SLOPE STABILITY AND AVALANCHING OF SEDIMENTS, THE EFFECTS OF BIOLOGICAL ACTIVITY

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In the Name of Allah, Most Gracious, Most Merciful

Thy Lord hath decreed,
That ye worship none but Him,
And that ye be kind To parents.
Whether one Or both of them attain Old age in thy life.
(Al-Qur' an S17: A23)

I would like to dedicated this thesis to my parents for their patience and tremendous support.

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ABSTRACT

An experimental analysis has been conducted on the stability of sediment slopes. This has included a study of the geotechnical properties of sediments and the effects of supporting medium and biological activity on avalanching. The thesis is divided into six sections with three appendices.

Section 1: Section one describes the geotechnical properties of Ardmore Bay sediments including particle size distribution, and the phase properties of void ratio, porosity, specific gravity, dry density and bulk density. This section also describes a permeability experiment and a packing and shear strength experiment. Particle size analysis show that there were considerable differences in the modality, sorting, skewness and kurtosis of the sediments. Based on bulk density values the sediments tested can be divided into three groups. The first group of sediments contain low values of bulk density. The second group of sediments contain bulk densities of middle range. The third group of sediments contain the highest values of bulk density. There was a highly significant positive relationship between bulk density and dry density, and between bulk density and specific gravity of the sediments. There was a highly significant negative relationship between bulk density and void ratio, and bulk density and porosity. The results of the permeability experiment showed that permeability decreased with an increase in tube diameter and with decreasing sediment core length. The results of the packing and shear strength experiment were as follows. Bulk density and dry density increased with packing. Void ratio decreased with increasing amplitude of packing. Bulk density was directly proportional to dry density and specific gravity. Shear strength increased as bulk density and dry density increased with increased packing density. Shear strength decreased as void ratio increased.

Section 2: Experiments were conducted on the effects of orientation and shape of the container, volume of sediment, and particle size, on angles of avalanche and repose. All of these factors had effects on the angles of avalanche and some of them had effects on angles of repose. In the well sorted sediments angles of avalanche and angles of repose increased with increasing mean particle size. In moderately sorted and poorly sorted sediments, the highest angles of avalanche occurred in the sediment containing the greatest percentage of fine sediment.

Section 3 and 4: Experiments were conducted on the effects of air, water, 50% glycerol, 100% glycerol and alginic acid (low viscosity) on angles of avalanche and angles of repose at successive intervals of time (termed settling time). The duration of avalanche was also measured. There were no differences between the angles of avalanche in air and water and between the angles of repose in air and water. Angles of avalanche and repose increased with settling time from 15 minutes to 15 hours in alginic acid and 100% glycerol. At 15 minutes the angles of avalanche and repose in GF/F water were higher than in alginic acid and 100% glycerol. However at 15 hours the angles of avalanche and repose were higher in alginic acid and 100% glycerol than GF/F water. The duration of avalanche increased with decrease in mean particle size. The highest duration of avalanche occurred in 100% glycerol and the lowest duration of avalanche occurred in air.

Section 5: The objectives of the biological experiment were to quantify the effects of biological activity on avalanching. Laboratory experiments were conducted on the effects of two species of intertidal infaunal invertebrates, *Nereis diversicolor* and *Corophium volutator* and of naturally occurring intertidal microbial plus meiofaunal populations, on angles of avalanche and angles of repose. The duration of avalanche, and the volume of sediment before and after avalanching were also recorded. Both *Nereis diversicolor* and *Corophium volutator* increased angles of avalanche. Microorganisms plus meiofauna also increased the angles of avalanche. Biological activity increased the factor of safety and angles of dilatation. Avalanches with the longest duration occurred with sediments containing animals. Intermediate durations of avalanche were shown by sediments containing both living and dead microorganisms and meiofauna.

Section 6: The objectives of the *Mytilus edulis* experiment were to quantify the production of byssus threads in relation to sediment stability. *M. edulis* were seeded onto *sand*, *sand/gravel* and *gravel*. *M. edulis* produced more threads in *gravel* than in *sand/gravel*. These were always attached to the gravel particles. *M. edulis* did not attach threads to sediment particles in *sand*. In *sand*, the highest number of threads were

attached to other animal's shells. In the *sand/gravel* mix, the highest number of threads were attached to other animal's shells. Intermediate number of threads were attached to grains of gravel.

Discussion:

The results of the experiments reported in sections one to six are discussed in relation to mechanisms controlling slope stability in terrestrial and aquatic environments. They are also considered with reference to environmentally friendly methods of stabilising slopes now under active investigation by civil engineers.

Topics covered include geotechnical properties, sediment phase relations, fluid viscosity, factors of safety, duration of avalanche and biological activity. I have also discussed slope failure mechanisms, and parallel between engineering and biological stabilisation of slopes.

The appendices include geotechnical details of the sediment properties and phase relationships of sediments, sediment permeability, and sediment shear strength. I have also included details of factors of safety and stability analysis of slopes, treated from a civil engineering point of view.

