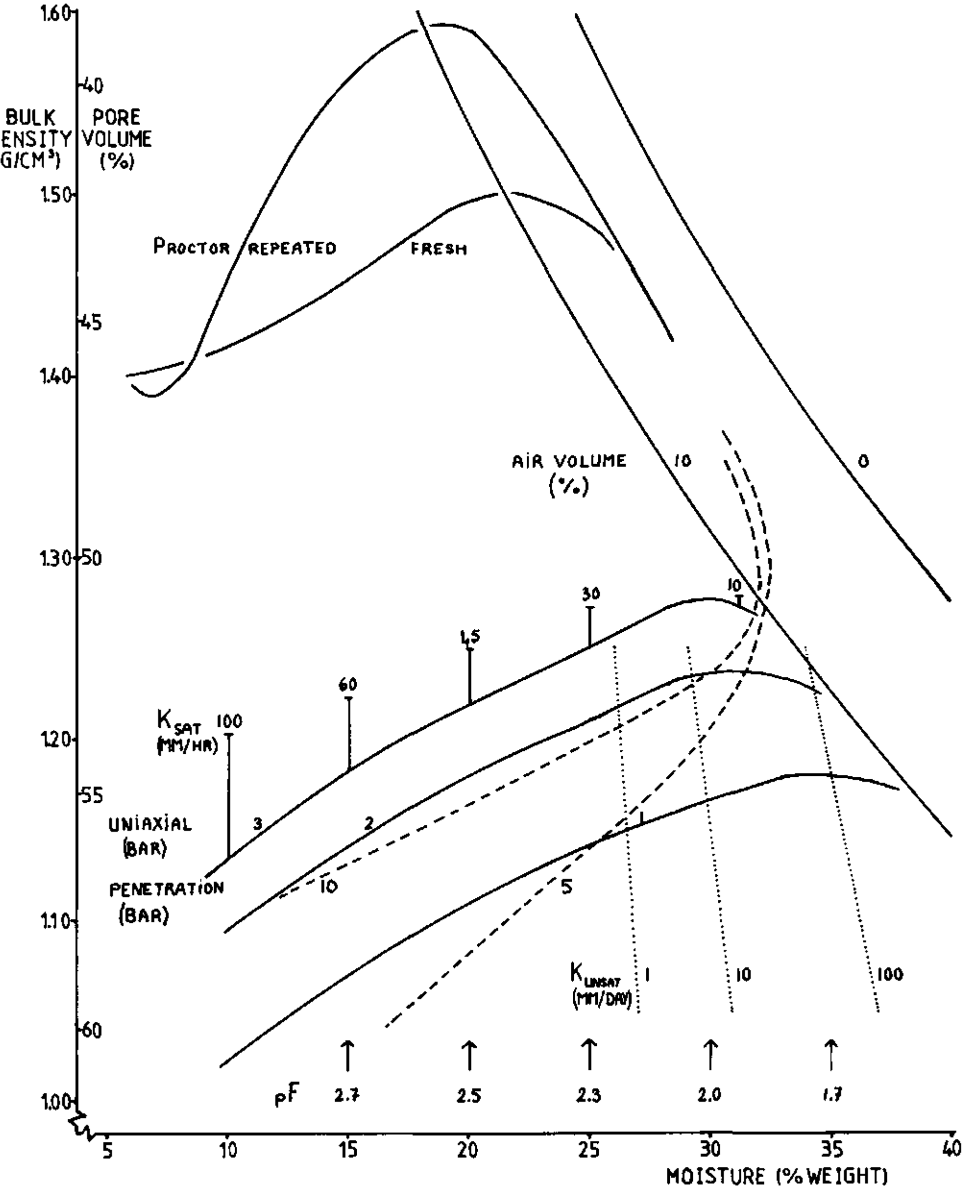

Figure 20: Soil strength diagram of a hypothetical soil (see text for explanations, specific density is 2.60 g/cm³).
—— = uniaxial compaction (bar)
---- = penetration (bar).

5 MODELLING OF SOIL STRENGTH

In chapter 4, I have described some of the more important aspects of the compressive strength of a number of sandy and loamy soils, based on experimental results. The results were summarised in a soil strength diagram (§ 4.5) which describes the change of soil structure and density upon compressive loading as a function of soil and load factors. In this chapter, I shall try to give a more generalised representation of soil strength, which synthesises the experimental results.

5.1 Modelling of the strength of a soil element

In paragraph 4.1 most of the variability in compressive strength of the experimental soils could be explained in terms of three basic strength factors which are modelled in the next few paragraphs: cohesion (§ 5.1.1), density (§ 5.1.2), and structure (§ 5.1.3). The influence of the fourth basic strength factor (§ 2.2), friction, could not be distinguished. This is largely caused by the negative correlation between cohesion and friction, and the positive correlation between structure and friction (cf. Cruse et al., 1981). In paragraphs 4.2 and 4.3 it became clear that the actual measured value of soil strength also depends on the measurement method (§ 5.1.4).

5.1.1 Cohesion

Cohesion can be described in terms of apparent cohesion and true cohesion (§ 2.2 and § 4.1.2). Apparent cohesion can be estimated as the product of the moisture tension and the surface over which this tension acts (effective surface). The effective surface, expressed as a percentage, is roughly equal to the degree of saturation of the soil or soil element for most soil conditions. Only in very dry soils, the effective surface may be relatively larger, as can be derived from the geometrical analysis of the surface area and the volume of a small amount of water which is retained by capillary forces around the contact point between two balls. The degree of saturation depends on the moisture retained and on the total pore volume, and thus on density. The moisture retention (as a weight percentage) at a given tension largely depends on the percentage of fine particles and organic matter

(§ 4.1.2, figure 6). Thus, moisture retention may be predicted quite accurately on the basis of soil composition (e.g. Arya and Paris, 1981; Rawls et al., 1982). However, at lower tensions or higher degrees of saturation, moisture retention becomes increasingly dependent on soil structure and density (§ 4.4.1), and, therefore, prediction becomes more difficult and less accurate. At high tensions, aggregation of the soil becomes more pronounced, especially in loose soils. Moreover, the cohesional bonds become orientated, and thus sensitive for disturbance, at high tensions (§ 4.3.2). Under those conditions, the cohesion of the total soil mass is not a simple function of tension and effective surface anymore.

Figure 21 shows the relative values of apparent cohesion for a hypothetical soil with given pF-curve, based on the product of percentage saturation and moisture tension. As explained above, the values become less accurate above 80 percent saturation and at tensions below pF 2.0 because of the effect of structure on the exact form of the pF-curve for those values. They are also less accurate at tensions above pF 3.0 because of the effect of aggregation, and below 20% saturation because of the relative increase of the effective surface. Nevertheless, the figure shows clearly the fairly regular and almost linear decrease of cohesion with increasing moisture content for a large, and in fact the most relevant, part of the diagram. At low moisture contents the changes in cohesion are much more pronounced. This corresponds very well with the measured compaction curves (§ 4.1.2, figure 5) which are almost linear for intermediate moisture contents, and often steeper for drier conditions. The figure also shows a gradual but slow and somewhat irregular increase of cohesion with increasing density.

The true cohesion in my experiments can be explained in terms of organic matter content and texture (§ 4.1.1). Organic matter content and texture are, apparently, the main determinants of both true and apparent cohesion. However, cohesion is much more sensitive to changes in the organic matter content than in texture. Despite marked differences in particle-size distribution, the six sands could be treated as one textural group, whereas small differences in organic matter content produced striking differences in soil strength (§ 4.1.1, figure 4). Therefore, the type of organic matter is likely to be an important factor as well (e.g. Drozd et al., 1982; Tisdall and Oades, 1982). This may partly explain the smaller strength-effect of the organic matter in the silt loams in my experiments.

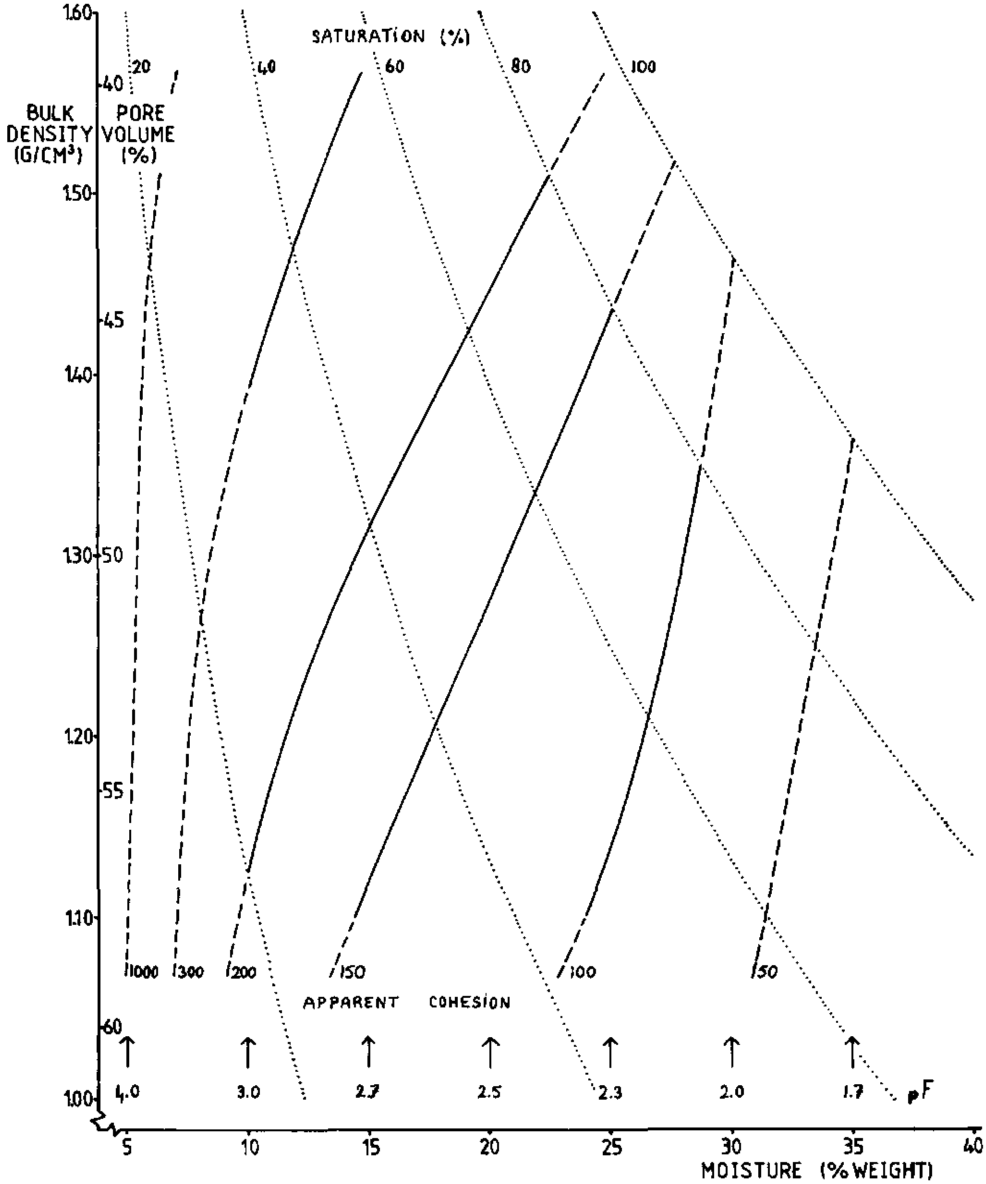

Figure 21: Apparent cohesion of a hypothetical soil, according to the model: apparent cohesion = moisture tension x percentage saturation (relative values, see text for explanation).

.... = percentage saturation
---- = apparent cohesion according to model, real values may be quite different due to soil structure
—— = apparent cohesion according to model, real values relatively independent of soil structure.

True cohesion is per definition independent of moisture content, but not of density and structure. Therefore, it is difficult to model true cohesion. In natural soils, true cohesion increases with increasing density. During compaction it usually decreases because of the disturbance of cohesional bonds. If we assume true cohesion to be independent of moisture and density, we may add a constant value to all values in figure 21. That changes nothing in the general pattern of cohesion, but the strength increase due to true cohesion is relatively larger for the wettest soil conditions with a low apparent cohesion which also is highly dependent on soil structure.

Cohesive soil strength largely determines tensil soil strength, and has an important influence on most other failure processes in soil. However, compressive strength of soil also is very much dependent on soil density. That relation is described in the next paragraph.

5.1.2 Density

In a cohesionless soil consisting of equidimensional particles, density depends on the configuration, and thus on the number of contacts per particle (§ 2.2). As a first approximation, we can expect soil strength to be related to the number of contacts per particle because each contact is subject to frictional forces (cf. Hartge and Sommer, 1982). However, compressive processes in soil are very complicated. For instance, the penetration of a cone in loose soil requires compaction of a small zone around it. As the soil gets denser, not only does it get stronger because of the increasing number of contacts per particle, but an ever increasing zone around the cone has to be compacted to create enough space for it. Penetration strength, therefore, increases much faster with increasing density than we would expect on basis of the number of contacts alone. Instead of a linear relation, a hyperbolical relation between density and strength seems likely. Compaction of a soil sample will show a similar pattern as penetration because an increasingly intensive re-shuffeling of the soil particles is necessary to obtain a certain increase in density within an increasingly dense material. Finally, the soil reaches its maximum density, and further compaction is impossible (apart from elastic deformation, cf. Bailey et al., 1984). Theoretically, the soil has not only a maximum, but also a minimum density.

A function which satisfies these conditions is:

$$\gamma = \gamma_{min} + (\gamma_{max} - \gamma_{min})s/(x + s) = (x \cdot \gamma_{min} + s \cdot \gamma_{max})/(x + s) \quad (8)$$

and thus:

$$s = x\ (\gamma - \gamma_{min})/(\gamma_{max} - \gamma) \quad (9)$$

with: γ = actual bulk density (g/cm^3)

γ_{min} = theorethical minimum density (g/cm^3)

γ_{max} = theorethical maximum density (g/cm^3)

x = constant (depending on soil material)

s = strength due to density

For $s = o : \gamma = \gamma_{min}$, and for $s = \infty : \gamma = \gamma_{max}$.

This function is illustrated in figure 22 for different values of γ_{min} and x, and for γ_{max} = 1.92 g/cm^3. Figure 22 also shows that this function can be fitted very closely with a logarithmic model for intermediate strength levels. Therefore, the good fit of the logarithmic model for the experimental results with the confined uniaxial compression (§ 4.2.1) does not contradict the hyperbolic model proposed here. For the range of densities of interest for my work, most variation of density can be explained in terms of variation of parameter x, whereas γ_{min} and γ_{max} are necessary to explain the variation of density at very low and very high density and strength. In a soil consisting of loose single particles, x represents the frictional properties of the particles.

For soils of mixed composition, the maximum density is more difficult to determine because smaller particles may fill the voids between larger (cf. Yong et al., 1984). However, the maximum density is, like the minimum density, not very important for the form of the γ-s curve in the middle ranges. In structured soils, the situation is more complicated because the parameters γ_{min}, γ_{max}, and x depend on the size and properties of the aggregates. Moreover, the aggregates change under increasing pressure, and so do the parameters of the model. As the size of the aggregates decreases, usually γ_{min} and x decrease, and γ_{max} increases, resulting in a steeper γ-s curve in figure 22. Under the relatively low pressures of my uniaxial compaction experiments, these changes are probably small, but the large effect of other loading types and of pulverisation of the soil material may be explained in these terms.

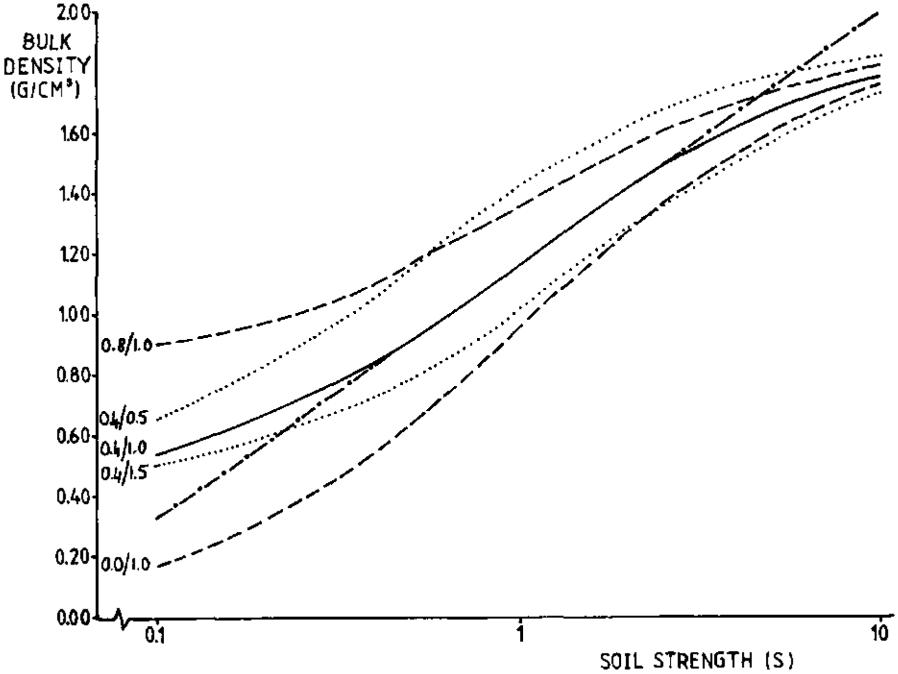

Figure 22: Soil strength according to the model $s = x(\gamma - \gamma_{min})/(\gamma_{max} - \gamma)$, for different values of γ_{min} and x, and for $\gamma_{max} = 1.92$ g/cm³.
0.8/1.0 = $\gamma_{min} = 0.8$ and $x = 1.0$
——— = standard curve (0.4/1.0)
------- = different values of γ_{min}, x constant (0/1.0 and 0.8/1.0)
.... = γ_{min} constant, different values of x (0.4/1.5 and 0.4/0.5)
·-·-·-· = logarithmic model: $\gamma = 1.16 + 0.36 \ln s$.