SUMMARY

Section 1:

The objectives of this section were to quantify the geotechnical properties of S1 sediments A, B, C, D, E, F, G & H and S2 sediment. S1 sediments: sediment A = 63 μm to 1 mm, sediment B = 1 mm to 2 mm, sediment C = 2 mm to 4 mm and sediment D = 4 mm to 8 mm. Sediment E = 1 mm to 8 mm (sediment E consists of sediments B, C & D mixed in a ratio of 1:1:1), sediment F = 63 μm to 8 mm (sediment F consists of sediments A & E mixed in a ratio of 2:1), sediment G = 63 μm to 8 mm (sediment G consists of sediments A & E mixed in a ratio of 1:1) and sediment H = 63 μm to 8 mm (sediment H consists of sediments A & E mixed in a ratio of 1:2). The geotechnical properties of S2 sediments (63 μm to 1 mm) were also measured.

Unimodal / Bimodal: Sediments A & E were bimodal and sediments B, C & D were unimodal. Sediments F, G & H were multimodal. S2 sediment was unimodal.

Sorting / Uniformity: Sediments A & H were moderately sorted whereas sediments B, C & D were very well sorted. Sediments E, F & G were very poorly sorted. S1 sediment was very well sorted. Sediments A, B, C, D & E were uniform however sediments F, G & H were poorly graded.

Skewness: Sediments A, B, D and H were positively skewed and sediments C, E & F were negatively skewed. However sediment G and S2 sediment were symmetrical.

Kurtosis: Sediments A, C, D, E, F, G & H were platykurtic and sediment B was very leptokurtic. S2 sediment was extremely leptokurtic.

Phase Relations:

Based on bulk density values the sediments tested can be divided into three group. The first group of sediments (e.g. sediments: A and B) contain low values of bulk density. The second group of sediments contain bulk densities of middle range (e.g. sediments: C, D, E and F). The third group of sediments contain the highest values of bulk density (e.g. sediments: G and H). There was a highly significant positive

relationship between bulk density and dry density, and between bulk density and specific gravity of the sediments. There was a highly significant negative relationship between bulk density and void ratio, and bulk density and porosity.

Permeability Experiment:

The objectives of permeability experiment were to asses the effects of tube diameter, sediment sample length and head of water on permeability. The permeability decreased with increase in tube diameter in the 100 mm sediment length sample. The permeability of the 100 mm length sediment core was higher than the permeability of the 200 mm length sediment core. Water head did not affect the permeability.

Packing and Shear Strength Experiment:

The objectives of the packing and shear strength experiment were to quantify the effects of packing on sediment densities, void ratio and shear strength. Bulk density and dry density increased with packing. Void ratio decreased with increasing amplitude of packing. Bulk density was directly proportional to dry density and specific gravity. The bulk density of sediment was inversely proportional to porosity and void ratio. Shear strength increased as bulk density and dry density increased with increased packing density. Shear strength decreased as void ratio increased. However the relationships of shear strength with bulk density, dry density, void ratio and porosity were non linear. Shear strength measured by using the cone was lower than shear strength measured by using the vane.

Section 2:

The objectives of avalanching experiment 1 were to quantify the effects of orientation of container, shape of container, volume of sediment, and particle size on first and second angles of avalanche and repose, and on the factor of safety.

The orientation and shape of the container affected the angles of avalanche and angles of repose. The first angles of avalanche and repose were highest when the length (15 cm) of the rectangular container was parallel to the inclined surface, intermediate in the circular container (ID = 9.4 cm), and lowest when the width (7.5 cm) of the rectangular container was parallel to the inclined surface.

The second angles of avalanche and repose were highest in the circular container, intermediate when the length (15 cm) of the rectangular container was parallel to the inclined surface, and lowest when the width (7.5 cm) of the rectangular container was parallel to the inclined surface. Volume of sediment did not affect angles of avalanche and angles of repose. Angles of avalanche and angles of repose increased with increase in particle size. The factor of safety was directly proportional to the angle of avalanche and inversely proportional to the angle of repose.

Section 3:

The objectives of avalanching experiment 2 were to quantify the effects of fluid medium namely air, fresh water and 50% glycerol on angles of avalanche and repose, and on the factor of safety of sediments of different particle size. The effects of medium on the duration of avalanche were also investigated.

There were no consistent differences between the first angles of avalanche (A_1) and between the first angles of repose (R_1) in air, water and 50% glycerol. The second angles of avalanche (A_2') were higher in air than in fresh water, and than in 50% glycerol. The second angles of repose (R_2) were higher in fresh water than in air. In the well sorted sediments A, B, C and D, angles of avalanche and angles of repose increased with increasing mean particle size. In the poorly sorted sediments E, F and G, and moderately sorted sediment H, made up of a mix of A to D, the highest angles of avalanche occurred in the sediment containing the greatest percentage of fine sediment (sediment F) The same was generally true for angles of repose.

In general the second angles of avalanche (A_2') were lower than the first angles of avalanche (A_1), and the second angles of repose (R_2) were higher than the first angles of repose (R_1).

There was no difference in the factors of safety in air and fresh water, but in some cases the factor of safety was greater in 50% glycerol than in fresh water. There was a strong positive linear relationship between the factors of safety and the angles of avalanche and a strong negative relationship between the factors of safety and the angles of repose.

The duration of avalanches were longer in 50% glycerol, intermediate in water and shortest in air. The duration of avalanche increased with decrease in mean particle size. Furthermore, there was a strong negative linear relationship between the duration of avalanche and mean particle size. This relationship was more obvious in 50% glycerol than in fresh water and was more obvious in fresh water than in air.