5.1.3 Structure

Soil structure has been shown to be a major strength-determining factor (§ 4.1.3 and § 4.2.1; e.g. Bradford, 1981; Koolen, 1978; Sommer, 1976). The strength increase due to soil structure can be caused by the cohesional and frictional properties of the aggregates, by changes of the stress distribution in the soil, and by changes of the permeability of the soil. Soil structure is a result of soil process (§ 2.2), and largely a dynamic factor which changes in the course of time. This variability of structure is a weak point in any soil strength analysis. However, in forest soils, soil structure can be expected to be less variable than in agricultural soils because of the permanent vegetation cover and the less intensive soil management. Nevertheless, seasonal variation does occur, as well as variation during the rotation of a stand, especially after clearcutting. This variability should be measured, if it can be expected to be relevant. Otherwise, soil strength should be characterised for the most relevant structural condition. The strength-effect of soil structure can be expressed by the density reached under a standard load, or by a test of aggregate stability if aggregation is the main aspect of soil structure. But quantitative modelling of the effect of differences of soil structure, and of the change of soil structure during loading, is difficult. A soil strength diagram is only valid for a given structural condition.

5.1.4 Load factors

Strength in the models developed above is a relative value. Measured strength values may be expressed as a function of this relative strength value. This loading function may take any form, depending on the spatial relations between loading process and soil reaction (§ 4.2 and § 4.3; e.g. Chancellor et al., 1969).

Generally, cohesive strength is more prominent in all loading processes which cause soil failure, in most cases together with frictional strength. Density, on the other hand, has more influence on all loading processes which cause soil compaction. The cohesion and density effect interact because the same cohesion increases the strength of a dense soil more than of a loose soil. The loading function, therefore, will have the following general form:

$$S = f_2([1 + f_1(c)]s) \tag{10}$$

with:
S = measured strength value (bar)
s = strength due to density (§ 5.1.2, formula 9)
c = cohesion (§ 5.1.1, figure 21)
f_1 = function which determines the relative importance of cohesion and density on soil strength
f_2 = function which determines the slope of the strength-density curve.

This model offers a relatively complete qualitative picture of the soil strength function as far as changes in density are concerned. It describes the importance of cohesion for the relevant soil strength function with the function f_1, the influence of frictional properties of the particles (or aggregates) with x (in s, formula 9), the effect of particle composition and aggregation with γ_{min} and γ_{max} (both in s, formula 9), and the loading process with the function f_2. Both f_1 and f_2 are dependent on soil properties and loading type, and, therefore, also on pressure and density.

It is difficult to determine the constants and functions directly from the soil properties. However, most elements of this model probably vary within a fairly narrow range for different soil types. The slope of the density-moisture curves is fairly constant (figure 5), which points to a reasonably constant form and value for f_1. The slope of the density-pressure curves (figure 11) is even more constant, which is no surprise in view of the independence of this slope for γ_{max} and γ_{min} (figure 22). Therefore, x and f_2 are the main determinants of this model. The value of x is determined mainly by aggregation, and thus by cohesion (that is, in sandy soils: by organic matter content; figure 4).

It is also possible to fit experimental results with this model by choosing appropriate parameters. For example, uniaxial compression of the hypothetical soil of figure 20 is represented reasonably well by:

$\gamma_{min} = 0.4$ g/cm^3
$\gamma_{max} = 1.92$ g/cm^3
$x = 0.7$
$f_1(c) = 0.006c$
$f_2(y) = y^{2.8}$

The strength model for these values is illustrated in figure 23. The model predicts a very steep slope for the moisture-density curve at very high and very low tensions, and a remarkably straight and moderately steep slope at intermediate tensions. The steep part at high tensions is only partly reflected in the experimental measurements because of the effects of aggregation and of disruption of orientated bonds (§ 5.1.1). The steep part at low tensions is not reflected in the experimental measurements of compression because of the effects of saturation and flow processes on compaction, but the curves of penetration resistance show a comparable form at low tensions. The exact form, of course, is very much dependent on soil structure (§ 5.1.1). The straight part, finally, shows a very good correlation with the curves of uniaxial compression. The Proctor curve on fresh soil samples is adequately

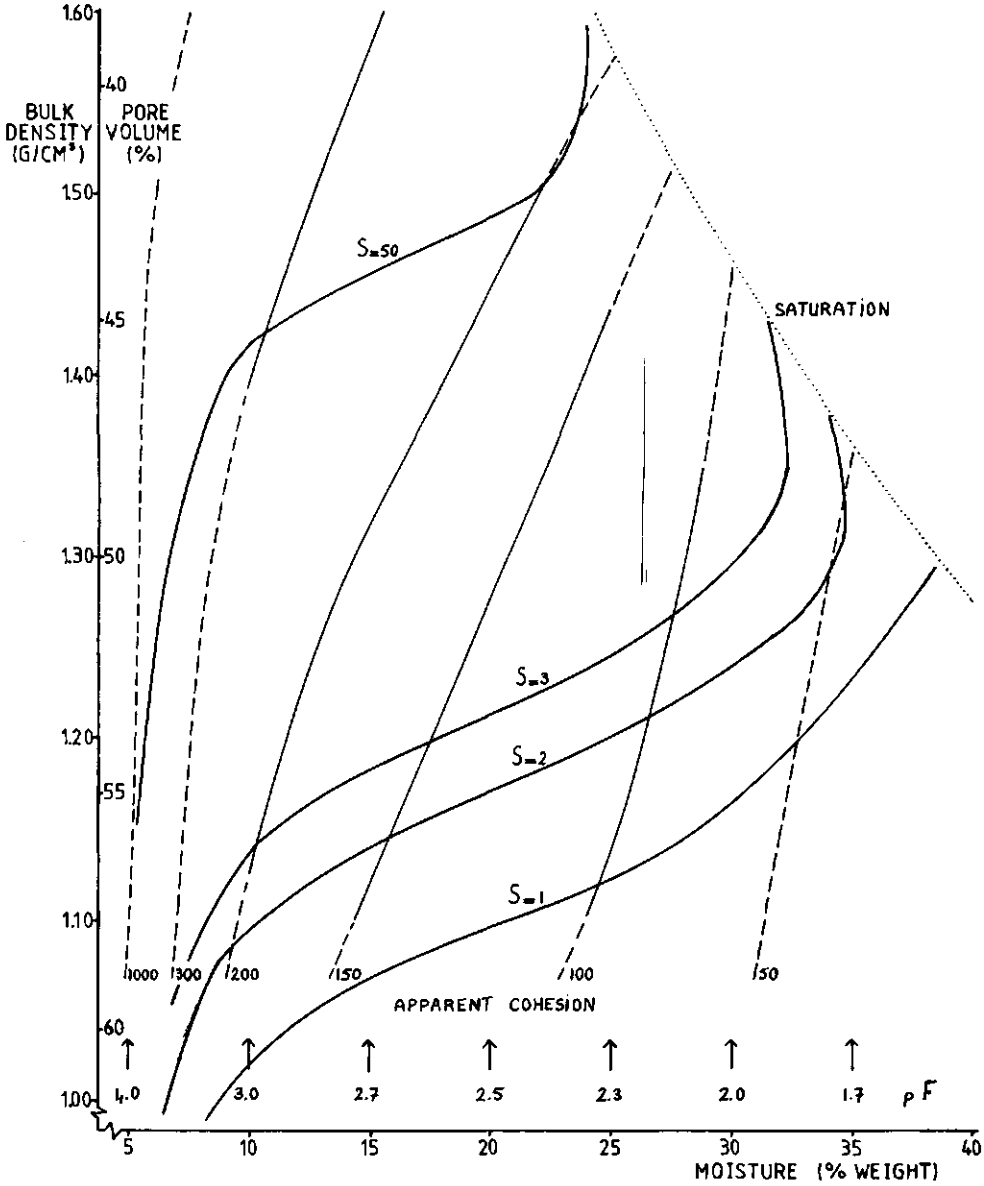

Figure 23: Model of uniaxial confined compressive strength, according to: $S = [(1 + 0.006c)0.7(\gamma-0.4)/(1.92-\gamma)]^{2.8}$ (bar).

represented in this model by the curve of 50 bar uniaxial pressure, like in the logarithmic model (§ 4.3.1).

Loading types such as the Proctor and hand compaction test can probably be represented by a loading function which closely resembles that of the uniaxial test. However, the relative importance of cohesion and pressure is somewhat larger, especially at lower densities. Moreover, their compactive effect is influenced by soil failure and by the change of soil factors caused by their effect on soil structure (§ 5.1.1). The function which describes penetration strength is even more complicated because of the less clearly defined border conditions.

5.2 Modelling of the strength of a field soil

Some basic assumptions used for the modelling of the strength of the soil element are not valid for the soil in the field. Neither stresses, nor the soil itself, can be assumed to be constant on any relevant scale. Variability exists not only in space, vertically (§ 5.2.1) and horizontally (§ 5.2.2), but also in time (§ 5.2.3).

5.2.1 Soil profile

In a completely homogeneous soil profile, the stress pattern under a moving, driven wheel is characterised by a very rapid decrease of deviatoric stresses with increasing depth and a much slower decrease of spherical stress, depending on soil strength (§ 2.4). This stress pattern typically causes soil failure at the surface, which desrupts soil structure and gives rise to relatively loose, and possibly puddled, soil conditions. At a somewhat lower depth, the density rapidly increases to a maximum because of the optimal ratio between spherical and deviatoric stresses (simulated by the hand compaction test, § 4.3.2). Further down, the density rapidly decreases again because of the rapidly decreasing deviatoric stresses, until deviatoric stresses are small. Then the density decreases more slowly in relation to decreasing spherical stress (simulated by the uniaxial test, § 4.2).

Obviously, the depth where maximum compaction occurs, and the density reached, depend on soil type, soil strength, applied shear stresses, and geometry of the loaded surface. In a stronger soil, at lower applied shear stresses, or under a smaller loaded surface, the maximum compaction occurs nearer the surface. Application of high shear stresses on small surfaces may effectively reduce soil compaction (e.g. Koger et al., 1984). As a rule of thumb, the depth of maximum compaction is often taken as half the smallest diameter of the loaded surface. Because of the importance of deviatoric stresses for compaction, the soil density profile after loading differs from the profile one would expect on the basis of elastic models of stress distribution (§ 2.4). This is illustrated by my own field observations (internal report) and by measurements reported in literature (Soane et al., 1981). In layered soils, more complicated stress patterns occur (e.g. Taylor et al., 1980; Wolf and Hadas, 1984).

Except for some recently deposited soils (e.g. sand dunes), pronounced changes of soil throughout the profile are the rule. All strength-determining factors usually change: particle composition may or may not change, organic matter content usually decreases with depth, density increases in most cases, moisture tension decreases (except just after rain), and, finally, structure and true cohesion change, being often most pronounced at some intermediate depth due to pedological developments. Another strength-determining factor is the presence of roots in the soil (e.g. Waldron and Dakessian, 1981). The concentration of roots usually decreases with depth. The surface layer, finally, may have completely different strength properties, characterised by very high cohesive and tensile strength due to its fibrous nature (e.g. Scholander, 1974). Obviously, strength of a soil profile is not a simple function of the strength of one sample taken from that profile. Several samples are usually needed to define the strength of the profile in detail. However, such a detailed definition often is not necessary for practical purposes. In most cases it suffices to define the strength of the most critical layer.

When soil strength increases with depth, the critical layer as far as strength is concerned is the layer just under the surface (e.g. 5-20 cm depth) where maximum compaction occurs. Unless soil composition changes drastically, a measurement of penetration resistance usually suffices to establish qualitatively if soil strength increases with increasing depth. If soil strength decreases with increasing depth, or if weaker layers occur, one has to compare strength and stresses at the relevant depth with strength and stresses near the surface. The absolute stress at any depth depends not only on the stress at the surface and on the stress spreading properties of the soil, but also on the total area under stress at the surface. Some typical strength and stress profiles are illustrated in figure 24.

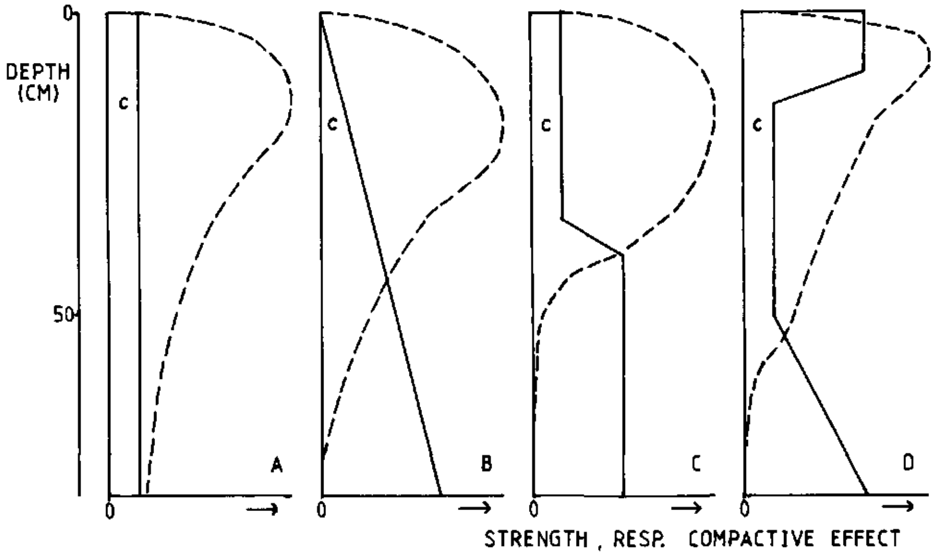

Figure 24: Soil compaction in the soil profile (relative values).
—— = strength of undisturbed soil profile
---- = compactive effect
c = critical layer
24a: profile with homogeneous strength
24b: profile with homogeneously increasing strength
24c: layered profile
25d: profile with strong surface layer.

The disruption of soil structure at the surface caused by high shear stresses causes mobility problems on soils where soil strength is largely determined by soil structure (e.g. organic soils, superficial mats of roots or ground vegetation) and on soils where water retention is very dependent on soil structure. In the latter soils, puddling may result in very wet soil conditions with little or no strength. In such soils, traction and sinkage are the main problems, but in addition these soils may shrink to high densities upon drying.

5.2.2 Land surface

Horizontal variability of stresses on the land surface depends on the loading pattern which is primarily determined by the exploitation pattern and the methods used. Horizontal variability of the soil profile may be caused by variability of the soil material itself (e.g. mineral composition, organic matter content), of the build-up of the profile (e.g. thickness of layers), or of the topography (e.g. drainage). The description of this variability in terms of average values is the main object of land classification efforts which will be discussed in chapter 7. Horizontal variability of the soil may also be caused by variability of the conditions in the soil material (e.g. density, structure, moisture content). Within a limited area, soil moisture content is often the most important variable as far as soil strength is concerned. Because of the great influence of soil moisture on soil strength, this variability is often the weakest point in any field-soil strength model.

Part of the variability of soil moisture is related to soil composition and soil structure. Generally, moisture tension shows less variability. Moisture tension in field soils depends on many factors: height above groundwater, drainage and conductivity, depth of soil layers, and capillary contact (and thus soil composition and structure); but also on rainfall and evapotranspiration (§ 5.2.3). A standard value of moisture tension is the field capacity tension. The field capacity tension is defined as the tension of the soil water at which the drainage rate is very low after the soil has been saturated. Although many soil factors influence this value, it can be estimated fairly well from data on soil composition, profile buildup, and groundwater level. Moreover, it can be measured directly with a tensiometer. Values vary from less than 6 cbar in loose topsoils to 10-15 cbar in fine sands and higher in loamy and clayey soils. Lower values occur when groundwater exists near the surface (10 cm depth corresponds to 1 cbar).

Mobility of a given machine depends on the weakest spot it has to traverse. Therefore, we can speak of critical areas of a land surface. However, unlike the critical layer in the soil profile (§ 5.2.1), these critical areas are not very relevant for the study of soil compaction. Soil compaction in a certain area better is estimated on the basis of average soil strength values, although such values give little information when soil variability is high. That is a problem of soil classification (chapter 7).

5.2.3 Time

Soil strength is also variable in the course of time. This is partly due to long term changes in density, structure, organic matter content, and fertility in response to soil processes which often are related to vegetation development (§ 5.3). Some of these factors also show a seasonal pattern under influence of the climate (e.g. Haines and Cleveland, 1981). On the short term, however, as well as seasonally, soil moisture tension is by far the most important variable as far as soil strength is concerned.

The modelling of changes in soil moisture tension requires data on field capacity tension, pF-curve, conductivity, drainage, evapotranspiration, and rainfall. Of these factors, conductivity is perhaps the most difficult to determine because of its sensitivity to soil structure, especially in loamy and clayey soils (e.g. Bouma et al., 1982). The effect of rainfall may also be estimated by direct measurement of a second standard tension value (for instance, one day after heavy rain on a soil which previously was at field capacity). Field capacity also often is estimated by measurement under standard conditions, usually three days after heavy rain. With such a model, soil strength may be determined as a function of standard rainfall data. The necessary soil data and their spatial variability are, once again, the subject of soil classification (chapter 7).

Soil strength conditions may be indicated in terms of the number of days with a minimum strength per year, or of the number of days after heavy rain until a minimum strength is reached. Soil compaction can only be accurately predicted for the actual conditions during forest operations.

5.3 Soil stability

One of the causes of variability of soil strength in the course of time is variability of soil density and structure (§ 5.2.3). Changes of soil density and structure, which define the effects of applied forces in the soil strength function, occur under influence of natural forces (e.g. Babel and Christmann, 1983; Ryan and McGarity, 1983). When we study the effect of applied forces over a longer period, it may, therefore, become difficult to differentiate between the effects of applied and natural forces.

Soil structure (including soil density) is the result of past and present processes and forces which have acted on that soil. The present state may or may not be in equilibrium with the present processes. When loading of the soil only influences the actual soil structure, it will return to its original equilibrium after the disturbance, but loading may also influence soil processes, which will change the equilibrium itself (degradation; e.g. Hildebrand and Wiebel, 1982). In those cases where soil structure is primarily determined by past processes (e.g. geology, cultivation, different vegetation), loading may just quicken the natural tendency towards a new equilibrium. Generally, the dynamism of natural processes in soil is small in comparison to the impact of applied forces. Therefore, even if soil processes are left intact, recovery of soil structure to the equilibrium may take several decennia (Blake et al., 1976; Froehlich et al., 1985; Jakobsen, 1983). The recovery time should be compared with the intervals between the loading cycles which arise from the exploitation pattern and methods, if progressive changes of soil structure are to be prevented (cf. Greacen and Sands, 1980).

Some of the more important structure-forming factors in soil are growing roots and the larger soil fauna. Both have a profound effect on the pore system, and also may loosen the soil (e.g. Hartge et al., 1983; Kalisz and Stone, 1984). The activity of these factors may remain constant over a range of soil structural conditions, and decrease suddenly when the soil structure becomes very unfavourable, as may occur after loading. On the other hand, important disturbances of vegetation structure, which are often correlated with heavy soil loading, often promote their activity (e.g. growth of grasses in cut-over forests, activity of ants, ground wasps, and some beetles in open sunny spots). Activity of soil fauna is very much dependent on the nutritional status of the soil. Therefore, there is often a general increase in activity in disturbed vegetation. Wetting-drying cycles (e.g. Dexter et al., 1984) and frost are other important structure-forming processes in soil. These also are often more pronounced in heavily disturbed vegetation and in bare soil. In the subsoil, the loosening effect of all these processes is usually small, the effect on soil structure may be more pronounced (e.g. Voorhees, 1983).

Some of the most important structure-degrading processes are the physical impact of rain on bare soil and the physical impact of overland flow on soils with restricted conductivity. Both processes often occur together on compacted or disturbed soils, especially after clear-cutting of the forest, but they are only partly related to the problem of soil strength and soil compaction as discussed in this study. A large amount of literature on the problem of soil erosion exists.

The soil stability concept is qualitatively illustrated in figure 25. The quan-

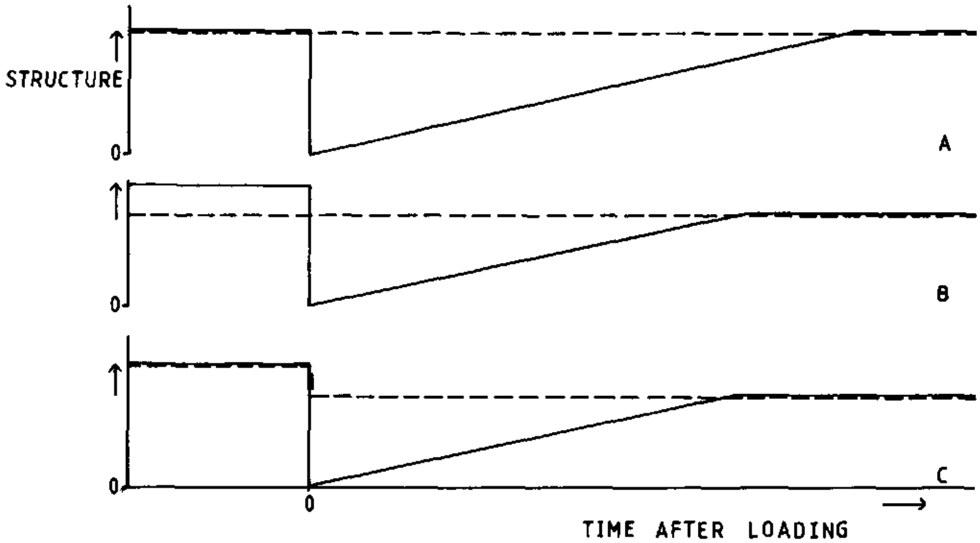

Figure 25: Development of soil structure after loading in the course of time (qualitative).
---- = equilibrium state
—— = actual state
25a: normal recovery
25b: relict state before loading
25c: new equilibrium after loading.

titative description of these dynamic soil processes is still barely touched upon. Some experimental results are available, but no more than a few rules of thumb can be given. The combination of the complicated soil material, diverse biological processes, and long periods involved forms a difficult object for research.

6 INTERPRETATION

So far, I have discussed the effect of forces on soil structure in an effort to model the effect of vehicles on forest soil. In this chapter, I shall return to some of the other relations depicted in figure 1 (§ 1.4) in order to indicate what relevance soil strength has for the forest manager.

6.1 Soil strength and vegetation

Plant growth depends on energy, carbondioxide, nutrients, and water. In most plants, energy and carbondioxide are taken in from the air above ground, whereas nutrients and water are largely taken in from the soil with the roots. In the next few paragraphs root functioning (§ 6.1.1), root growth (§ 6.1.2), and the possible effects of soil disturbance (§ 6.1.3) will be discussed.

6.1.1 Soil process and root functioning

The intake of water and nutrients is a complicated process which depends on the supply capacity of the soil and the availability and transport possibilities in the soil, as well as on the exchange capacity of the soil-plant interface and the transport possibilities in the plant. The supply capacity of the soil is largely a soil characteristic which depends in the case of water on water table, capillary rise, and water retention, and in the case of nutrients on the content of weatherable minerals and on the cation exchange capacity of the soil. The availability of water depends on the moisture tension which may be influenced by soil structure. The availability of most nutrients depends on physical (e.g. temperature, moisture), chemical (e.g. pH, air, presence of other minerals), and biological (e.g. binding and release in organisms) processes, and these processes in turn are influenced by the soil and vegetation. The transport through a soil depends on the porosity of that soil. Easily dissolved nutrients are transported with the water flow which is negatively correlated with the water tension in the soil, or they diffuse through the water in response to a concentration gradient. Less easily dissolved nutrients usually diffuse only in response to very high gradients and thus over very short distances, and often only under special conditions of, for instance, pH.

The contact between soil and plant in most plants and in all trees is established by a complex system of special organs of the plant: the root system. The root system not only enlarges the exchange surface between plant and soil, but it also promotes the intake of some nutrients by its influence on the chemical condition of the soil around it, often in association with microorganisms. Moreover, roots form transport routes through the soil, with a much higher transport capacity for water and nutrients than the soil has, thus decreasing the dependence of the plant on the soil and on soil moisture tension. Finally, roots provide support and stability for the plant, which is more important the higher the plant grows, as in the case of trees.

Notwithstanding the transport function of roots, most roots need an external supply of oxygen for their growth and functioning, although marked differences exist between and within species (e.g. Miller, 1984). Soil aeration may be even more important to prevent a buildup of toxic substances which may result from respiration and anaerobic processes (e.g. Sanderson and Armstrong, 1980). Aeration depends on the distribution and continuity of air-filled pores in the soil, because of the very slow air diffusion in water. The volume of air-filled pores is, therefore, not a good measure of aeration, and aeration may be restricted in loose soils with high air volume (e.g. Eavis, 1972). The total surface area of all air-filled pores (as determined from the pF-curve) may be a better measure (Visser, 1977).

The extent and intensity of the root system needed for optimal plant growth on a given soil depend on the soil. The higher the concentration in and transport capabilities of the soil, the less the need for a well-developed root system (e.g. Boone and Veen, 1982; Vogt et al., 1983), except for the stability of the plant. This is illustrated by the long life cut flowers and plants may have in nutrient solutions without roots at all. Usually, a greater intensity of the root system is needed in the case of low concentrations and low availability of nutrients, whereas greater extensiveness of the root system facilitates the intake of water and the stability of the plant. Of course, roots form an investment of the plant and theoretically an optimum between costs and benefits for the plant must exist. In most poorer soils, like the sandy soils in this study, most nutrients are concentrated in the topsoil and the organic surface layer as a result of atmospheric input and the recycling of nutrients in the vegetation. Consequently, rooting intensity is important in the topsoil for the uptake of nutrients. Rooting intensity in the topsoil is further increased by a symbiosis of roots and soil fungi, the mycorrhiza. These mycorrhiza enhance the intake of poorly dissolvable nutrients in poor soils, partly because of their greater rooting intensity and partly because of their better contact with the soil. Sands have a very low water conductivity at high tension, but this does not stimulate intensive rooting in such soils. Apparently, the low volume of water to be recovered is not worth the investment in the root system for a plant, and rooting depth is the main factor determining the intake of water. Rooting depth and size and strength of the roots are also the main factors for stability.

For each function and for each nutrient the optimal configuration of the root system will be different. Root growth is influenced by a large number of factors ranging from genetically determined relations, via availability of photosynthesis products, to soil factors like temperature, strength, aeration, moisture, and nutrients. Therefore, it seems highly unlikely that the end result would be the optimal configuration. Unfortunately, it is extremely difficult to determine theoretically which rooting density is optimal, mainly because we do not know enough about the intake process of nutrients with low availability. Experimental evidence suggests that rooting density will be over-optimal in most soils, but sub-optimal in soils with pronounced shortages of some nutrients. In the first case, plant growth does not decrease when root growth is restricted, whereas restriction of root growth may have dramatic effects on plant growth in the second case.

The intake function of the roots is concentrated in a short zone of the root behind each growth point, and is enhanced by the development of root hairs in this zone. As the root grows older, it suberises and becomes more and more impermeable to water. Moreover, soil zones around roots may get (temporarily) exhausted. Thus, the intake function depends on continuous growth and ramification of the roots. This growth is concentrated in places where conditions for extension are most favourable. Thus, roots may follow a retreating water table, or explore new soil areas for nutrients. Temporary shortages of water have a greater influence on plant growth than temporary shortages of nutrients because the concentration of nutrients in a plant may vary within fairly wide limits, and redistribution of most nutrients occurs normally in plants.

6.1.2 Soil strength and root growth

Soil structure influences most soil processes to some extent and aeration to a very large extent, and may thus influence root growth and functioning indirectly in many ways. However, soil strength has a direct impact as well. The primary diameter of roots is species-dependent and relatively fixed, decreasing from main axes to lateral roots of increasing order. Typical values range from 100 µm to 1 mm for roots, and 10-15 µm for root hairs (the latter with a length of up to 1 mm). While root hairs usually can develop in existing pores, the roots themselves often have to push aside soil particles. The maximum pressure exerted by roots depends on the osmotic potential of the elongating cells, and maximum axial pressure measured directly ranges from 9-13 bar (Whiteley et al., 1981). The resistance against compression of well-watered cells as well as the radial pressure of secondary thickening roots are of the same order. The penetrating root may be simulated with a penetrometer, but a number of basic differences exists (§ 2.5). Not surprisingly, therefore, the penetration resistance which correlates with the ceasing of root elongation is commonly cited to be between 8 and 40 bar, and sometimes even higher, depending on the presence of large pores. In homogenised soils (such as disturbed samples), the correlation will be better.

Under experimental conditions, root elongation is seriously hampered at very low pressures, but it is not clear how these translate to soil conditions (Scott Russell and Goss, 1974). It is likely that root growth is negatively correlated with soil strength over much of its range, but this depends on soil type, available pores, and aeration (e.g. Heilman, 1981; Sands and Bowen, 1978; Wästerlund, 1985). This has more effect on rooting density than on the extent of the root system. Not only is the latter facilitated by the few pores and cracks which are present in almost all soils, but also the roots of perennial plants can grow in other periods when soil strength is lower (for instance, because of a lower moisture tension). Mycorrhiza, however, may well be more sensitive to soil conditions than the roots themselves (Skinner and Bowen, 1974).

In soils with pronounced pores or aggregates, root growth may be hampered at much lower soil strength than in more massive or homogeneous soils. This is caused by the low bending and buckling strength of roots. Thus, the pressure which a root can exert upon re-entering the soil after traversing an open space decreases with the increase of the length of the unsupported root, and with the deviation from vertical of the angle under which the root touches the soil (Whiteley and Dexter, 1984). In such soils, rooting may be restricted almost completely to the pores and cracks, even at low soil strength. In clayey soils, this is furthered by the physical damage to any root bridging the gap between two aggregates caused by the swelling and shrinking of the aggregates. If the aggregates are relatively large, a very poor rooting pattern may be the result.

Not only root growth depends on soil strength, but other soil processes as well. Larger soil animals such as earthworms are sensitive to soil strength. Others, such as dungbeetles, actually prefer stronger soil. The smaller soil animals largely depend on the existing pores, and thus benefit from loose and crumbly structures with small aggregates which have a large surface area. The same holds for many physical and chemical processes, which are related in intensity to the surface area too.

6.1.3 Effects of soil disturbance

The effects of soil disturbance and soil compaction on forest growth may be manifold, but remain difficult to quantify. Usually, root growth decreases in the affected areas as a result of increased penetration resistance and decreased aeration (cf. Boone et al., 1986). However, this may have little or no effect on tree growth on the better soils, and very large effects on poorer soils where trees are dependent on mycorrhiza. The effect on the intake of water will usually be minimal, although the water retention characteristic of the soil may change slightly. In some cases, the unsaturated conductivity is considerably higher in a compacted soil. This promotes the capillary rise from the groundwater (where present, e.g. Boone et al., 1978), and generally increases the field capacity tension. Aeration in disturbed soils usually is much worse than in natural soils of the same density because of the disruption of the continuity of soil pores (e.g. Hildebrand, 1983a). If aeration of the topsoil becomes limiting over larger areas, the effects may be more pronounced because that will limit the aeration of all deeper soil layers proportionately. Thus, soil processes and root growth may be hampered in substantial parts of the total soil volume. Estimations of the effect on forest growth may be based on the percentage of the total soil volume influenced, and the estimated decrease of root functioning for the most critical factor in that part of the soil volume. The measurement of such effects in the field is difficult because of the interaction with thinning effects and the large variability of soils, trees, and effects (Bredberg and Wästerlund, 1983; Wert and Thomas, 1981). Unlike most agricultural plants, trees are perennial, and forest stability depends very much on the ability of the trees to survive extreme conditions. Therefore, we should judge soil conditions in relation to such extremes. Aeration, for instance, may become limiting in an extremely wet year, causing the death of parts of the root system, which in turn may cause an outbreak of root diseases (cf. Delatour, 1983).

More incidental effects should be taken into account as well. The root system of seedlings may get misformed when a very strong, compacted soil layer underlies a looser topsoil, as is often the case in vehicle paths (§ 5.2.1). Whether this leads to instability or serious root problems in a later stage is uncertain but not unlikely (cf. Deleporte, 1981). Increased soil strength and decreased aeration also influence the occurrence of damage to the roots and the development of parasites and diseases. However, except in extreme cases, this is probably not an important factor. Disturbance of the topsoil may also have beneficial effects. Aeration may be improved when thick layers of moss are broken up, and germination of seeds may be enhanced where mineral soil is exposed. Plants adapted to poorly aerated ground may develop or become dominant on some compacted or disturbed soils. Thus the floristic composition of the forest floor may change. This process may also be promoted by the unintended transport of seeds by machines and man working in different areas.

6.2 Forest management and loading pattern

The occurrence and magnitude of stresses in the soil, in space and time, are primarily determined by management-related factors. The loading pattern can be distinguished by factors related to the machine (forces and stresses, § 6.2.1), to the operation (spatial pattern, § 6.2.2), and to the exploitation (occurrence in time, § 6.2.3).

6.2.1 Forces and stresses

The static weight of the machine and load cannot be varied at wish. The minimum load is largely determined by the size of the trees, and the weight of the transport vehicle is roughly equal to its maximum payload in the case of a forwarder and twice that in the case of a skidder. In the case of machines which perform operations which involve handling of trees, the machine also has to be relatively heavy for reasons of stability. Within these limits there is usually a choice between smaller and larger machines, the smaller machines taking more time to perform a given operation and making more trips to transport a given load. Because of the almost constant relation between vehicle weight and maximum payload, the product of weight and distance travelled remains constant for transport operations when the same transport system is used.

The total load usually is not distributed equally over the vehicle. Moreover, it may shift to one side due to load handling or when driving on a slope (e.g. Lysne and Burditt, 1983). The magnitude of this shift depends on the location of the centre of gravity of the loaded vehicle. Dynamic effects also may greatly increase the total load: they are provoked by the motor, the soil surface, de- and acceleration, swinging of the load, and movements during load handling. These dynamic weight factors may be considerably reduced by an adequate distribution of mass and springs in the vehicle.

Next to weight, driving forces are a second source of stresses exerted on the soil. In order to move, the vehicle has to overcome rolling resistance, possibly drag resistance, slope and obstacle resistance, and it has to accelerate (e.g. Fabre and Martinez, 1983; Iff et al., 1984; Perumpral et al., 1977). Most vehicles develop the forces needed by contact with the soil. These forces may be considerably reduced by adequate design parameters of the running gear of the vehicle (thus lowering rolling and obstacle resistance), and by carrying the load partly or completely (thus reducing or eliminating drag resistance which is almost always higher than the equivalent rolling resistance). Acceleration forces may be smoothened through the use of hydrodynamic transmission or of continuously moving vehicles. Rolling and obstacle resistance depend partly on the soil, and may be lessened by choosing adequate paths, as is the case with slope resistance.