Section 4:

The objectives of avalanching experiment 3 were to test the effects of viscosity of liquids on avalanching. This was done by using GF/F filtered tap water, alginic acid 2 % solution (low viscosity) and 100% glycerol. The effect of settling time - time for which the sediment was left to stand in a liquid before avalanching (15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours), was also tested.

The first angles of avalanche and repose were higher in GF/F water than in alginic acid and 100% glycerol. Settling time affected angles of avalanche and angles of repose. The first angles of avalanche increased with time from 15 minutes to 15 hours. The trend was more obvious in alginic acid and 100% glycerol than in GF/F water.

The factor of safety and angle of dilatation were higher in 100% glycerol than in alginic acid and GF/F water. The factors of safety and angles of dilatation at 15 minutes were lower than the factors of safety and angles of dilatation for longer time periods. The durations of avalanche were longer in 100% glycerol than in alginic acid and GF/F water. Settling time did not affect the duration of avalanche.

Section 5:

The objectives of the biological experiment in section 5 were to quantify the effects of biological activity on avalanching. In this section, laboratory experiments were conducted on the effects of two species of intertidal infaunal invertebrates, *Nereis diversicolor* (Biological experiment 1) and *Corophium volutator* (Biological experiment 2) and of naturally occurring intertidal microbial plus meiofaunal populations (Biological experiment 3), on angles of avalanche and angles of repose. The duration of avalanche, and the volume of sediment before and after avalanching were also studied.

Biological activity affected angles of avalanche and repose. Both *Nereis diversicolor* (Biological experiment 1) and *Corophium volutator* (Biological experiment 2) increased the angles of avalanche when compared with control sediments. *Nereis diversicolor* had a greater effect than *Corophium volutator*. This effect increased as the experiment progressed, being most marked at 48 hours.

Both *Nereis diversicolor* (Biological experiment 1) and *Corophium volutator* (Biological experiment 2) also increased the angles of repose. However the effects of the two species on angles of repose were much less marked than their effects on angles of avalanche. Microorganisms plus meiofauna (Biological experiment 3) also increased the angles of avalanche, but did not affect angles of repose.

Ashed sediment in sea water had a higher angle of avalanche than both ashed sediment in air and sediment containing dead (formalised) microorganisms plus meiofauna in water. The lowest angle of avalanche was shown by the ashed sediment in air. The angle of repose of ashed sediment in air was higher than the angle of repose of ashed sediment in sea water and sediment containing dead (formalised) microorganisms plus meiofauna.

Biological effects on the second angle of avalanche and second angle of repose were less marked.

Biological activity increased the factor of safety and angles of dilatation. The factor of safety and angles of dilatation were higher for the sediments containing animals than for the control sediments in *Nereis diversicolor* (Biological experiment 1) and in *Corophium volutator* (Biological experiment 2). In biological experiment 3, the factor of safety and angles of dilatation of the sediment containing living microorganisms plus meiofauna were higher than those of controls: sediment containing formalised microorganisms plus meiofauna, ashed sediment in water and ashed sediment in air.

Avalanches with the longest duration occurred with sediments containing animals in biological experiments 1 and 2. Intermediate durations were shown by sediments containing both living and dead microorganisms and meiofauna. The ashed sediment in air treatment had an extremely short durations of avalanche. The duration of the first avalanche increased with angles of avalanche. There were a strong positive relationships between the angles of avalanche and the duration of avalanche. All the sediments increased in volume during the first avalanche. The sediments containing animals *Nereis diversicolor* (Biological experiment 1) and *Corophium volutator* (Biological experiment 2) showed a greater increase in volume than the control sediment not containing animals.

Section 6:

The objectives of the *Mytilus edulis* byssus thread attachment experiment in section 6 were to quantify the effects of the mussel *M. edulis* on sediment stability. *M. edulis* were seeded onto three different types of sediments made up of fine sediment (*sand*: 63 µm to 500 µm) and coarse sediment (*gravel*: 4 mm to 8 mm) as follows. The first type contained fine sediment (*Sand*) only. The second type contained mixed sediment (*Sand/Gravel* mix): fine and coarse sediment mixed in a ratio of 1:1 and the third type contained coarse sediment (*Gravel*) only. The number of byssus threads attached by the *M. edulis* to their own shell (itself), the number of byssus threads attached by *M. edulis* to other *M. edulis* shells, the number of byssus threads attached to sediments, and the number of threads attached to glass were then recorded. The lengths of these threads were also recorded.

M. edulis produced more threads in *gravel* than in *sand/gravel* mix. These were always attached to the gravel particles. *M. edulis* did not attach threads to sediment particle in *sand*. In *sand*, the highest number of threads were attached to other animal's shells. An intermediate number of threads were unattached or broken, and a few threads were attached to the animals own shell. In the sand/gravel mix, the highest number of threads were attached to other animal's shells. Intermediate number of threads were attached to grains of *gravel*. A small number of threads were unattached or broken, and very few threads were attached to the animals own shell. The highest number of threads were produced in gravel. They were all attached to the gravel particles. An intermediate number of threads were unattached or broken. A small number of threads were attached to other animal's shells and only four threads were attached to the animal's own shell. There was no difference between the attached byssus complexes and released byssus complexes.