The forces on the soil associated with vehicle activity in forest management are transferred from the vehicle to the soil in a relatively small contact zone, the running gear, which may consist of tyres, tracks, sledges, or otherwise. The total forces on the elements of this contact zone are determined by vehicle, soil, and operation parameters as discussed above. The resulting stresses on the soil depend primarily on the running gear, although the soil has some influence as well. The larger the surface of the contact zone and the more homogeneous the stresses are distributed over this surface, the lower the maximum stress exerted on the soil, which limits soil compaction. A homogeneous stress distribution depends mainly on the flexibility of the contact surface. For that reason, flexible tyres are usually superior to other running gear types, even though other types (e.g. tracks) may have a larger surface area. Other advantages of flexible tyres are the dampening of dynamic forces (acting like a spring), and the fact that the contact surface adapts itself, within limits, to the total load, thus leaving the surface stress almost independent of the load. Unloaded, therefore, the stress may be higher than it would be under an unflexible contact surface. New developments in tyre technology, in design (e.g. Abeels, 1983) as well as in material, will further optimise the tyre as running gear.

The lower the average stress in the contact area, the greater the contact area needed to carry the same load. With regard to tyres, this means the use of larger tyres, or of more tyres which may be placed next to each other or behind each other. Larger tyres and tyres which are placed closely together have the disadvantage of increasing stress in deeper soil layers. They also broaden the vehicle when larger tyres are used or when separate tyres are placed next to each other. On the other hand, placing the tyres in a row is only possible when the vehicle is long enough. Moreover, this solution is more costly for off-road vehicles because of the need for a complicated suspension system and an all-wheel drive system. A common solution for forwarders is the use of eight low pressure tyres, mounted on bogies, with all wheels driven. Skidders usually have four wheels, all of them driven. Typically, the weight on each tyre of a loaded forwarder or skidder is between one and a half and two and a half tons. Tractive forces are usually higher on skidder tyres because of the high drag resistance of skidded logs. The stability of the skidder is better because of its lower point of gravity, enabling the skidder to travel steeper slopes, which, however, may be another reason for high tractive forces.

Apart from their size, low-pressure tyres also have technical disadvantages. Tyre wear and high bending stresses on the axle of the vehicle may be overcome by better materials and design, but are a problem with existing vehicles. Tractive ability may be limited due to rim-slip and poor soil penetration, and these tyres are less suitable for on-road use at higher speed. These problems may be overcome by a central tyre inflation system which would make it possible to adapt tyre pressure to soil strength and operation conditions (cf. Della-Moretta and Hodges, 1982). Such systems have been developed, but are not yet commercially available. The same holds for slip control systems and differentials between the axles which may optimise the distribution of tractive forces over all tyres (e.g. Erickson and Larsen, 1983).

Of course, in many cases soil strength or soil stability are such that unsophisticated vehicles cause little damage. In other cases, damage control cannot succeed without restricting vehicle traffic (§ 6.2.2 and § 6.2.3). Nevertheless, the impact of vehicles on the soil can be appreciably reduced through technological developments. As developments proceed, such technologies will become commercially available, and affordable in light of the decreased damage levels and improved productivity in forest operations. However, the forest manager should remain careful not to misuse the increased mobility of such vehicles on very sensitive soils (cf. Hildebrand, 1983b).

6.2.2 Pattern

Within the context of the total land surface, the pattern of stresses depends on the stresses exerted by the vehicle in the contact zone or path, on the width of each path, the number of paths, and the spatial distribution of those paths. Other circumstances being equal, the forest manager may choose between higher stresses, longer loading times, repeated loading of the same surface, or spreading the stresses over a larger surface. This choice exists for the vehicles (§ 6.2.1) as well as for the operation patterns.

In all cases where a negative loading effect on the soil is expected, spatial limitation of this influence should be contemplated (e.g. Froehlich et al., 1981; Olsen and Seifert, 1984). The effect of longer loading times (associated with larger tyres or tracks) often is minimal (§ 4.2.2), which in itself is an advantage of tracks. The effect of repeated loading usually is less than the effect of higher stress (§ 4.2.3), and therefore the first is preferred, either by using more wheels in line on the same vehicle or by using the same path for several passes of the vehicle. The time interval between successive passes has some influence because the soil will adjust itself to its new configuration after some time. The soil may become wetter after compaction, causing some loss of compressive strength. Thus the effect of repeated passes of a vehicle may be more pronounced than the effect of repeated passes of different wheels of the same vehicle. This may be a point in favour of larger machines which take larger loads or perform different operations in one pass. Another advantage of larger machines is their better stability which may facilitate the use of load-handling equipment such as cranes, thus reducing the need to drive close to each load.

Often, soil strength may be sufficient to support one pass of the vehicle, whereas repeated passes cause increasing damage. This situation occurs most frequently where soil strength depends on the uppermost layer consisting of ground vegetation and the root mat, and where soil strength is largely determined by soil structure. Usually, such soils are very wet and not compactable because of their nearly saturated condition. Therefore, bearing capacity and aeration are the main problems on such soils. In the case of ground vegetation and root mats, it may be advisable to spread the stresses as much as possible, using wide tyres and many different paths. On other wet soils, traffic should be concentrated to prevent aeration problems in large parts of the surface. Obviously, this may cause mobility problems which may be reduced by using an adequately designed and equipped vehicle (e.g. Nipkow, 1983).

Apart from the effect of large loading surfaces on the stresses in deeper soil layers (§ 5.2.1), the width of each path should remain limited on sensitive soils for another reason. The wider the disturbed soil area is, the more pronounced will be its influence on the aeration of the subsoil and its effect on root growth, because roots are usually able to traverse a certain distance of unfavourable soil. For the same reason, natural regeneration of soil structure will be slower, the wider and more continuous the disturbed soil area is. Loading of a non-continuous strip, therefore, has advantages. The horse (and man himself) is probably the best known example, but cage-wheels may also serve this purpose, and walking machines may become more common in future (e.g. Sorensen, 1984).

6.2.3 Time

Strength of most soils is highly variable in the course of time, and the effect of a given load, therefore, will be very variable as well. Thus, the choice of operation time may be a critical factor in limiting soil damage. Moreover, this choice also determines which operation pattern is optimal (§ 6.2.2). Soil strength is usually maximal under dry or frozen conditions, and minimal under wet and thawing out conditions. For reasons of economy, it usually is not possible to restrict forest operations to optimal conditions. Therefore, operations under poor conditions should be concentrated in those areas which best support them, and favourable conditions should be used to work in the most sensitive areas. Any planning system which leaves no room for such considerations, even at very short notice (e.g. in the case of frost periods), should be changed. Often, the concentration of operations in favourable periods is much cheaper than the use of specialised machinery or exploitation methods in unfavourable periods. The indication of sensitivity of soil strength for weather conditions should be a major concern of terrain classification (chapter 7).

Vehicles return into the forest for the next operation after 3 to 20 years, depending on the growth of the forest, management aims, and the intensity of separate operations. If the soil has completely returned to its pre-impact condition, the new operation may be performed independently of the last as far as the soil is concerned. Usually, however, that will not be the case. Therefore, it should be advised to re-use the paths of the last operation in order not to increase the affected area too much. Thus, there is often a case for the designation of (semi-)permanent paths through the stand, which can be used for all operations. Whether or not such paths should remain in use during successive forest generations depends on whether there is within a generation a period long enough for complete recovery of soil structure (e.g. after clear-cutting, and in the juvenile phase of a forest), or a possibility for soil cultivation (§ 6.3).

6.3 Soil management

It often is possible to modify the soil for the requirements which plants or vehicles may make on it. Soil management usually involves either the addition of components, thus changing soil composition (§ 6.3.1), or direct interference with soil structure (§ 6.3.2). Vegetation management can be used as an indirect method of soil management, and is mentioned whenever appropriate.

6.3.1 Soil composition

The stability of the natural soil structure can be improved either by increasing soil strength or by intensifying soil processes. Relatively small additions to the composition of the soil may have large effects.

Several substances increase the strength of soil structure via a change of pH (§ 4.1.1) and soil processes, or otherwise. Calcareous compounds are commonly used for this purpose, and some compounds of iron may be effective as well (e.g. Shanmuganatan and Oades, 1982). In some cases where a very dense soil structure prevails, the increased strength may hamper root growth. Moderate amounts of organic matter also increase compressive soil strength (§ 4.1.1) and may be added for that purpose. However, high contents may cause problems because the high water retention of organic matter may reduce aeration and may cause loss of strength when near-saturated conditions are reached under pressure. The common practice of loading all logging debris on (future) paths through the stand is, therefore, not advisable on some soils, even though at first it may increase bearing capacity.

Many minerals or fertilizers not only stimulate plant growth, but soil processes as well. Fertilisation may speed up the restoration of soil structure after disturbance. At the same time, it may make plant roots more tolerant for adverse soil conditions (especially in the case of phosphorus), and plant growth less dependent on rooting density. Although fertilisation may be an effective method for decreasing the impact of vehicles and increasing forest productivity at the same time, it is not commonly used as such. Lack of knowledge, or the high costs in view of the long investment period in forestry, may be the reason. But there is also a widespread hesitation to use fertilisers in forestry because of the possible effects on the stability of the forest and the break-down of organic matter (e.g. Ulrich and Matzner, 1983). Finally, of course, there is opposition from those who think it unnatural, or who reject any activity which could be described as "curing the symptoms".

Soil moisture content, as one of the main determinants for soil strength (§ 4.1.2), is an obvious candidate for soil management. Drainage decreases moisture content effectively if water conductivity of the soil is sufficient, provided that the moisture content is effectively dependent on the drainage situation. Drainage not only increases soil strength (which is often the most important reason for drainage in agriculture) but it also increases the stability of the forest (which is often the most important reason for drainage in forestry), and it may also increase growth, depending on the water supply in dry periods. However, drainage is expensive, especially on soils with low conductivity. Moreover, neglect of a drainage system is disastrous for the forest if the temporary high water table provokes the death of large parts of the root system. The installation of a drainage system may also cause damage to the forest if the trees cannot adapt quickly enough to the new situation. Strong objections against drainage are also expressed because of its often pronounced effect on ground flora. Much more common is the local drainage of roads in order to increase their strength. The construction of a rounded road surface to prevent water pools, and of shallow ditches on both sides of the road are commonly considered minimum standards for all forest roads.

It should be kept in mind that closed forests intercept and use much more water than other vegetation types. Thus, the forest itself lowers the moisture content of the soil in comparison with the situation in the open field. This may become conspicious after heavy thinning or clear-cutting. In such cases it may be better to use paths through the closed forest instead of through the much easier open terrain.

6.3.2 Soil structure

Soil structure is influenced indirectly via soil processes when the soil composition is altered (§ 6.3.1), or through vegetation management. Soil structure is also influenced by the forces exerted by passing vehicles, which is the main theme of this thesis. However, soil compaction or soil loosening (soil cultivation) may also be the explicit aim of many operations designed to modify soil structure for vehicular traffic or for root growth and plant development.

Compacting the soil is often the easiest way to increase soil strength, and thus to increase bearing capacity and decrease rolling resistance for vehicles, but it may also be done to increase soil conductivity in planting operations. On compactable soils, even the second wheel in line on a vehicle profits from the compactive effort of the first. This is one reason why several wheels in line are often to be preferred above fewer very broad wheels, and why re-using the same path for further traffic increases the efficiency of vehicle operation. The possibilities of compacting the soil with normal vehicles are somewhat limited because of the limitations to the dimensions and pressures of the tyres: low pressure tyres exert too little pressure for achieving high densities, and high pressure tyres may cause soil failure because of their limited surface area. Therefore, specialised machinery has to be used if high soil densities are required. Extensive literature on soil compaction for engineering purposes exists and need not be repeated here. However, it is of interest that many purpose-built compaction machines resemble in their action the action of wheels and tyres. For non-cohesive soils, this action is often supplemented with, or replaced by, vibratory action. On very wet and other noncompactible soils, soil compaction is often not a practical option, and trafficability tends to decrease when the same path is reused.

Loosening the soil is a more complicated process than compacting it. Compactive stresses spread throughout the soil, which stimulates a homogeneous result, but soil loosening is mainly based on soil failure, which hampers the homogeneous distribution of the associated stresses. Thus, the result of soil cultivation is highly variable depending on the implement and method used as well as on the soil condition. Soil cultivation has been extensively studied for agricultural purposes and most of the results of that research should be valid for forestry as well. Without going into detail, I shall mention some of the most important aspects and points of discussion.

It should be realised that the primary aim of soil cultivation in agriculture often is the control of weeds, the disposal of crop remnants, or the working in of fertilizers and manure, and not the loosening of soil. If in fact soil loosening is the main purpose, the results are often poor. A dense soil may be easily broken up in larger or smaller clods (depending on the intensity of the operation), but this usually does not change the density of the clods themselves. Aeration within the clods may remain problematic and root development may be restricted to the open spaces (§ 6.1.2), in which case little has been won. In the subsoil, aeration is often dependent more on continuity of pores than on pore volume. Soil cultivation may do more damage by destroying the existing continuous pores than it improves the soil by the creation of larger open spaces which are poorly connected with each other. In fact, some damage to the soil structure is almost always associated with soil cultivation. If the soil is not protected against forces (e.g. rain, or renewed passes of a vehicle), soil structure may end up worse than it was before cultivation. Soil cultivation is almost impossible in existing forests because of the damage to the roots of the trees. That limits the possibilities largely to afforestation and to (semi-)clear-felling systems.

Soil cultivation may be effective if the right implements are used on the right soil condition, but this is even more problematic in forestry than it is in agriculture, because of the less intensive management. The best effect is often reached when the cultivation promotes subsequent natural processes (for instance, frost action on clayey soils after plowing). The same applies to the breaking up of well-defined layers with very low saturated conductivity either at the surface or deeper in the profile, because stagnating water hampers soil processes and root growth, and may cause erosion. The breaking up of rigid layers, and the loosening of very dense subsoils without larger pores also facilitates deeper rooting of trees, which may greatly increase their stability. Such layers are usually pedogenic or geological. Generally it is useless to loosen the soil beyond the equilibrium which is relevant to the particular situation (§ 5.3).

In many forest soils the organic matter content is very important, not only for the strength, but especially because of its water retention and nutrient exchange capacity. Soil cultivation may stimulate the decomposition of the organic matter through improved aeration and other effects on soil processes, or because of physical fragmentation. This may promote early growth of young trees, but usually results in poorer growth at a later stage. Increased decomposition is often most obvious on the soil surface. However, that increase is likely to be the result of changes in the water regime and light intensity caused by the opening up of the forest, which is usually associated with vehicle activity. Moreover, a stimulance of decomposition rates at the surface is often welcome when natural rates are slow. The surface layer also rapidly re-establishes itself. The effect on the organic matter in the soil is more serious because it is more slowly restored. Once again, it is sometimes difficult to separate the effects of soil cultivation and of clear-cutting. The effect of cultivation is probably most pronounced when the relative position of the layers of the soil profile has been changed. The layer which has been brought to the surface oxidises rapidly while the replacement of organic layers deeper in the profile may result in unwanted processes because of the poorer aeration, especially in wet soils. Nevertheless, it may be advisable to work some organic material into the soil, especially when the soil is poor and decomposition at the surface is slow. The best approach might be to limit the working depth and to re-compact the soil afterwards, thereby preventing excessive decomposition rates.

Any soil cultivation operation in forestry, when compared with agriculture, is hampered by logging debris, surface vegetation, stumps and roots, and stones. Therefore, the power requirements are not directly dependent on soil strength. On the other hand, roots may be effective in transplanting stresses through the soil. The pulling out of stumps or roots might well prove an effective means of soil cultivation.

6.3.3 Roads

Modern off-road vehicles generally make few demands on the soil and, therefore, the main objective of soil management within the stand is usually the reduction of the impact of these vehicles on those soil properties which may influence tree development. Nevertheless, the productivity of forest operations may be increased if the soil and the forest are adapted to the requirements of the vehicles used.

In view of the changing technology used in forest exploitation, it is probably not very relevant to plan further ahead than 20 or 30 years. Nevertheless, it may be useful to facilitate off-road transport through the forest from the planting stage onwards (e.g. by espacement, line thinning, etc.). This will not only reduce the impact on the soil and on the vegetation, but it will at the same time increase the efficiency of forest operations and decrease the need for formal forest roads which are more costly to develop and to maintain, less flexible, and which have greater influence on forest growth. The optimal density of forest roads depends on the relative costs of terrain transport. These costs decrease with increasing size of the terrain vehicles.

Speed and load capacity are the two main determinants of vehicle productivity. On compactable soils the operation speed may be increased when existing paths are used because of the lower rolling resistance. Better visibility for the driver may be another reason for increased operation speed. Pre-used or pre-compacted paths represent the first step towards optimisation of the soil condition for vehicle activity. Occasionally, such paths may be bulldozed to level the surface and to remove stumps and other material which may limit the tractive forces developed by the vehicle.

Both load capacity and speed of off-road vehicles are limited because of the restrictions to size imposed by the forest and the inefficiency of loading relatively small loads, and because of sub-optimal path conditions. Therefore, the load is transferred from the off-road vehicle to road vehicles in most forest operations, although in the future such a transfer may become unnecessary because of technological developments of off-road vehicles (§ 6.2.1). Road vehicles have greater load capacity and are capable of higher speeds, but also make greater demands on soil strength and soil surface. These demands are difficult to reconcile with the demands of plant roots. Consequently, complete separation of plants and vehicles becomes necessary, and road development becomes a main task for the forest manager.

Sometimes compaction and egalisation of the existing soil profile is enough to form a good road (§ 6.3.2), but usually the soil composition has to be changed as well. This may be done with soil stabilizers, by changing the sequence of soil layers (if layers with greater strength occur within easy depth), or by the addition of new soil material from elsewhere. The surface may be paved for additional strength and smoothness, and for greater independence of weather conditions. The technical details of road building are described in many handbooks and need not be repeated here (e.g. Dietz et al., 1984). Suffices it to remark that the financial costs of roads are high, often much higher than would be warranted from the micro-economic point of view in forestry. However, road building is often considered a government task because of the supposed additional benefits involved. Too often, roads are built to very low standards, with great risks for erosion and landscape. Moreover, intensive road systems use up an appreciable amount of otherwise productive forest soil. Development and use of off-road vehicles may well have many advantages.

7 SOIL CLASSIFICATION FOR FORESTRY

7.1 Systems of land classification

From time immemorial, man has tried to optimise his land use on a local scale, concentrating his activities on those places where he got the best results with the least effort. In many old agricultural landscapes, land use is an almost perfect reflection of natural soil- and drainage-patterns. In modern times, the need for such a perfect match of land use to land has diminished through the increased possibilities of adapting the land to the land use (e.g. fertilisation, irrigation, drainage). Nevertheless, the rapidly rising costs of energy- and labour-related inputs are forcing people to greater efficiency and a second look at their land.

The need for regional or national land-classification systems has been growing too, sometimes as a basis for taxation, but generally under influence of the increasing demand for land for the different needs of the growing population, and the gradual development of centralised planning of land use. In the seventies, the concept of land evaluation came to the foreground, primarily for the purpose of agricultural development in the (sub-)tropical countries (e.g. Beek, 1978; Brinkman and Smyth, 1973; FAO, 1976). Land evaluation procedures were specified for forestry by the FAO (1984), largely based on a meeting in Wageningen (Laban, 1981) and on the general procedures of the FAO (1976). The concept of land evaluation (§ 7.1.1) embraces much of the older and more limited land classification systems such as those based on site (§ 7.1.2), terrain (§ 7.1.3), and soil (§ 7.1.4).

7.1.1 Land evaluation

Land evaluation is defined by the FAO (1976) as *the process of assessment of land performance when used for specified purposes*. The final comparison of land and land use in this approach is executed by matching the 'land use requirements' of each 'land utilisation type' of interest with the 'land qualities' of each 'land unit', by assigning factor ratings which indicate partial suitabilities based on each land quality considered. The separate ratings are then combined to 'land suitability classes'. This combination involves rather subjective decisions, except when all partial suitabilities are expressed in quantitative terms, which is unlikely. Poor suitabilities may be overcome by corrective measures, in which case we may speak of potential suitability as opposed to actual suitability.

Land evaluation in this form has little meaning in the developed world, and probably also elsewhere. Land use is too much the product of history and social and economic circumstances, to allow more than relatively minor variations of present land use patterns. Partial suitabilities, based on the comparison of one land quality with the requirements of a given land utilisation type respective to that land quality, are used on a much larger scale, also in forestry (site classification, terrain classification).

Land qualities may be estimated as a function of one or several 'land characteristics', the latter being basic, independent, and stable properties of the land, which can be measured directly. Sometimes, aggregate land properties, or even land qualities, can be measured directly or indirectly. Generally, the more aggregated the properties measured, the higher the accuracy of subsequent land quality estimation and the lower the number of measurements needed. However, measurements of aggregated properties often have little value outside their original purpose, necessitating new measurements whenever other land qualities are to be studied. Most estimations of land quality are based on a mixture of basic survey data (e.g. soil, climate) supplemented with more specific measurements.

7.1.2 Site classification

Site classes are the expression of a partial suitability of land, the suitability for growth of a given tree species. Site may be considered an aggregate land quality, which integrates features of soil, drainage, and climate which are relevant for tree growth, and which are all land qualities in the FAO system. Site classification has a long history in forestry, and it is a widely used bases for forestry planning (Hägglund, 1981).

The site class can be measured directly by tree growth. This usually gives good results in areas with established forestry and few commercial species, although problems occur where stands are of different genetic origin, and where different establishment and management methods have been used. Direct measurement of site is not possible in afforestation projects or in the case of the introduction of new species with different site requirements. A further problem is the fact that site, because of its extremely aggregated character, shows very little correlation with other aspects of land suitability or potential land suitability, even for growth (e.g. effect of fertilisation, risk of damage through storm, fire, or disease).

Two indirect methods of site classification, which avoid some of these problems, are widely used. The first is classification of (spontaneous) vegetation. The vegetation, whether trees, shrubs, or herbs, can give much information about the environment. This information can be derived from species composition, vitality, and growth. Compared with the direct measurement of site index from tree growth alone, the inclusion of species composition and vitality should, theoretically, give an important improvement and extend the possibilities of predicting growth beyond the present range of the tree species of interest. However, this use of vegetation science presupposes a strong relation between species occurrence and environmental conditions, an important effect of competition between different plants, and the occurrence of succession.

These presuppositions are often not valid. The occurrence of a given species has much to do with the availability of seed and of good conditions for germination. There is no reason to believe that good germinative conditions are equal to good growth conditions or vica versa, because plants are usually most sensitive to competition in the germinative stage. It is quite common that species do not occur naturally in places where they grow optimally in the absence of competition (which, of course, is one of the basic foundations of plantation forestry). The development of a plant in a given environment is influenced by static environmental factors and by the competitive effect of the other plants present, but the dynamics of the environment are often a much more important factor. These dynamics often have a largely chance character. Most species-rich vegetations are, therefore, not the result of an intricate reflection of the variability of the environment, but the product of history (past vegetation, seed availability) and chance events. Such vegetations are not stable in terms of species composition, but show a random shift. Comparable objections are possible for the concept of successional development. Succession has often more to do with germinative conditions and growth rate of individual plants, than with different preferences of successional species. Moreover, environmental dynamism and the overall change of environmental conditions (e.g. climate) will often overshadow any internal successional process of the vegetation.

Vegetation science has a long history, and has been used extensively in forestry, especially in Europe (cf. Jahn, 1982), but it has seldom provided much practical information beyond the very obvious. In view of the tremendous amount of work and research involved in the development of a working knowledge of vegetation, such development cannot be advised as a practical option for forestry projects in other parts of the world. The tropical forest zone presents a clear example of the difficulties and risks involved. Not only that sofar nobody has succeeded in finding clear relations between vegetation and environment in the tropical forest (not surprisingly, in view of the dynamic environment), but the lush and rich growth of the natural forest has too often been mistaken as a proof of great development potential.

A second approach to indirect site classification is the comparison of measurements of the physical environment with the requirements of the tree species of interest. This comparison can be based on theoretical or statistical analyses (e.g. Hunter and Gibson, 1984). Unfortunately, it has proved to be very difficult to describe the environment, and especially the soil, in such terms that tree growth can be predicted quantitatively. So far, the emphasis in soil classification has been on soil morphology, but the morphology often correlates poorly with tree-extractable nutrients and with soil water regime. The latter may be critical for tree growth, especially as far as timing and duration are concerned (§ 7.1.4). Little progress in this field is to be expected before basic knowledge about nutrient dynamics and soil processes in forests is developed, and before standard techniques for measurement of available nutrients and soil water regime become available. For the time being, extensive field trials and subsequent direct measurement of site index remain necessary.

One of the problems with site classification for a given tree species is the genetic variability within many species. The margin between success and failure of a tree can be small. It may be much more practical to use trees which grow well over a range of site conditions, than to try to find the optimum species for each site. The need for 'broad-spectrum' trees has been given too little attention by tree breeders.

7.1.3 Terrain classification

Terrain classes are the expression of another partial suitability of land, the suitability for forest operations. Terrain is an aggregate land quality which integrates relevant features of topography, soil, and infrastructure, and some aspects of drainage, climate, and possibly vegetation. The interest in terrain classification is of a more recent date than that in site because it has been closely connected with the increasing mechanisation of forest operations since the late sixties. Forest operations are dominated by transport processes. Transport productivity is a function of load, speed, and path length, which is reflected in all terrain classification systems (e.g. Anonymous, 1969).

Terrain classes can be measured directly, but the large number of available machines with different specifications and the constantly changing technology make this measurement almost impossible in practice. The alternative are theoretical or statistical approaches of correlating measured terrain parameters to machine specifications. This is not as easy and straightforward as it may seem, primarily because of the variability of terrain, even over short distances and within short time periods, and because of the sensitivity of machine productivity for even minor patches of unsuitable terrain. The main elements of terrain are discussed hereunder.

Macrotopography (slope condition) influences the necessary forces for transport, the stability of machinery, and path length. Slope is generally a stable terrain factor, both in space and time, which may be measured on aerial photographs. Slope may be indicated continuously on contour maps, or classified in terms of slope form and average (or maximum) slope percentage. Slope is often the major factor in terrain classification as far as the choice of operating systems is concerned.

Microtopography (ground roughness) covers all small-scale variability in soil slope which occurs randomly in relation to the overall slope. Ditches, stones or rocks, stumps, ground vegetation, and organic debris can all be described in terms of ground roughness. Standing trees may also be brought into this category. Ground roughness has a major influence on the stability of vehicles, on their speed, and on path length if obstacles are to be avoided. However, the quantification of this effect is extremely difficult, partly because the comfort of the driver is often the limiting factor for vehicle speed. Ground roughness may be stable (protruding rocks) or unstable (organic debris) in time (with snow as a special case), and is usually highly variable in space. Ground roughness has to be described according to type, size, and incidence of obstacles, possibly in statistical terms. Classification is usually rather arbitrary.

Soil strength determines the possibilities of force transfer for a given machine, both vertically and horizontally, and thus influences speed and load, as well as path length if low-strength spots are to be avoided. The occurrence of soil damage may form a further limitation to vehicular traffic, a point which is poorly quantified so far. Any measure of soil strength should include the strength of the uppermost organic soil layers which may be crucial in natural terrain. Spatial and temporal variability are generally large, and no relevant universal field strength measurement exists. Classification is usually indirect, based on soil type and moisture condition (e.g. Anonymous, 1969; Sutton, 1980; Turvey, 1980), and more seldom direct, based on strength measurements (e.g. Terlesk, 1983).

Infrastructure (internal accessibility) is defined as all land which has been modified by man with the purpose of increasing the suitability for transport operations. Such land is primarily characterised by its non-random aberration from the surrounding terrain. Infrastructure may take many forms, from row planting and line thinning in dense forests, via simple earth roads (decreased surface roughness), to tarred highways (increased soil strength). Consequently, there is no single measurement of infrastructure. It has to be described in terms of quality (width, curve-length, maximum slope, etc.) and quantity (length per surface unit, corrected for unequal distribution). However, the effect on operational productivity may be quantified relatively easily.

External accessibility, finally, may be included in a terrain classification in qualitative terms because it has important effects on the actual access to the terrain.

7.1.4 Soil classification

Soil classes may also express a partial suitability of the land, but the relation to land use is often only vaguely defined. The same soil classes may serve rather different purposes, for instance, in site and terrain classification. Consequently, soil classification has developed relatively independently of the actual or intended land use, which has resulted in a fairly abstract and theoretical approach. Two systems of soil classification, concerning soil profile and soil material, have evolved over the years.

Classification of the soil profile, developed primarily for agricultural purposes, is mainly based on pedogenetic development as expressed in soil morphology. Theoretically, this is an attractive procedure because pedogenetic processes not only reflect soil material and soil structure, but also aspects of climate, vegetation, and topography (§ 1.4, figure 1). Nevertheless, the method has some serious drawbacks (cf. Butler, 1980). In the first place, pedogenetic development is a very slow process and, therefore, it often does not reflect the actual soil condition. Changes in climate, vegetation, and drainage, in addition to fertilisation and cultivation, may have changed the soil properties completely. In the second place, it is often difficult to separate the effects of different elements of the environment on soil process. For instance, a soil may show a pronounced podzolic morphology because of poor soil material, high rainfall, acid-forming vegetation, or a combination of these factors, which can make quite a difference in the suitability of the soil. Finally, it has been proven very difficult to quantify soil processes on the basis of soil morphology. This holds especially true for the water regime of the soil and the availability of nutrients, two factors which are crucial to plant growth (e.g. Mackintosh and Hulst, 1978; Topp et al., 1980).

The shortcomings of morphological soil classification may be compensated by direct measurement of soil properties or soil characteristics such as texture, nutrient status, and moisture regime. Additional observations on, for instance, geology (parent material), climate, and vegetation may also serve to quantify soil processes. The first approach, direct measurement of soil factors, is costly and the results are sometimes difficult to interpret in terms of soil suitability because of the interaction of many different soil properties and environmental processes. The second approach, additional measurement of environmental factors, seems to be a rather cumbersome way to classify the soil if we have to describe the whole environment in the process.

Classification of soil material was developed primarily for the use of soil as a building material, as a foundation for roads and structures, in dams and walls, and for other purposes. Here it was clear from the beginning that soil morphology was a poor guide to go by, and direct measurement of relevant soil characteristics prevails. Some of the most often used characteristics are particle size composition, organic matter content, and a range of properties measured in standard tests such as plasticity, maximum density, and strength. The results of classification on the basis of these characteristics are not always very good and often additional information is needed (clay type, particle surface characteristics, etc.).

Classification of a given soil profile or material is one thing, classification of a soil area quite another. Vegetation, topography, ground surface, and many other elements of site and terrain are relatively easy to assess on an area-basis because they can be observed continuously. However, observations of the soil itself are always restricted to a few very small areas, often less than one point per hectare. The representativity of these observation points is a great problem, and in standard soil surveys much of the information on the distribution of different soil classes is actually deduced from the topography and vegetation. Whether these show a good correlation with the morphological soil classes is already questionable, and the correlation with many relevant soil properties is often very poor in this approach. Only recently has more attention been given to this problem, resulting in the application of statistical techniques (cf. Burrough, 1982; Webster, 1977). Some of these were originally developed in geology where the problem of the representativity of observation points is even more urgent. With these techniques, the spatial distribution of directly measured soil characteristics and properties is estimated without pre-classification of observations. Soil suitability for any soil use is found by interpretation of the combined distribution of all relevant soil properties and characteristics. This method is still in an early stage of development and not fully operational, partly because many of the old field-data are not exact enough for use in this system. Relevant soil properties and characteristics, measurement methodology, data handling, and interpretation systems all need to be developed. Nevertheless, this methodology is an important improvement on present soil classification procedures, and a sounder basis for land suitability classification.

7.2 Soil data in forestry

The soil is undoubtly a key factor in forestry, not only for tree growth but also for forest operations. In order to improve productivity in forestry, information on the soil is necessary. However, soil information is often costly, and costs and benefits of acquiring such information should be compared. Soil data are only useful when management can be adapted accordingly, but this depends on local circumstances. Whether it is useful to acquire data which have no immediate use but which may be useful in the future is doubtful because of the changing information needs caused by developments in management, technology, and circumstances.

Soil data may be derived from secondary sources but they are, basically, measured in the terrain (soil survey, § 7.2.1). Interpretation of soil data for management purposes almost always involves classification of these continuously variable data in order to match them to the distinct management possibilities (soil classification, § 7.2.2). The actual use of (classified) soil data, finally, is an important but often neglected topic (use of soil data, § 7.2.3).

7.2.1 Soil survey

Soil data which can serve as a basis for site and terrain classification should comprise information on the following soil properties:

- soil water regime	(retention, drainage, conductivity)
- soil aeration	(conductivity, distribution)
- nutrient supply	(availability, capacity, buffering)
- rootability	(root growth conditions, soil-root contact, soil volume)
- strength and stability of soil structure	(susceptibility to compaction, erosion, degradation, biological activity)
- trafficability	(bearing capacity, shear strength of surface layer)
- workability	(soil strength, aggregate stability)
- engineering properties	(compactibility, cohesion, friction).

Most of these properties are related to each other because they partly depend on the same soil characteristics. The most important soil characteristics in this respect are particle composition (particle size distribution, type and form of particles, organic matter content) and soil structure (including soil density and profile buildup). Although theoretically it should be possible to derive most soil properties from these characteristics, this has so far proven to be impossible in practice. This can be explained by the importance of some minor fractions of the particle composition (e.g. in the cases of nutrient supply and strength-related properties) and the difficulties encountered in the quantitative description of soil structure. Direct measurement of some soil properties, therefore, is not only necessary as an addition to the measurement of soil characteristics, but it also, usually, much easier.

The soil water regime is extremely important both for plant growth and for all strength-related soil properties. Most aspects of the water regime show good correlation with particle composition (in the case of water retention and conductivity at medium or high tension) or soil structure (in the case of water retention and conductivity at low tension and in the case of drainage in relation to profile buildup), but they merit direct measurement because of their importance. Moreover, measurement of soil water regime often provides an easy characterisation of soil structure. Field capacity tension and the pF-curve of undisturbed soil can be considered basic soil data in this respect (§ 5.2.2).

Soil aeration may be estimated on the basis of soil water data (§ 6.1.1), and separate measurements are usually not necessary. Nutrient supply is correlated with particle composition (amount and type of fine particles, parent material, organic matter), but it merits direct measurement because of its importance to plant growth. Some basic measurements are pH, CEC, and base saturation, but more detailed measurements may prove necessary. Indirect measurement through foliar or needle analysis is often the most effective and practical method for a detailed classification. Rootability may be qualitatively assessed from particle composition and soil structure, but soil depth should be measured directly because of its importance to tree stability (§ 6.1.1).

Strength and stability of soil structure are not easily assessed on the basis of particle composition and soil structure and should, therefore, be measured directly. Some sort of standard compaction test should be used to asses the susceptibility to compaction (e.g. confined uniaxial compression or hand compaction test, both at field capacity tension), and a test of aggregate-stability to asses the risks of erosion and degradation, whenever appropriate. Biological activity is usually well correlated with nutrient supply.