Parts of section 5 and section 6 are in press in Geological Society of London special publication 1998. The authors and titles of the papers are:

<u>Publications from the Thesis</u>

1 Shaikh. M. A., Meadows, A. & Meadows, P. S. (1998). Biological control of avalanching and slope stability in the intertidal zone. Special publication of the Geological Society of London. In press.

2. Meadows, P. S., Meadows, A., West, F. J. C., Shand, P. S. & Shaikh, M. A. (1998). Mussels and mussel beds (*Mytilus edulis*) as a stabilisers of sedimentary environments in the intertidal zone. Special publication of the Geological Society of London. In press.

INTRODUCTION

1. General Background

Avalanching or landsliding is a down-slope movement of soil and sediment under the influence of gravity. Avalanching is a common environmental hazard throughout the world. Every year disastrous avalanches claim hundreds of lives and also cause an immense amount of damage and loss of property. Catastrophic avalanching on land destroys buildings, roads and railways, and dams on rivers. Avalanching and mass earth movements into the sea can also create huge tidal waves known as tsunami that devastate the shoreline. Avalanching in the sea generates relatively slow moving turbidites which can affect marine life in the sea (Allen 1977; Dodge *et al.* 1974; Dodge & Vaisnys 1977; Elrobrini 1985; Babcock & Davis 1991; Juniper *et al.* 1992; Alexander & Morris 1994). Avalanches on land are mainly caused by earthquakes, rain, and changes in the level of the ground water table, while avalanches in the sea are mainly caused by earthquakes (Ferentinos 1990; McDonnell 1990; Anastasakis & Piper 1991; Shih & Komar 1994; Anderson & Sitar 1995). Avalanching on river banks and shorelines is often caused by water currents and waves that produce undercutting (Dolan *et al.* 1990; Jones *et al.* 1993; Komar & Shih 1993; Mitchener & Damgaard 1997).

Landslides and erosion are a major problem on shorelines. The erosion of shorelines and the removal of sediment by near shore currents cause the progressive retreat of the shoreline. Recession of shorelines is now common and therefore the shoreline environment is under increasing pressure in many parts of the world. Despite efforts that have been made to improve our knowledge about the causes and factors controlling shoreline erosion, there is still a need to improve our understanding and knowledge about the shoreline environment. A considerable amount of work has been done on the physical aspects of shoreline erosion (Dyer 1980; Zabawa *et al.* 1981; Shabica *et al.* 1984; Hall *et al.* 1986; Dolan *et al.* 1990; Frihy & Komar 1991; Jones *et al.* 1993; Komar & Shih 1993; Thorne 1995). However, an understanding of the relationship between biological activity and shoreline erosion/protection is far from adequate. Some researchers think that biochemical and biomechanical processes enhance stability of sediment (Paterson 1987; Dade *et al.* 1990; Gerdol & Hughes 1994; Meadows *et al.* 1994a) whereas others have argued that the same processes can destabilise sediment (Dillon & Zimmerman 1970; Rhoads & Young 1970; Eckman *et al.* 1981; Hecker 1982; Spencer 1988; Fischer 1990).

Sometimes avalanches are also triggered by wave energy and undercutting of the shore. Shore erosion and avalanching can involve large volumes of sediment (Mudler *et al.* 1994). This slope erosion and avalanching may affect biological communities in the coastal zone. For example light attenuation by suspended sediment due to erosion can limit photosynthesis (Spence 1976; Dennison & Albert 1982) as well as limiting the depth, distribution and rate of growth of aquatic plants in estuaries (Chambers & Prepas 1988). In tropical environments heavy sedimentation and erosion can result in fewer live corals, lower growth rates, reduced recruitment of larval settlement and slower rates of reef accretion (Dodge *et al.* 1974; Dodge & Viasnys 1977; Babcock & Davis 1991; Cobb *et al.* 1992). Therefore an aspect of slope or sediment stability should be included in ecological studies.

Sediment geotechnical properties play an important part in determining where and when slope instability occurs (Yallin 1977; Dyer 1979; Lowe 1982; Lee *et al.* 1983; McCave 1984; Dyer 1986; Anderson & Richards 1987; Baraza *et al.* 1990; Shiati 1990; Baraza *et al.* 1992; Van Rhee & Bezuijen 1992; Auer & Shakoor 1993; Bertran 1993; Cochonat *et al.* 1993; Lee *et al.* 1993; Baltzer *et al.* 1994; Baraza & Ercila 1994; Dijkstra *et al.* 1994; Kenneth 1994; Robert & Cramp 1996; Wang & Zhang 1996; Coleman & Garrison 1997). These properties include grain size distribution, water content, density and shear strength. Geotechnical properties such as these are also essential to engineers for the construction of buildings, harbours, dams, irrigation work, the citing of oil and gas rigs and for the laying of gas and oil pipe lines (Lamb & Whitman 1979; Cheng & Jack 1991; Herbich 1991; Craig 1992; Komar & Shih 1993; Mehta 1993; Thorne *et al.* 1995). These geotechnical properties can also be important to marine scientists studying the interactions between biological activity and slope stability (Frey & Howard 1972; Allen 1977; McCall & Tevesz 1982, Meadows & Tait 1989; Meadows & Meadows 1991; Meadows *et al.* 1994b).

There is a quite lot of evidence that the grain size decreases downslope (Baraza *et al.* 1990; Lee *et al.* 1993; Baraza & Ercila 1994). Coarser sediment rests at a higher gradient whereas fine sediment rests at a lower gradient. The grain size distribution has a direct effect on geotechnical properties of sediment. The presence of fine sediment, for example clay, decreases porosity and permeability of a sediment (Bennett *et al.* 1990).

The decrease in porosity of a sediment increases both its dry density and bulk density. This effect of porosity on the bulk density is less when sediment is submerged in water as compare with the moist sediment or completely dry sediment. The stability of sediment increases with the increase in dry density and the bulk density. In water, sediment containing a high percentage of clay has a high water content because of the low permeability of clay. The bulk density and shear strength of soil and sediment depends on voids and water content and soil and sediment of a high water content has a low bulk density and shear strength (Lee *et al.* 1993; Jepsen *et al.* 1997). The stability of a soil and sediment is related to the shear strength and increases with the increase in shear strength (Jones *et al.* 1993; Tian *et al.* 1994; Perret *et al.* 1995; Rahardjo *et al.* 1995).

2. Factors Contributing to Avalanching

Generally, avalanches occur due to natural or human factors causing alteration in the forces acting on a slope. Avalanches due to natural factors are very common, are often disastrous, and occur on a large scale. Avalanches due to human factors are less common and occur on a smaller scale.

The two main natural factors contributing to an avalanche are earthquakes (Piper *et al.* 1985; Evans *et al.* 1987; Schwab & Lee 1988; Wetmiller & Evans 1989; Lee *et al.* 1991; Owen 1991; Alkema *et al.* 1994; Wolfe *et al.* 1994; Duperret *et al.* 1995) and water (Takahshi 1981; Buchanan & Savigny 1990; Anderson & Lloyd 1991; Brooks & Richards 1994; Middleton & Wilcock 1994; Okada & Sugiyama 1994; Midriak 1995). Secondary factors include uplifting or change in gradient and length due to earthquakes, or alteration in pore pressure mainly due to rain (Fig. I). Human activity alters the slope inclination by cutting at the bottom of the slope and putting extra burden of soil or sediment at the top of the slope. Furthermore, people living on hillsides alter the water table using artesian water.