Trafficability may be estimated on the basis of particle composition, profile buildup, and soil water regime (cf. Löffler, 1982). In critical cases, measurement of penetration resistance at field capacity tension may provide additional information. However, trafficability in forests often depends mainly on the surface layer which is strengthened by roots, ground vegetation and organic debris. So far, no standard methodology has been developed for quantitative assessment of this soil strength factor. Vegetation type probably shows the best correlation with trafficability in such cases. What holds true for trafficability also holds true for workability: soil factors are often less important than the type and amount of debris, ground vegetation, roots, and stumps. Stones and rocks are often additional obstacles. Only a rough, largely qualitative classification is possible, but this is not really relevant in many forest areas. The engineering properties of the soil are mainly determined by the particle composition, but some aspects are nevertheless measured more easily directly (e.g. maximum density, plasticity index; cf. Anonymous, 1953).

In conclusion, I propose the following measurements:

- field capacity tension and pF curve	(soil water, soil aeration, soil strength)
- pH, CEC, and base saturation	(nutrient supply, biological activity)
- penetration strength profile	(rootability, trafficability)
- compactability and aggregate stability	(soil strength, erodibility)
- particle composition and organic matter content	(soil strength, correlation with most other soil properties).

These measurements should cover the vertical and horizontal variability of the soil. Optimal sampling frequency and accuracy should be determined for each measurement separately, according to local variability, costs, relevance, and available data.

7.2.2 Soil classification

Soil data are often classified to facilitate representation. However, classification inevitably causes a loss of information, and classes should be chosen so as to minimise that loss. A further loss of information occurs when soil data are grouped and when these groups are then classified. Classification of a soil as such, therefore, is bound to give poor results unless this classification is directed towards one single purpose. With the present possibilities of data storage and data processing there is no reason any more to classify the data first and then to interprete the classification. Instead, the data should be selected and interpreted for the specific purpose on hand. The resulting interpreted values may subsequently be classified to match specific management options.

Soil shows a continuous variability in space and time. However, forest management has to be homogeneous over fairly large areas for reasons of economy and technology. Thus, there is not only a limited number of management options (which necessitates the classification of different soil types into groups which match these options), but these options are also applied to a continuous area with a certain minimum surface (which necessitates the classification of continuous soil areas of appropriate scale). Such soil areas will include different soil types. Depending on the purpose of the classification, the soil area may be classified according to average or extreme values. Usually, the survey intensity is also adapted to the scale of management with obvious consequences for the accuracy of the survey.

A classification may be qualitative or quantitative. A qualitative classification permits the forest manager to assign priorities and to make choices (for instance, the choice of which compartment to work in under poor weather conditions may be based on a qualitative rating of soil sensitivity). A quantitative classification should also permit making quantitative predictions of performance (e.g. machine productivity, forest growth). Although theoretically attractive (cf. Golob, 1981), it is doubtful whether a quantitative classification is worth its costs in practical forestry (cf. Haarlaa, 1975). Performance is usually determined by a large number of factors (e.g. available personnel, stand characteristics, climatic conditions). Even intensive efforts to model all these factors quantitatively may yield little more information than the offhand estimation of an experienced manager. The relevance of such modelling appears to be limited to research purposes.

7.2.3 Use of soil data

In agriculture, the farmer must choose each year the crops and fertilisation schemes he wants to use, and he must each year cultivate the soil and perform a large number of field operations. In forestry, the choice of tree species may not be relevant over much of the area within the lifetime of a forester, and fertilisation and heavily mechanised operations may occur only once every ten years or less. A forester probably enjoys looking at a soil survey interpretation map which tells him where a certain species can best be planted, but he may never use it. When he finally has to plant a certain area, he may decide for another species because the recommended species proved to be rather sensitive for a certain insect the last few years, or because it fits the landscape better in that place; or he may decide to check the soil in the field because he does not trust a 20-year-old soil map. In forestry, therefore, there seems to be little scope for large-scale classifications, and only limited scope for small-scale classifications which may be used for general management planning (on a regional or national scale).

Forestry would benefit much more from easy and accurate diagnostic techniques which enable the forester to decide in the field what to do under given conditions, and which enable him to monitor the effects of his management. For the interpretation of the measured values, the forester should be provided with constantly updated tables based on the latest research results. All measured values as well as data about the applied management should be stored in data bases for future use and interpretation.

8 SOIL STRENGTH IN DUTCH FORESTS

8.1 Introduction

The soil in the western and northern parts of the Netherlands consists mainly of Holocene peat and marine clays, the latter often surfacing in polders after the peat has been removed. This is the typical Dutch landscape of water and windmills. A landscape which is sometimes very open, sometimes rich in trees, but always very poor in forests.

The eastern and southern parts of the country are largely covered with well sorted (loamy) fine Pleistocene sands deposited by wind during the Weichsel Ice Age (roughly 10,000 BC). In this material podzolic soils have developed, which are usually within reach of groundwater in winter. Most of this coversand landscape has supported heaths as a result of agricultural exploitation. In some places overexploitation has led to the formation of dunes. During the 19th and the early decennia of the 20th century, most of these heaths have been reclaimed for more intensive agricultural use or for forestry. The formerly extensive areas of upland peat, which developed in the lower parts of the cover-sand landscape, have been almost completely exploited for fuel. The underlying sandy soils are used for agriculture.

Locally, ice-pushed ridges and fluvioglacial plains occur, made up of sands and loams deposited during the Middle and Lower Pleistocene by rivers, mixed with moraine material from the Saale Ice Age. The ridges also date from this ice age but have been heavily eroded since. Nevertheless, they still rise up from the surrounding almost flat landscape to heights of between 30 and 100 meters. The higher parts of these ridges were little influenced by the cover sands. Consequently, the soil material is variable but characterised by a certain proportion of coarse sand of fluvial origin, and of stones of glacial origin. In this material, soils range from extreme podzols on coarse poor sands of erosion fans and fluvioglacial plains, to brown forest soils on loamy sands; most soils are out of reach of the groundwater. These ridges support some of the oldest remaining forests of the Netherlands, but most of their surface has also been covered with heaths at one time. Because these soils are generally droughty, there has been little agricultural development on them and most reclamation work has been for forestry. Today they carry the largest closed forest areas of the Netherlands, but large areas of heath and some sand dunes remain and are now protected as nature reserves.

Table 14: Forest types according to land use before afforestation.

period of afforestation	type	percentage of present forest area
before 1800	-	11
1800-1900	moist heath	5
	dry heath	12
	inland dune	5
	old field	3
after 1900	moist heath	10
	dry heath	17
	inland dune	7
	old field	2
	other	8
non-classified	-	18

From: National Forest Inventory 1980-1983.

The total forest area was recently estimated at 334,000 hectares (National Forest Inventory 1980-1983), of which 311,000 hectares are closed forests. Only 235,000 hectares are classified as productive high forest (the remainder being coppice, park forest, forest in settlements, etcetera), but not all this is used for commercial production. These statistics represent a 30-35 percent increase over the statistics of the second National Forest Inventory (1952-1963: total forest area: 256,000 ha; productive high forest area: 183,000 ha). This increase is due partly to afforestation (some old fields, in connection with re-development of the agricultural land, and some large-scale afforestation in new polders), partly to the natural seeding with trees of remaining heaths and other half-natural lands, and partly to redefinition and survey techniques. The National Forest Inventory of 1952-1963 included a soil survey (table 15) which still illustrates the importance of different soil types for Dutch forestry (with the exception of clay soils which have become more important because of polder afforestation).

Table 15: Soil types of the forest area.

soil types	percentage of: total forest area (256,000 ha)	percentage of: productive high forests (188,000 ha)
dry podzol	23	26
old arable land	2	2
brown podzolic sandsoil	6	5
loamy brown podzolic soil	11	11
low humic gley soil	5	4
wet podzol	21	22
blown sand	25	25
clay	4	2
loamy brook-soils	3	2
loess	0	0
peat	1	1

From: National Forest Inventory 1952-1963.

When comparing tables 14 and 15 some differences draw the attention. For instance, only 12% of the forest is classified as dune-afforestation, but 25% of the soils are classified as blown sand. The difference is largely due to the fact that many soils were covered with a thin layer of blown sand which buried the original soil profile, but which did not destroy the vegetation completely and did not give rise to the formation of dunes. If the layer of blown sand is less than 40 cm thick, the soil is classified as the buried profile; otherwise it is classified as blown sand. A comparable discrepancy exists between the old field afforestations (5%) and the percentage old arable land as a soil type (2%): the soil profile of many old fields has not been changed sufficiently to classify it as an old arable soil. The moist heath afforestations (15%) correlate with a large part of the wet podzols (21%), and the dry heath afforestations (29%) with a large part of the dry podzols and brown podzolics (together 40%). The brown podzolics also support an important part of the forests dating from before 1800.

Most of the dry and wet podzols and blown sands as well as a part of the brown podzolic soils are developed in cover sand. These soils originally differ from each other in particle composition (depending on period and conditions of deposition) and in moisture regime (depending on subsoil and topography). Soil formation has been further influenced by climate (regional differences), vegetation, and human influences. Some dry podzols and blown sands as well as an important part of the brown podzolic soils are developed on the glacial ridges. There, particle composition is originally the main variable. As most of these ridges lay in the central part of the country, climate is relatively homogeneous, but man also has profoundly influenced soil development. The development of the other soil types is dominated by soil material (loess, clay, peat) or extreme soil conditions as regards moisture (brooksoils, humic gley). Human influence on these soils is probably much less important. Some of the latter soil types carry the most productive forests of the Netherlands, together with the better brown podzolic soils. Thus, their importance is only partly reflected by the surface they cover.

The choice of study areas is largely explained by the above: one podzol on cover sand, one brown podzolic soil on a glacial ridge, one clayey soil representative for recent polder afforestation, and one loess. The latter soil has been included because of its importance for forestry in neighbouring countries.

8.2 Experimental sites

The soils of the experimental sites are classified according to the Dutch system (De Bakker and Schelling, 1966); corresponding names in other systems are given by De Bakker (1979).

8.2.1 Garderen

This soil has developed in loamy fine cover sand, 25 meters above sea level on the western slope of the Veluwe massif, the largest complex of glacial ridges in the Netherlands (State Forest 'Garderen', compartment 137b). The soil shows some influence of ridge material and of blown sand. The original soil profile, a humuspodzol grading into a brown podzolic soil (Dutch: Haarpodzol/Holtpodzol), has been disturbed by cultivation at the beginning of this century when the heathlands of the time were afforested. At present the soil profile consists of a greyish A-horizon (0-20 cm), a brownish B/C-horizon (20-50 cm), and a C_1-(50-80 cm) and a C_2-horizon (> 80 cm). The water table is deep (> 2 m) but conductivity of the C_2 is low. (cf. Soil survey report no. 622, Stiboka, Wageningen, 1964.)

The A-horizon is fairly loose (penetration strength at field capacity approx. 10 bar), the B/C- and upper part of the C_1-horizon are firm (approx. 20 bar), and the C_2-horizon is extremely dense (> 50 bar). The field capacity tension in the topsoil is approximately 15 cbar (pF 2.2), and the tension seldom decreases below 10 cbar because of the high unsaturated conductivity at low tension and the good drainage. Roots are concentrated in the topsoil and in the lower part of the C_1-horizon where short thick roots have developed on the transition to the C_2-horizon. The soil shows little evidence of earthworms or other large soil fauna. The pH-KCl of the topsoil is low (3.5) which is typical for sandy topsoils in Dutch forests. The vegetation consists of a closed Douglas fir forest, approximately 60 years old. Undergrowth is virtually absent apart from mosses which grow on the litter layer. However, a dense natural regeneration of Douglas fir, larch, and birch occurs in gaps. Growth and health of the trees are reasonable, but wind damage occurs locally.

The A-horizon is probably critical for soil strength because of the higher strength of the lower horizons. Figure 26 illustrates the high strength of this soil material. Four bar uniaxial pressure (which simulates the compactive effect of tyres with a pressure of 2 bar, cf. § 4.3.2 and § 5.2.1) leaves the soil in a reasonable condition respective to pore volume, air volume, penetration strength, and saturated conductivity. Compaction or soil disturbance under wet conditions increases water retention at pF 2.0 considerably, which may locally restrict aeration. High water retention also restricts the bearing capacity of this soil material for roads. Under higher pressure or repeated loading, penetration strength increasingly limits root growth (20 bar penetration strength causes deformation of roots, and of root systems of young trees on this soil). Because of the high strength of the soil profile, compaction of the subsoil is negligible except under extreme conditions.

This soil raises few limitations to forest operations. Random traffic of low-pressure equipment (< 1.5 bar) can be allowed. Other equipment should be concentrated on skid roads. A fairly dense system of skid roads is accept-

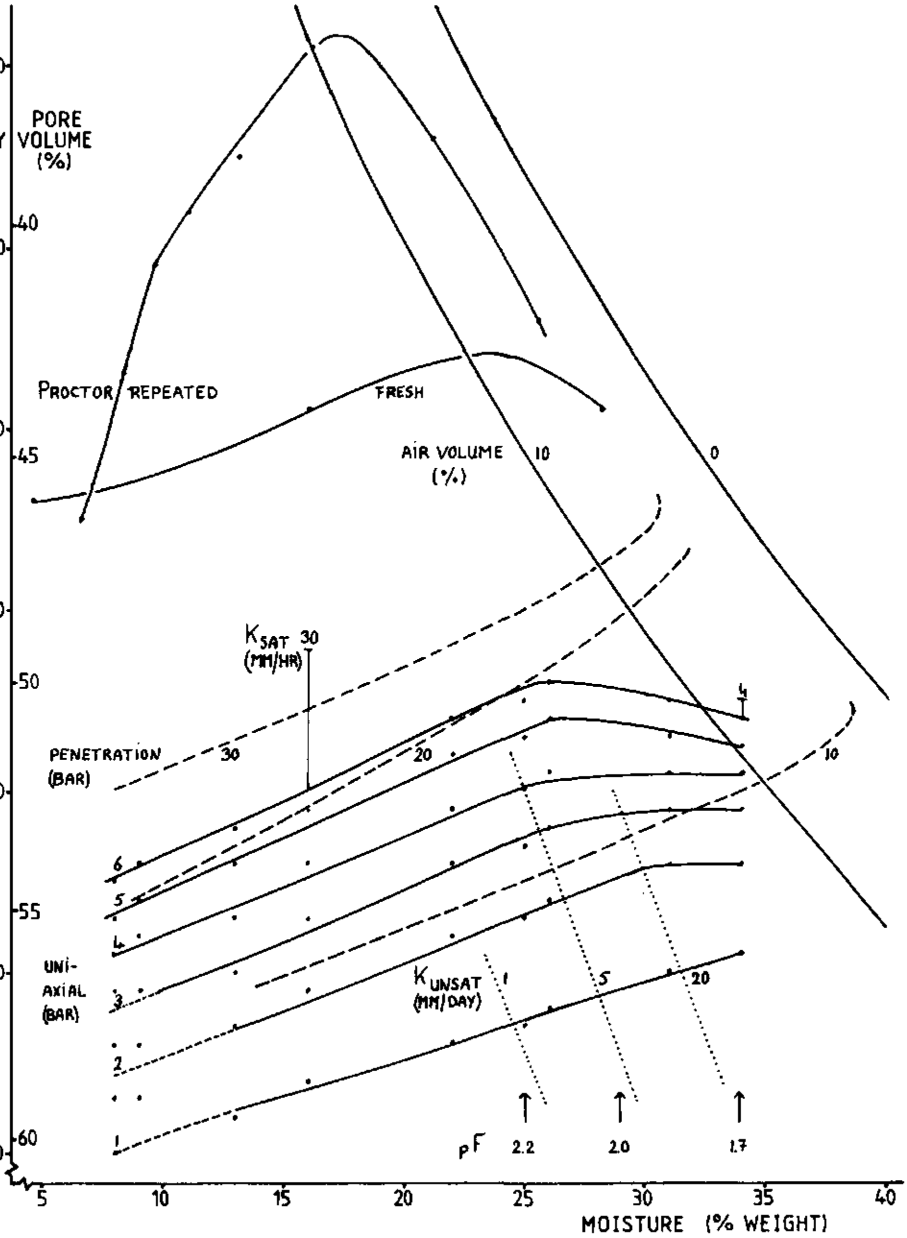

Figure 26: Soil strength diagram Garderen (depth: 5 cm).
soil analysis: soil type no. 5 (table 1, § 4.1.1)
field capacity tension: 15 cbar (pF 2.2)
field density: 1.00-1.10 g/cm³.

able in view of the limited effect on tree growth, but skid roads should be (semi-)permanent because of the low level of biological activity in the soil. There are few limitations due to weather conditions in view of the good drainage and conductivity, although the somewhat restricted subsoil drainage may necessitate restriction of total vehicle weight in wet periods. Heavy traffic on unimproved forest roads should also be limited during wet periods if damage due to soil failure is to be prevented. In dry periods, roads are firm but dusty. Soil cultivation is risky because of the chance of loosing part of the organic matter in the soil, and it will have little effect on tree growth. Fertilisation, on the other hand, is advisable to remedy nutritional deficiences.

8.2.2 Speulde

This soil has developed in coarse pre-glacial sand, 35 meter above sea level on the western slope of the Veluwe massif (State Forest 'Speulder- and Sprielderbos', compartment 105 I). The original soil profile, a brown podzolic soil (Dutch: Holtpodzol), has been disturbed by repeated cultivation (to approx. 60 cm depth) for oak coppice. At present the soil profile consists of a greyish new A-horizon (0-10 cm), a mainly yellowish cultivated A/B/C-horizon (10-60 cm), and a yellow C-horizon (> 60 cm). The water table is very deep. (cf. Soil survey report no. 610, Stiboka, Wageningen, 1962.)