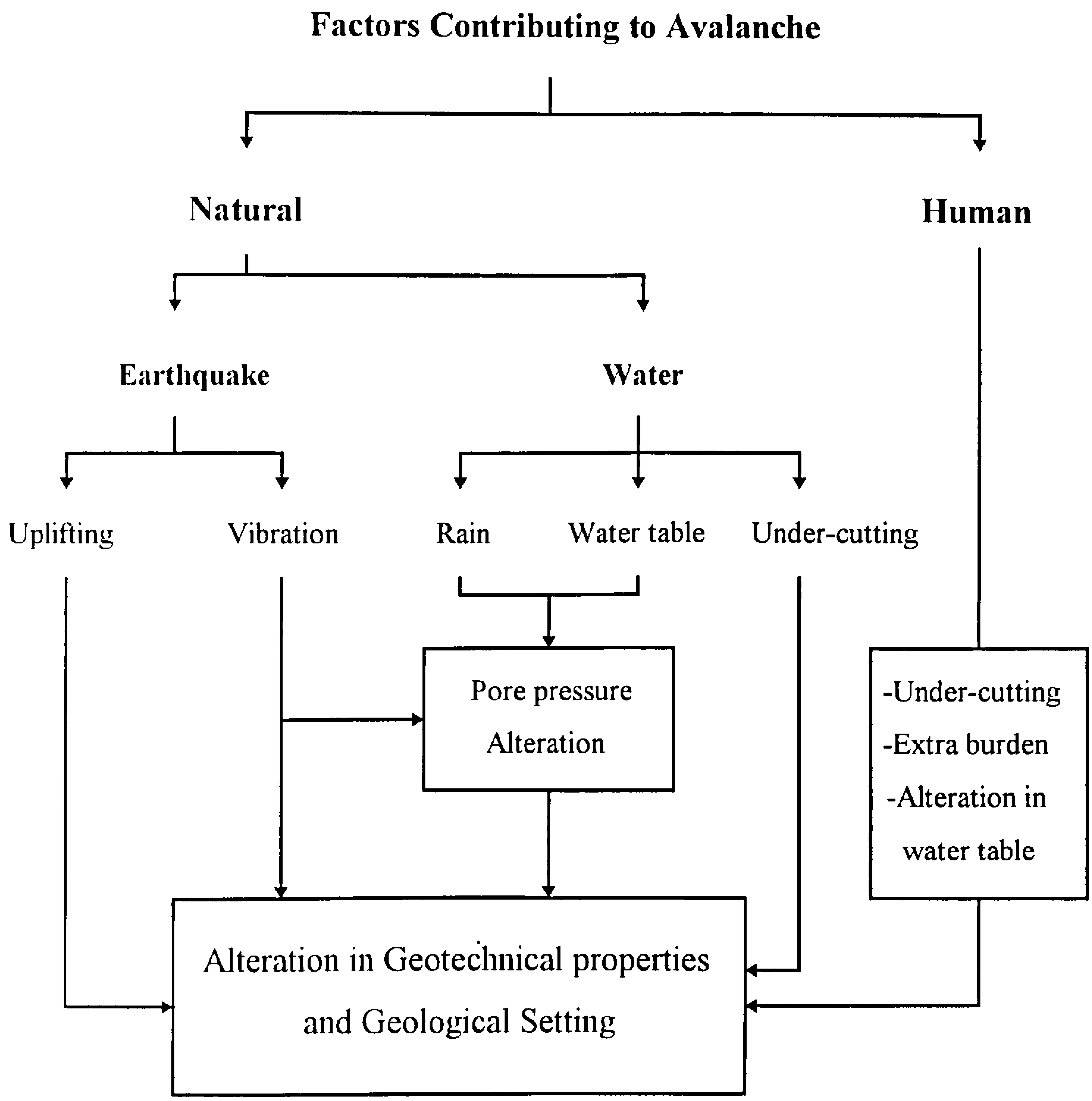


Figure 1 Factors contributing to the avalanching process.

3. Terminology and Classification of Sediment Movement

Gravity movements of sediments and soils occur in a wide range of sizes, shapes and types. In addition, researchers working in fields such as engineering, geology, sedimentology, glaciology and mining use different terminologies. As a result, a new worker reading the literature can be easily confused. For example, gravity movements of sediments and soils are referred to as slope failures, landslides, mass failures, mass wasting or avalanching, depending on an author's research speciality (Flint & Skinner 1977; Carter & Carter 1985; Kaiser & Simmons 1990; Chandler & Richard 1991; Auer & Shakoor 1993; Meadows *et al.* 1994a; Mulder *et al.* 1994; Muir Wood *et al.* 1994; Chu *et al.* 1995; Metcalfe *et al.* 1995; Shaikh *et al.* 1998). I have used the word "avalanching" throughout my thesis.

The literature distinguishes three major classes of gravity movement of sediments and soils (Brunsden & Prior 1984; Bromhead 1992; Pickering & Lewise 1997). These are falls, slides and flows. A fall is a quick down-slope movement of rock and mixed sediment, in which a sudden collapse and fall of rock and debris occurs. A slide is a slow movement and flow of sediment which may involve rotational and translational movement. Flow is a rapidly moving mixture of sediment and air, sediment and water, or sediment and air and water.

Fall Failure:

A fall is a toppling or overturning of a block of soil or sediment. It is a characteristic of extremely steep slopes and generally occurs due to the alteration in forces acting on the slope. These forces are either due to natural factors such as earthquakes, weathering, wave action and water current undercutting or due to human factors such as careless excavation of the toe of a slope.

Slide Failure:

A slide refers to the situation in which the moving mass of soil or sediment is well-defined and separated from the underlying and adjacent earth by a plane, or a zone comprising a number of planes along which slippage results (Lee *et al.* 1983 Chapter 7; Bromhead 1992; Craig 1992; McCarthy 1993). Shear rupture and movement occur along the slip plane when the shear stress in the sediment and soil exceeds their shear strength. In slides the failure mass remains essentially intact, although it may fracture into subunits.

According to the shape and direction of movement of soil or sediment slides are classified as rotational and translational. In rotational failure, the slip surface is curved, forming a bowl shaped trench after failure. The failed mass characteristically slumps in the toe area of the original slope. Rotational failure is associated with slopes of homogenous material possessing cohesion. Generally, translational failure is associated with slopes of layered material. It involves sliding of a layer of sediment over another layer of significantly higher strength. During failure the sliding surface remains roughly parallel to the slope and the sliding mass remains essentially intact or subdivided. Unlike rotational slides, whose movement tends to cease when the mass reaches the slumped position, translational slides can continue over a long distance. Translational failure, which also includes block and wedge failure, refers to the displacement of an intact mass of sediment because of the action of an adjacent zone of earth. In block and wedge failure cracks develop over the surface of the sediment after failure.

Flow Failure:

Flow is a more complex type of soil and sediment movement. Flows of sediment depend on the viscosity of the fluid in the interstitial spaces and on frictional forces between the sediment particles. Flows involve lateral movement of soil or sediment in which the consistency of the moving mass may vary from very wet to dry. The causes of sediment flow are similar to those for sliding failure and involve weakening of resisting forces due to gravity. Flows can be classified as a grain flow, debris flow, liquefied flow, and turbidity flow (Flint & Skinner 1977 Chapter 7; Leeder 1982 Chapter 7). An avalanche may be influenced by its flow mechanism. Debris flows are mobile on very low slopes, whereas grain flows require relatively higher slopes than debris flows to maintain their mobility.

Grain flow: Grain flow occurs differently at high and low energies. In high energy grain flow, the particles are separated by the fluid in the interstitial spaces (entrapped fluid). In low energy slow grain flows the particles touch each other, and intergranular collisions occur. In addition, as the concentration of sand increases sand grain interactions dominate the mechanical behaviour of the flow. During grain flow reverse grading can occur in which coarse particles are more abundant at the top of the flow and fine particles are more abundant at the bottom of the flow. This effect is probably caused by larger particles moving upward through the flow and small particles moving down by filtering through the gaps between the large particles (Bagnold 1954, 1966; Stanley & Swift 1976; Leeder 1982 p76).