The whole profile is fairly loose (penetration strength at field capacity approx. 10 bar, slightly increasing and more variable in the C-horizon). The field capacity tension in the topsoil is approximately 10 cbar (pF 2.0), but very variable due to differences in profile buildup. The tension seldom decreases much below the field capacity tension because of the good unsaturated conductivity at low tension and the very good drainage. Roots are concentrated in the A_1 and in those parts of the soil profile which have some organic matter. The soil shows little evidence of earthworms or other large soil fauna. Under old beech forests the structure of the topsoil degrades and becomes massif (penetration strength 15 to 20 bar), but this degradation does not occur under Douglas fir or mixed forests. The pH-KCl varies from 3.5 to 4.5 depending on organic matter content. The vegetation consists of a closed Douglas fir forest, approximately 60 years old, with a rich undergrowth of Douglas fir, ferns, and other plants. Growth and health of the trees are good.

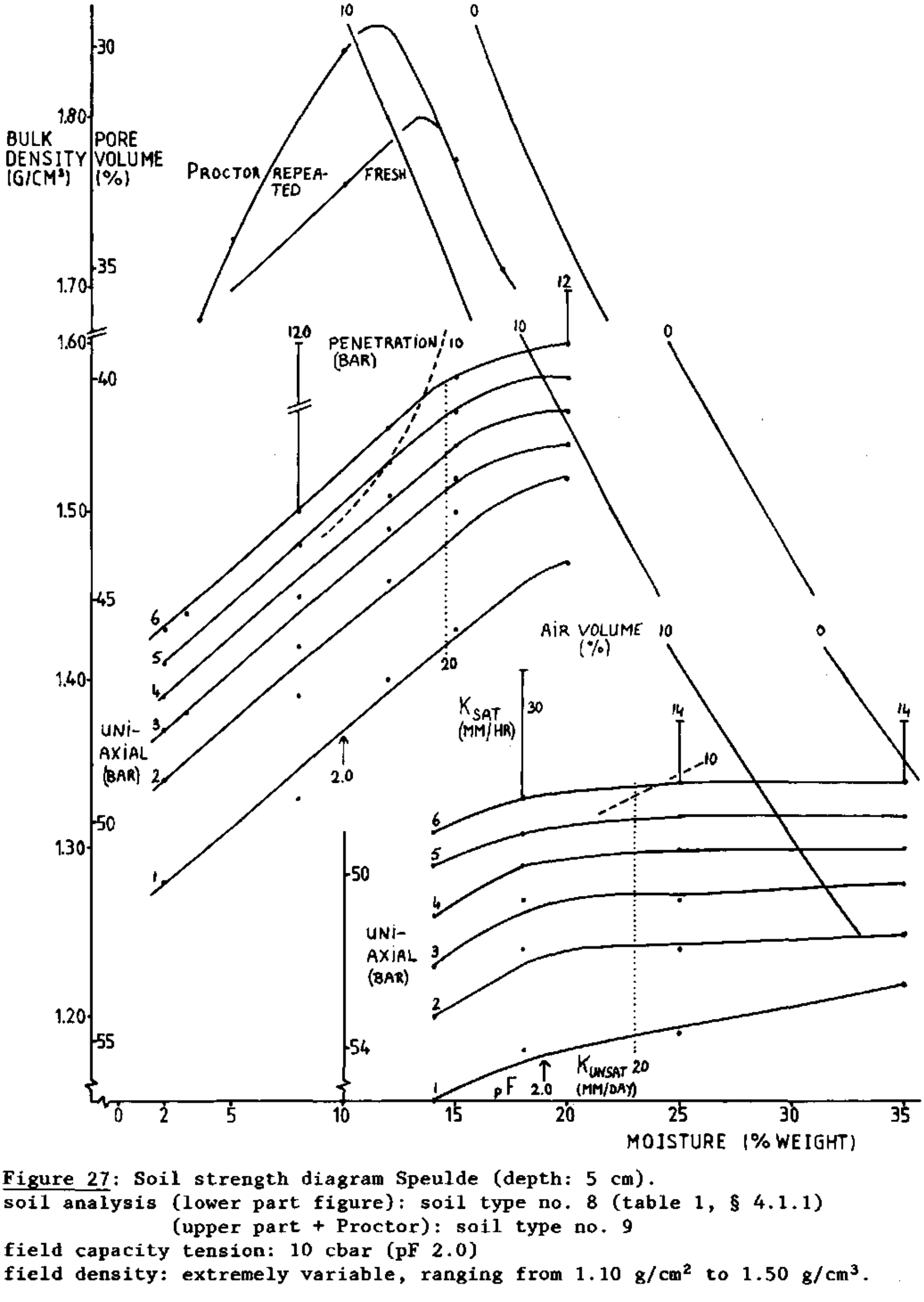

Figure 27: Soil strength diagram Speulde (depth: 5 cm).
soil analysis (lower part figure): soil type no. 8 (table 1, § 4.1.1)
(upper part + Proctor): soil type no. 9
field capacity tension: 10 cbar (pF 2.0)
field density: extremely variable, ranging from 1.10 g/cm² to 1.50 g/cm³.

The depth of the critical layer in this profile depends on the distribution of organic matter. Therefore, two samples have been taken from the topsoil which differ in organic matter content and which are representative for the cultivated part of the profile. Figure 27 illustrates the strength of this soil. Four bar uniaxial pressure leaves the soil in a reasonable condition (especially for the higher organic matter content); even penetration strength remains remarkably low. However, compaction of this soil is more sensitive to deviatoric stresses than the soil of paragraph 8.2.1 (§ 4.3.2). Therefore, under higher pressure or repeated loading, pore volume may become critical (for the lower organic matter content). Wet conditions seldom occur and have little influence on the effect of loading. Compaction of the subsoil may occur under heavy equipment due to the loose profile.

This soil raises very few limitations to forest operations. Random traffic of standard equipment can be allowed. Only very heavy or intensive traffic should be concentrated, but then a dense system of skid roads is acceptable. However, skid roads should be (semi-)permanent because of the low level of biological activity in this soil. There are virtually no limitations because of weather conditions. This soil material has high bearing capacity for roads (good compactibility, high friction angle due to coarse particles, good drainage). Soil cultivation is risky because of the chance of loosing part of the organic matter. However, superficial cultivation may be necessary to promote the seeding and development of forest regeneration. Fertilisation may also be useful to promote forest regeneration and to remedy nutritional deficiences.

8.2.3 Middachten

This soil has developed in loess which covers coarse pre-glacial sand, 20 meters above sea level on the south-eastern slope of the Veluwe massif (Private Forest 'Middachten', compartment II 21). This small loess deposit is isolated from the large European loess-belt, which has its nothern-most border in the very south of the Netherlands. Nevertheless, the particle composition of this soil closely resembles that of the more southerly loess soils. A gradual transition to the normal coversands occurs. The soil profile is very homogeneous, but for a lightly developed texture-B horizon (40-70 cm; Dutch: Ooivaaggrond). The water table is deep (> 2 m), but lateral soil water flow may occur on some slopes. (cf. A.P.A. Vink, dissertation, Agricultural University Wageningen, 1949.)

The whole profile is fairly loose (penetration strength at field capacity approx. 10 bar, somewhat higher in the B-horizon and rather variable in the subsoil related to iron-indurated zones). The field capacity tension in the topsoil is almost linearly related to the depth of the loess deposit (up to 2 meters depth which corresponds to 20 cbar or pF 2.3) because of the very low unsaturated conductivity of the coarse sands underneath. Under wet conditions, the moisture tension decreases to around 10 cbar. Roots are frequent throughout the profile. The soil shows little evidence of earthworms or other large soil fauna. Under old beech forests the structure of the topsoil degrades as in Speulde (§ 8.2.2). The pH-KCl is just under 4.0. The vegetation consists of closed beech forest, over 100 years old and of remarkable quality for Dutch circumstances. Undergrowth is absent, but a dense natural regeneration of beech, bramble, and other plants develops in gaps.

The layer around 25 cm depth is probably critical for soil strength because of the somewhat stronger top layer and B-horizon and because of the heavy vehicles needed in this forest. The strength of this layer is illustrated in figure 28. Four bar uniaxial pressure at pF 2.1 compacts this soil to approximately 50% pore volume. This density limits aeration under wet conditions (pF 2.0 or lower), and root growth under only slightly drier conditions (pF 2.3 or higher) because of high penetration strength (> 20 bar). Saturated conductivity remains reasonable unless very wet compaction occurs.

On this soil, the restriction and concentration of traffic is highly recommended unless low-pressure equipment is used on relatively dry soil. The skid road system should not be too dense because of the rather poor rooting conditions which develop in skid roads. Moreover, it should be permanent because of the low level of biological activity in the subsoil. Forest operations should be restricted under very wet conditions both in the field an on forest roads. Unimproved forest roads are slippery but firm under moist conditions. Soil cultivation is disastrous for the structure of deeper soil layers which have a low organic matter content. Superficial cultivation, however, is acceptable because of th higher aggregate stability, and often necessary to facilitate regeneration. Fertilisation may also be effective to improve soil structure and tree growth.

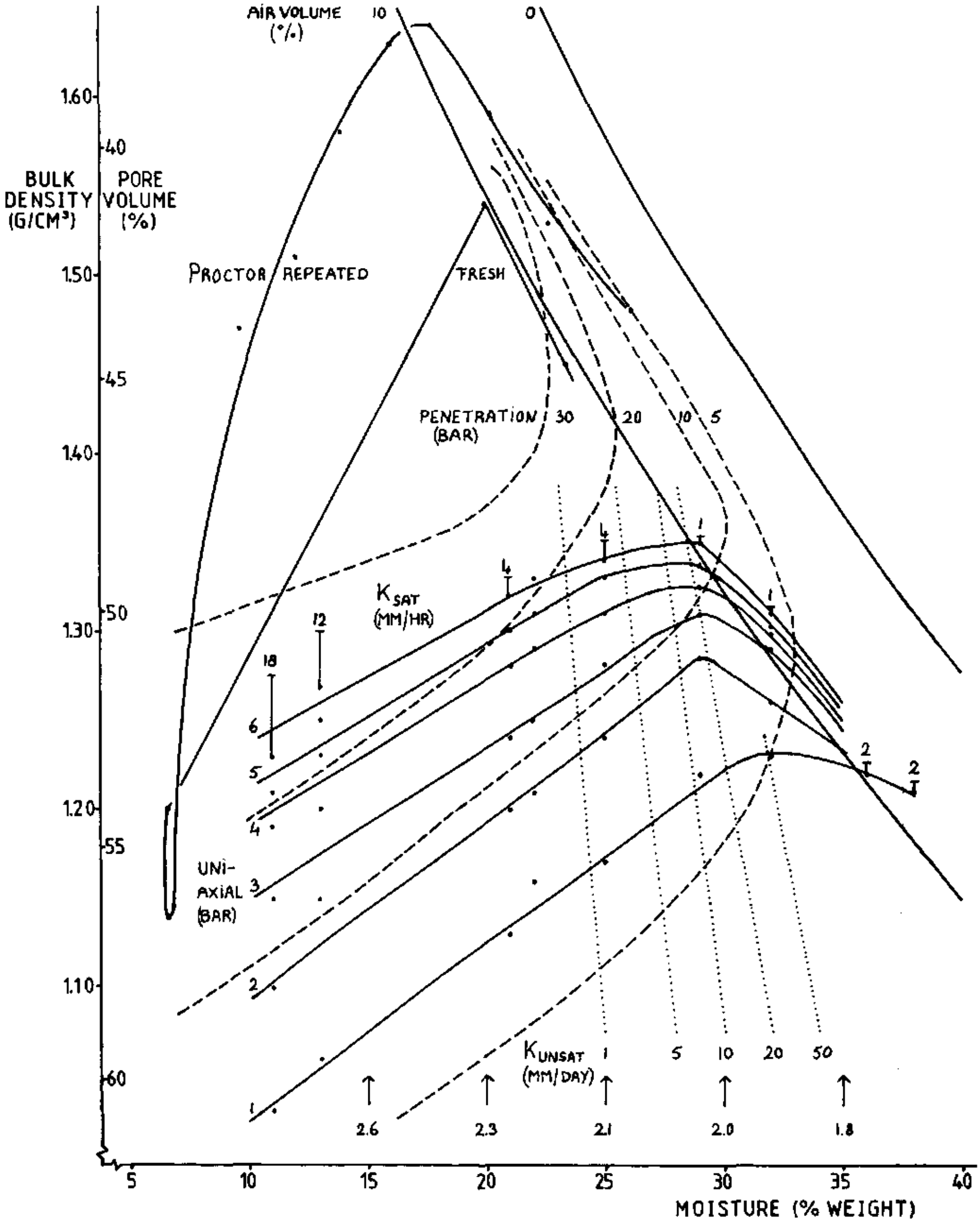

Figure 28: Soil strength diagram Middachten (depth: 25 cm).
soil analysis: soil type no. 3 (table 1, § 4.1.1)
field capacity tension: 10 to 20 cbar (pF 2.0-2.3), depending on soil depth
field density: 1.10 g/cm³.

8.2.4 Bremerberg

This soil has developed in a clayey sea deposit which covers coarse Pleistocene sand, 3 meters below sea level on the bottom of the former 'Zuiderzee' (State Forest 'Bremerberg', compartment Z 85a). The original soil profile consists of a 10 to 15 cm thick layer of very fine sand and a 50 cm thick layer of heavy clay on the Pleistocene sand. The soil has been cultivated to ∿ 20 cm depth for agricultural purposes, mixing the sand layer with some clay. Soil formation is still in a very early stage, although the clay subsoil has ripened completely (Dutch: Poldervaaggrond). The water table is high: 50 cm in winter; 100 cm in summer. (cf. Flevo-berichten nr. 116, RIJP, Lelystad, 1975/1976.)

The profile is fairly loose in the top layers (penetration strength at field capacity approx. 5 bar in the topsoil and 10 bar in the clay layer) but the sand subsoil is extremely dense (> 50 bar). The field capacity tension depends on the water table (approx. 5 cbar in the topsoil in winter; pF 1.7), but lower tensions often occur in the field because of the low conductivity of the clay. Roots are concentrated in the topsoil and in the upper part of the clay. The topsoil has a loose and crumbly structure due to a high biological activity. The pH-KCl is very high (7.5). The vegetation consists of a closed poplar forest, 22 years old, with a rich undergrowth of shrubs and herbs. Growth and health of the trees are good.

Because of the extreme textural differences between the top layer and the second layer, and the relatively low penetration strength of both layers, two samples have been taken for strength measurements: one at 5 cm from the loamy topsoil (figure 29) and one at 25 cm from the clay layer (figure 30). Four bar uniaxial compaction of the topsoil at pF 1.7 (figure 29) compacts the soil to saturation. Any compaction will in fact reduce aeration to critical values. Penetration strength becomes a problem when slightly higher densities are reached. Aeration is also the main problem in the clayey subsoil (figure 30) because penetration strength is almost independent of soil density.

Almost any compaction on this soil limits aeration, and the soil will seldom be dry enough to support vehicles without compaction. However, the soil is chemically rich, well watered, and biologically active. Surface compaction,

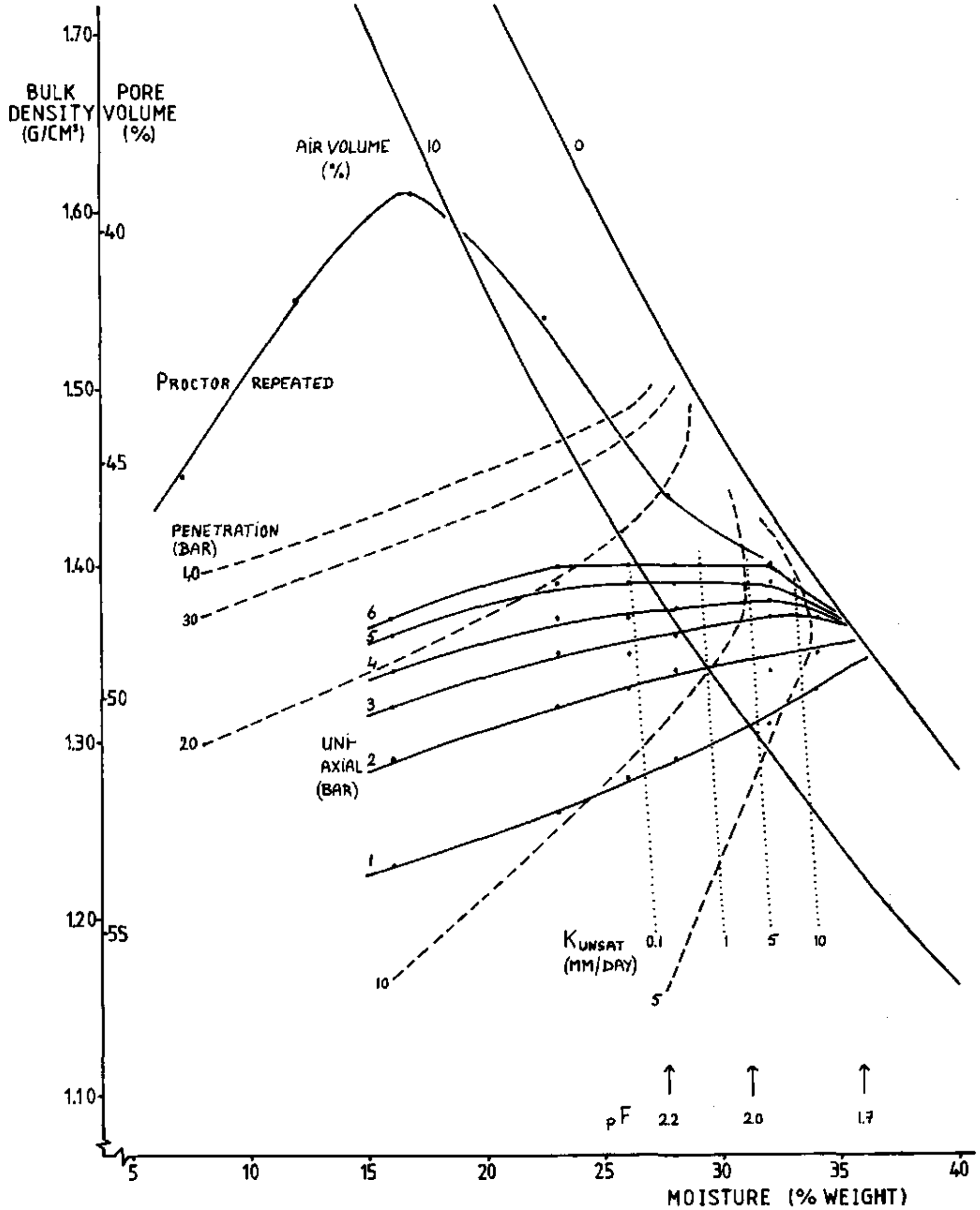

Figure 29: Soil strength diagram Bremerberg (depth: 5 cm).
soil analysis: soil type no. 4 (table 1, § 4.1.1)
field capacity tension: 5 cbar (pF 1.7)
field density: 1.20-1.25 g/cm^3.