Debris flows: Debris flows occur on very gentle sub-aerial and sub-aqueous slopes. Debris flows are episodic events and are generally initiated by a heavy rainfall (Buchanan & Savigny 1990; Anderson & Lloyd 1991; Anderson & Sitar 1995). Particle size distribution has a very important influence on the formation, transport and deposition of debris flow. During debris flow, silt and even boulders remain in a floating state, set in a slurry of clay and water. The clay acts as a lubricant and also has sufficient strength to support and buoy the silt and boulder particles (Hampton 1979; Wang & Zhang 1990). Movement of debris flow depends on the viscosity, the water content, the cohesion of the clay slurry, and the frictional forces between the sediment particles (Vallejo 1979; Major & Pierson 1992).

Liquefied flow: Liquefied flow generally occurs due to earthquakes. It is a feature of very loosely packed beds of sediment. Sediment particles become suspended momentarily in a pore fluid under a cyclic shock and then avalanche even on a very low angle. Liquefied flow soon ceases when the sediment particles start settling and frictional forces between the sediment particles develop again. Following liquefied flow, sediment packing increases and void ratio decreases due to the expulsion of pore fluid upward (Leeder 1982 Chapter 7; Negussey & Islam 1994).

Turbidity flow: In turbidity flow, sediment particles remain suspended in the body of the flow. Turbidity flows occur in rivers and on the sea bed. The suspended sediment particles are transported long distances by water currents. Turbidity flows depend on the viscosity of the water and water currents. The viscosity of the water helps in holding sediment particles in suspension and the water current helps in transportation. Turbidity flows can occur at very low angles of slope (Leeder 1982).

4. Engineering Methods of Slope Stabilisation

Advancement in technology has now made it possible to construct a stable steep slope by using a homogenous soil and sediment, and geomembranes (Rankilor 1981; Barker 1991; Benson & Khire 1994; Fishman & Pal 1994). Furthermore, the stability of an existing slope can be increased by using engineering techniques such as cutting and filling to reduce the angle of inclination, the construction of retaining walls, wire gabions, riprap, piles and the construction of drainage systems to control pore water pressure (Allison *et al.* 1991; Barley 1991; Ginzburg 1991; Gerco 1991; Olcese *et al.* 1991; Popescu 1991; Poulos 1995; Ghiassian *et al.* 1996). The stability of soil and sediment can also be improved by soil stabilisers or conditioners such as lime, cement, gypsum, bentonite, polyacrymide and polysaccharides (Agassi & Benhur 1992; Chapius *et al.* 1992; Morgan 1995 p 135).

There are limitations to increasing stability of natural slopes using the above engineering techniques. On land the best way by which a natural slope can be made saffer is growing trees on it (Donald 1982; Buchanan & Savigny 1990; Agassi & Benhur 1992; Bromhead *et al.* 1994; Morgan & Rickson 1995). However at present, there is no environmental solution to improving the slope stability of river banks, shore lines and slopes under water. Biological control may be an environmental solution.

5. Biological Activity and Sediment Stability & Strength

The role of biological activity in sediment stability, either in the form of vegetation or algal mats and animal burrows or microbial glues has recently received considerable attention, and is a forefront area of research (Rhoads *et al.* 1978; Paterson 1987, 1989; Paterson *et al.* 1990; Meadows & Meadows 1991; Eckman & Nowell 1984; Daborn *et al.* 1985, 1993; Meadows & Tait 1989; Gerdol & Hughes 1994; Pender *et al.* 1994; Underwood & Paterson 1993; Meadows *et al.* 1994a; Paterson & Daborn 1991). The stability of sediments depend on their geotechnical properties such as particle size, shear strength, critical erosion velocity, permeability, density and packing of the sediments. Biological activity modifies these geotechnical properties and can also affect sediment stability by burrowing, producing microbial glues, forming sediment pellets and by reworking the sediment. Suspension feeders take in suspended sediment and form pellets on or in the sediment bed. Pelletisation affects particle size distribution and critical erosion velocity of the sediment (Amos *et al.* 1992). The viscous and elastic binding mucus secretion by bacteria as well as macro and meiofauna fills up pore spaces between the sediment and reduces the porosity and permeability of the sediment (McCall 1982 p 25, 31; Tufail, 1988; Miller *et al.* 1996). Moreover the tubes produced by the burrowing invertebrates into the sediment act as piles that help in stabilising the sediment. Marine plants such as grasses also stabilise the sediment by trapping and binding the sediment. These reduce the incoming current velocity and trap the settling sediment due to the reduction in velocity (Scoffin 1970).