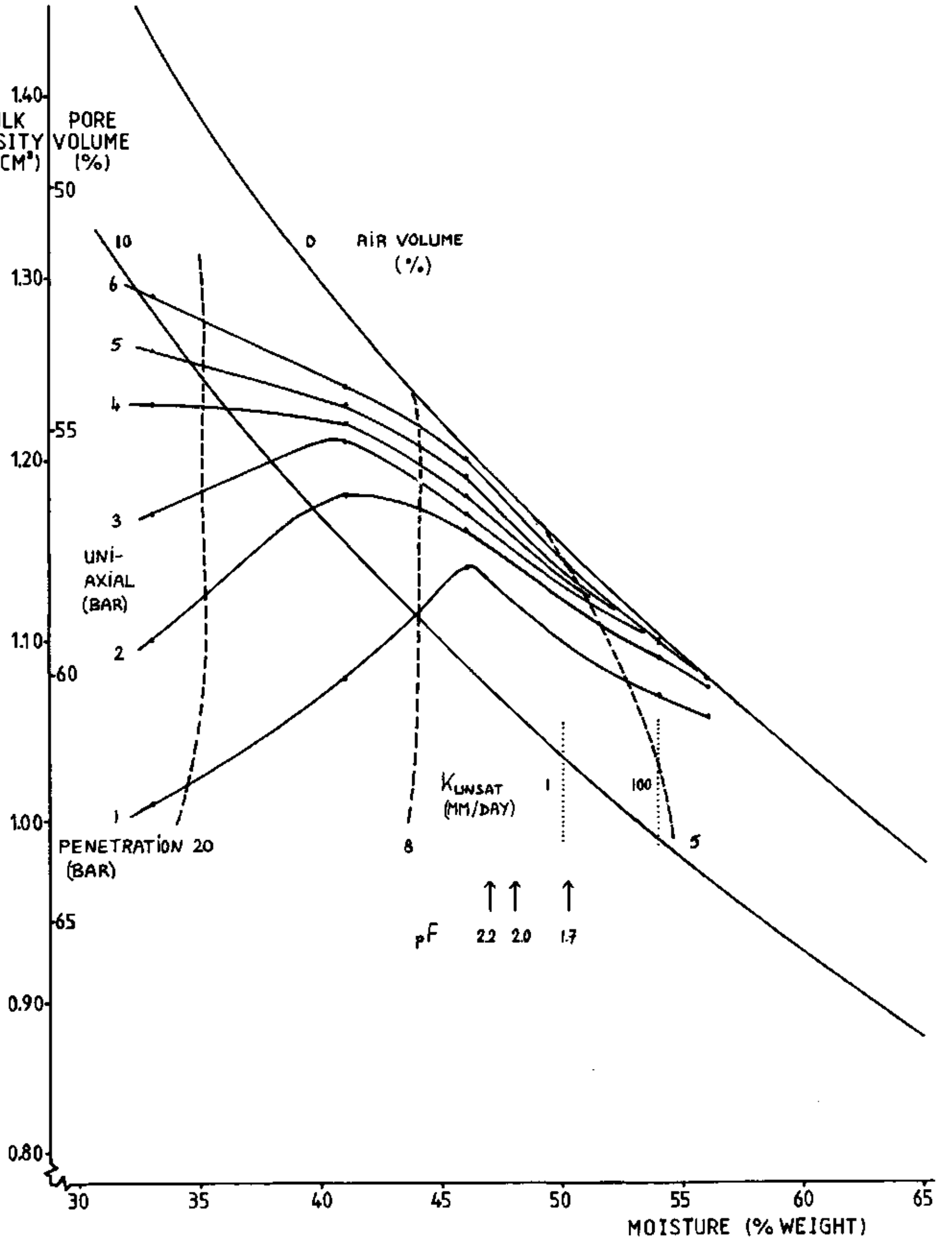

Figure 30: Soil strength diagram Bremerberg (depth: 25 cm).
soil analysis: soil type no. 1 (table 1, § 4.1.1)
field capacity tension: 3 cbar (pF 1.5)
field density: 1.00-1.05 g/cm³.

therefore, is acceptable, especially in clear-felling operations, unless sensitive species are used (e.g. beech). Compaction of deeper soil layers probably restores much slower and heavy vehicles should, therefore, be concentrated on (semi-)permanent skid roads. These may form a fairly dense system in poplar forest, but a more extensive system is recommended when sensitive species are used. Roads have low bearing capacity under wet conditions, except when the sandy toplayer is thick enough. Soil cultivation is probably not effective on this clay soil, but dense paths with stagnating water should be ripped. Fertilisation is not necessary unless deficiences due to the high pH develop.

8.3 *Soil classification*

Soil profile 'Garderen' (§ 8.2.1) is fairly representative for a large area of dry soils on coversand and on blown sand: slight variations in texture probably have little influence. However, variations in organic matter content may profoundly influence soil strength. Such variations often occur as a result of soil cultivation, or of circumstances during deposition of blown sand. The strength may be considerably increased by ground vegetation (especially grasses provide an effective protection against soil compaction because of their intensive rooting). The B-horizon of podzols may be indurated, which restricts conductivity and thus increases the moisture content of the topsoil during wet weather. A large area of podzols on coversand is influenced by the water table. Such soils are wetter than the Garderen-profile and, therefore, more sensitive to compaction of top- and subsoil. Aeration easily becomes critical in such soils. Traffic should, therefore, almost always be restricted to skid roads unless operations are performed under dry conditions.

Soil profile 'Speulde' (§ 8.2.2) is representative for most dry soils on the ice-pushed ridges: variations of texture have little influence. Variations of organic matter content have more influence, and such variations often occur as a result of soil cultivation, but most of this variation is probably covered by the two samples described in figure 27. Wet variants of this soil profile only seldom occur.

Soil profile 'Middachten' (§ 8.2.3) is texturally representative for large loess areas in Europe. However, many loess soils under forest are considerably wetter than this profile because of higher rainfall or because of poor drainage. Vehicle traffic, therefore, should be restricted to permanent skid roads in most of the forests on loess.

Soil profile 'Bremerberg' (§ 8.2.4), finally, with its two contrasting soil layers, covers most of the variability of soils in recent polder forests in the Netherlands, although pure sands occur too. Aeration is the main problem for all these soils, especially in the subsoil. Therefore, vehicle traffic should generally be restricted to skid roads, unless the combination of natural regeneration of soil structure and tolerant tree species permits a higher level of soil compaction.

A classification of these soils with regard to soil strength can, apparently, be based on textural group (coarse sand, fine sand, loess, clayey soil), on organic matter content, and on soil water criteria (field capacity tension, conductivity, drainage). For a small scale classification, these criteria can be derived from existing soil maps, with the exception of the organic matter content. A more detailed classification effort is not worthwhile because of the importance of weather conditions, ground vegetation or ground cover, and local variability on actual soil strength during forest operations.

9 CONCLUSION

Plants and vehicles are both literally soil-based, but the requirements which they make on the soil contrast strongly, especially as far as structure and strength are concerned. As foresters need both plants and vehicles (chapter 1), some sort of compromise has to be found. For instance, plants or vehicles (depending on the priorities of the manager) which make low requirements on the soil can be used. Thus, selected trees are used for planting along streets and on parking lots, while specialised off-road vehicles are used for forest exploitation work. On the other hand, plants and vehicles can be separated spatially. A wide range of roads from the smallest path to paved highways illustrates the popularity of this approach. Finally, plants and vehicles can be separated in time. This is a common approach in agriculture where soil cultivation should optimise soil structure for plant growth after the soil has been disturbed by vehicle traffic for the harvest.

Each of these options has major implications for the forest, the management system, and for the costs of forest operations. A deliberate choice is only possible if fundamental knowledge of the effects on soil structure is available. Soil strength is a key factor for the analysis of such effects.

Theoretically, soil strength can be described in terms of four interdependent factors: cohesion, friction, density, and structure (§ 2.2). However, in the model developed in paragraph 5.1, friction and structure can be expressed by a single parameter because friction in aggregated soils is almost completely determined by the aggregates, and thus by structure. In completely unstructured soils, interparticle friction is an independent factor. However, structure proved to be important in all experimental soils, even in the most sandy, being strongly related to organic matter content (§ 4.1.3). Unfortunately, it is rather difficult to describe soil structure quantitatively in relation to soil strength. Moreover, structure is an unstable soil property which changes under the influence of soil processes and external forces. Therefore, strength of natural soils has to be determined experimentally (§ 5.1.3).

Measured strength values also depend on the measurement method, partly because the contribution of each strength factor to total soil strength depends on the stress field, and partly because strength of natural soils is a heterotropic quality. So far, no universal quantitative model which relates different loading types to each other is available. The loading type of experimental strength measurements should, therefore, preferably resemble that of the relevant field process. A properly standardised version of my hand compaction test (§ 3.3, § 4.3.2) should be developed for the purpose of simulating the effect of tyres on the topsoil. The confined uniaxial compaction test exerts rather low deviatoric stresses and simulates subsoil compaction. The Proctor test is less suitable because of its impact-loading. On many soils, penetration resistance can be used for a first estimation of soil strength.

The effects of loading on soil properties are highly complex. The most important effects for tree growth are those on aeration, penetration strength, conductivity, and water retention (§ 6.1). These effects, together with the strength factors cohesion and density, are in this study clearly arranged in a figure called soil strength diagram (§ 4.5, § 8.2). In most cases, the relation between soil structure and tree growth probably resembles a rather flat-topped curve. In loose soils, the low unsaturated conductivity is a negative factor; in dense soils, poor aeration and high penetration strength are the main problem factors. No absolute threshold values exist, but the curve may be fairly steep on the dense side of the optimum. Because of the interaction of all important factors with soil moisture content, the actual effect depends on weather conditions and drainage, and is variable in the course of time. The topsoil, where most soil processes occur and where rooting is most intensive, is not often too loose, but the subsoil has a higher optimum density.

Free traffic is acceptable where soil strength is high enough, and where soil structure rapidly recovers either naturally (e.g. after clear felling) or artificially (soil cultivation). Much damage can be prevented by using periods of high soil strength (summer, frost) for operations in forest stands on weak soils. A very effective way of decreasing the impact of vehicular traffic on the soil is to concentrate it (§ 6.2). If the impact remains within reasonable limits, a dense system of paths is perfectly acceptable. Forwarding is generally a more attractive transport system than skidding from the point of view of damage prevention. The use of technologically advanced (§ 6.2.1) large terrain vehicles greatly reduces the need for forest roads. This is an attractive option in most forests (§ 6.3.3), especially in forests where the preservation of the natural aspect is considered important, since the vehicle paths are relatively inconspicuous. This also facilitates the control of public access.

Soil management is an important and often under-valued option in forestry (§ 6.3). Soil management serves not only to restore soil damage and to prevent erosion of paths, but, more generally, to optimise soil conditions both physically and chemically. However, present agricultural practices should not be copied as such. Thus, slowly releasing fertilisers and localised soil cultivation (especially in the case of subsoil cultivation) should generally be preferred. Drainage and irrigation are not advisable unless proper maintenance is absolutely guaranteed.

The local forest manager, and thus forestry, is much more served with good diagnostic tools which he can use in the field as an aid to his decisions than with classification systems and central planning (§ 7.2.2). In forestry as much as elsewhere, planning is as good as it is flexible. Too many foresters live from disaster to disaster because every whim of nature causes havoc with his plans. Even with much simpler systems than living forests, centralised planning is a still unproven concept, notwithstanding its theoretical attractiveness.

SAMENVATTING

De sterkte van de bodem in het bosbeheer

Het gebruik van machines en transportvoertuigen in het terrein is tegenwoordig om technische, sociale en economische redenen een vrijwel onmisbaar middel voor de uitvoering van het bosbeheer (H1). Tegelijkertijd kan de inzet van terreinvoertuigen ook negatieve effecten hebben. Schade kan met name worden toegebracht aan de blijvende opstand, verjonging en overige vegetatie en aan de bodem. Daarnaast kan ook schade worden toegebracht aan de fauna en aan de mens. De schade aan de bodem kan zowel chemisch (vervuiling) als mechanisch (verstoring, verdichting) zijn. De mechanische effecten op de bodem staan centraal in deze studie omdat deze vaak het minst zichtbaar en mede daardoor potentieel het meest schadelijk zijn. Bovendien ontbreekt fundamenteel inzicht in dit probleem vrijwel, terwijl met de preventie grote kosten gemoeid kunnen zijn. De studie draagt een fundamenteel karakter en is toegespitst op de Nederlandse situatie en daarmee voornamelijk op zandige gronden.

De sterkte van de grond, welke is gedefinieerd als de weerstand van de grondstructuur tegen de inwerking van krachten, staat centraal in deze studie (H2). Deze sterkte kan beschreven worden als een functie van cohesie, frictie, dichtheid en structuur. Helaas is er geen universeel model voor grondsterkte, waardoor empirische metingen vaak het beste resultaat geven. Fundamentele analyse van meetresultaten is vrijwel alleen mogelijk wanneer de variabiliteit van de natuurlijke bodem zoveel mogelijk onder controle is. Het experimentele deel van dit onderzoek is daarom in het laboratorium uitgevoerd op gehomogeniseerde grondmonsters (H3). Drie verdichtingstesten zijn toegepast: uniaxiale en Proctor verdichting en een op deze twee testen gebaseerde nieuwe methode. Het effect op de grondstructuur is gemeten aan de hand van dichtheid, indringingsweerstand, (on-)verzadigde doorlatendheid en pF curve.

De resultaten tonen het belang aan van vochtspanning, structuur en belastingstype voor de sterkte van de grond (H4). In de zandgronden blijkt de sterkte voornamelijk gecorreleerd te zijn met het percentage organische stof.

Het effect van verdichting onder verschillende omstandigheden kan per grondtype overzichtelijk samengevat worden in een zogenaamd sterkte diagram (figuur 20, p. 93, figuur 26-30, hoofdstuk 8). Op basis van de experimentele resultaten is een kwantitatief model ontwikkeld voor de sterkte van grond als een functie van vochtspanning, dichtheid en belastingstype (H5). Dit model is niet zonder meer toepasbaar voor de sterkte van de bodem in het veld, omdat zowel de belasting als de bodem zelf in ruimte en tijd variabel zijn. De belasting onder een voertuigwiel wordt in de bovengrond het best benaderd met de nieuw ontwikkelde verdichtingstest en in de ondergrond met de uniaxiale test.

Verstoring en verdichting van de bodem kunnen de groei van een boom belemmeren door de doorluchting van de grond te verminderen en door de indringingsweerstand te verhogen (H6). Het effect op de boom hangt af van bodemtype, boomsoort, ontwatering, klimaat en andere factoren. Het effect op het bos in zijn geheel hangt ook af van het percentage van het bodemvolume dat beïnvloed is en van de mate van beïnvloeding. De mate van beïnvloeding kan beperkt worden door het gebruik van aangepaste voertuigen. Vaak is het beperken van het bereden oppervlak door een systeem van vaste rijpaden een effectievere manier om te grote schade te voorkomen. Veelal zal het nodig zijn dergelijke paden bij opeenvolgende werkzaamheden te blijven gebruiken, tenzij de bodemstructuur zich snel herstelt. Soms is het mogelijk dit herstel door bemesting of grondbewerking te versnellen.

In vele landen worden bij het bosbeheer classificatiesystemen gebruikt voor de bodem en de groeiplaats. Sinds de zestiger jaren is de belangstelling voor terreinclassificatie gegroeid in verband met de toenemende mechanisatie van het bosbeheer. Helaas blijken de bestaande classificatiesystemen slecht te correleren met een aantal fundamentele bodemeigenschappen (met name vochthuishouding, humusgehalte, vruchtbaarheid). De voorspellende waarde van deze systemen is dan ook gering. Met moderne statistische opnametechnieken en met geautomatiseerde gegevensverwerking zijn veel betere resultaten mogelijk, maar het is de vraag of dit voor de bosbouw zal lonen. Gedetailleerde voorspelling van de bodemsterkte op basis van classificatiegegevens blijft moeilijk door de grote variatie van enkele belangrijke factoren (met name vocht- en humusgehalte). De bosbeheerder heeft waarschijnlijk meer baat bij een eenvoudige veldtest die hij onder lokale omstandigheden kan toepasssen.

De Nederlandse bossen staan voor het overgrote deel op zandgronden (H8). Ondanks de veelal behoorlijke draagkracht van deze gronden is er toch een vrij groot gevaar voor verdichting, met name in profielen die onder invloed van grondwater staan. Het gebruik van vaste rijpaden lijkt hier de aangewezen weg de schade te beperken. Op de drogere gronden zijn nauwelijks beperkingen noodzakelijk.

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Curriculum vitae

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