There has been considerable discussion in the literature which suggests that biological activity significantly affects sediment stability (Rhoads *et al.* 1978; Yingst & Rhoads 1978; Forster & Nicolson 1981 a, b; Meadows & Meadows 1991; McCall 1982; Jones & Jago 1993; Pender *et al.* 1994). These effects may be caused by animal tubes (Yingst & Rhoads 1978; Eckman *et al.* 1981; Eckman & Nowell 1984; Luckenbach 1986; Grant & Daborn 1994), by benthic diatoms producing polysaccharides and microbial exopolymers (Holland *et al.* 1974; Daborn *et al.* 1985, 1993; Deco *et al.* 1990; Delgado *et al.* 1991; Rao *et al.* 1993). The polycheate worm *Nereis diversicolor* and the crustacean *Corophium volutator* alter the shear strength of sediment (Meadows & Tait 1989; Meadows *et al.* 1990; Gerdol & Hughes 1994; Pender *et al.* 1994). These two burrowing invertebrates also modify the permeability of sediment (Girling 1984; Meadows and Tait 1989; Meadows & Hariri 1991;). *Arenicola marina* can affect critical erosion velocity (Meadows & Tufail 1989). Microalgae and bacteria may also alter sediment stability (Frostick *et al.* 1979; Iversen *et al.* 1991; Madsen *et al.* 1993; Underwood & Paterson 1993; Meadows *et al.* 1994a). *In situ* sediment containing algal mat patches are higher than the bare sediment. Bacterial and algal films reduce sediment erosion (Dapples 1942; Neumann 1970; Holland *et al.* 1974; Paterson 1987, 1989; Young & Mourato 1990; Paterson & Daborn 1991; Underwood & Paterson 1993; Dade *et al.* 1996). The mussel *Mytilus edulis* also affects physical properties of sediment (Meadows & Shand 1989; Shand 1991).

All the above studies are related to the effects of biological activity on the geotechnical properties of sediment such as shear strength, water content, permeability, surface texture and erodability of the sediments. Effects of vegetation on stability of slopes are well-known on land (Perla & Martinelli 1976; Wu *et al.* 1979; Donald & Andrew 1982; Gray & Leiser 1982; Bache & MaCaskil 1984; Barker 1986; Agassi & Benhur 1992; Brooks *et al.* 1995; Collison *et al.* 1995; Morgan & Rickson 1995; Gray &

Sotir 1996; Schiechtl & Stern 1996; Schiechtl & Stern 1997). Surprisingly little is known about the influence of biological activity on the stability of sediment on inclined surfaces (slopes) in aquatic environments. Only a few studies have demonstrated the significance of macro and microorganisms on the stability of slopes specially in relation to the angle of avalanche and the angle of repose (Mehta & Rao 1985; Meadows *et al* 1994a; Muir Wood *et al.* 1994).

6. Objectives of my research

With this background, the overall objectives of my research are to investigate avalanching of non-cohesive sediments and in particular the effects of biological activity on the avalanching parameters; first angles of avalanche and repose, second angles of avalanche and repose, factors of safety and angle of dilatation. My thesis is divided into six sections.

In the first section, I have investigated geotechnical properties of sediments. These include grain size distribution, void ratio, porosity, dry density, bulk density, permeability and shear strength of sediment. In this section, I have also investigated the effects of vibration on sediment packing and shear strength.

The second section of my thesis consists of preliminary investigations on avalanching technique. In this section, I describe the avalanching technique. The experiment in this section was designed to test the effects of shape and size of containers on the avalanching parameters given above. In this section I have also investigated the effects of sediment volume and sediment grain size on avalanching.

In the third section, I have investigated the effects of fluid medium namely air, fresh water and 50% glycerol on avalanching parameters. In this section I also recorded duration of avalanche in air, water and 50% glycerol. In addition, I have also investigated the relationship between the avalanching parameters and geotechnical properties of sediments in the three media.

The experiments in the fourth section were designed to test the effects of viscosity of liquids; GF/F filtered tap water, alginic acid 2 % solution (low viscosity) and 100% glycerol on avalanching parameters. Effects on avalanching of sediments settling time, sediment grain size and the duration of avalanche were also studied.

In the fifth section of my research, I have demonstrated the importance of biological activity in sediment stabilisation. This section consists of experiments on the effect of two burrowing infauna *Corophium volutator* and *Nereis diversicolor* and of microorganisms and meiofauna on avalanching.

In the sixth and last section of my research, I have investigated the effect of the mussel *Mytilus edulis* on sediment stability. It was my plan to study the effects of *M. edulis* on avalanching however time constraints did not allow me to complete the work on the effects of *M. edulis* on avalanching. The investigation consists of a laboratory study on thread production by *M. edulis* on sand and gravel.

7. <u>Ardmore Bay and Lang Bank at Clyde Estuary of United Kingdom</u>

The sediment and organisms used in this study were collected from the Clyde estuary. The Clyde estuary is located near Glasgow in the west of Scotland, United Kingdom. The sediments and organisms *Corophium volutator* and *Mytilus edulis* were collected from the Ardmore Bay at Clyde Estuary (Lat: 55° 58′ 32″ N Long: 4° 41′ 29″ W Nat. Grid: NS 321 792) (Fig. II). Fine sediment (63 µm to 1 mm) was collected from mid-tide level at point A on figure II and coarse sediment (1 mm to 8 mm) was collected from high-tide level on a near by exposed shore at point B on figure II. *Corophium volutator* (Cv) was collected from the high-tide site and the mussel *Mytilus edulis* was collected from the mid-tide area at point C on figure II. The polycheate worm *Nereis diversicolor* (Nd) was collected from the mid-tide area at Langbank, in the Clyde Estuary (Lat: 55° 55′ 39″ N Long: 4° 33′ 49″ W Nat. Grid: NS 398 735).

8. Note: The following starring system for probability is used throughout the thesis: $0.05>P>0.01$ *; $0.01>P>0.001$ **; $P<0.001$ ***

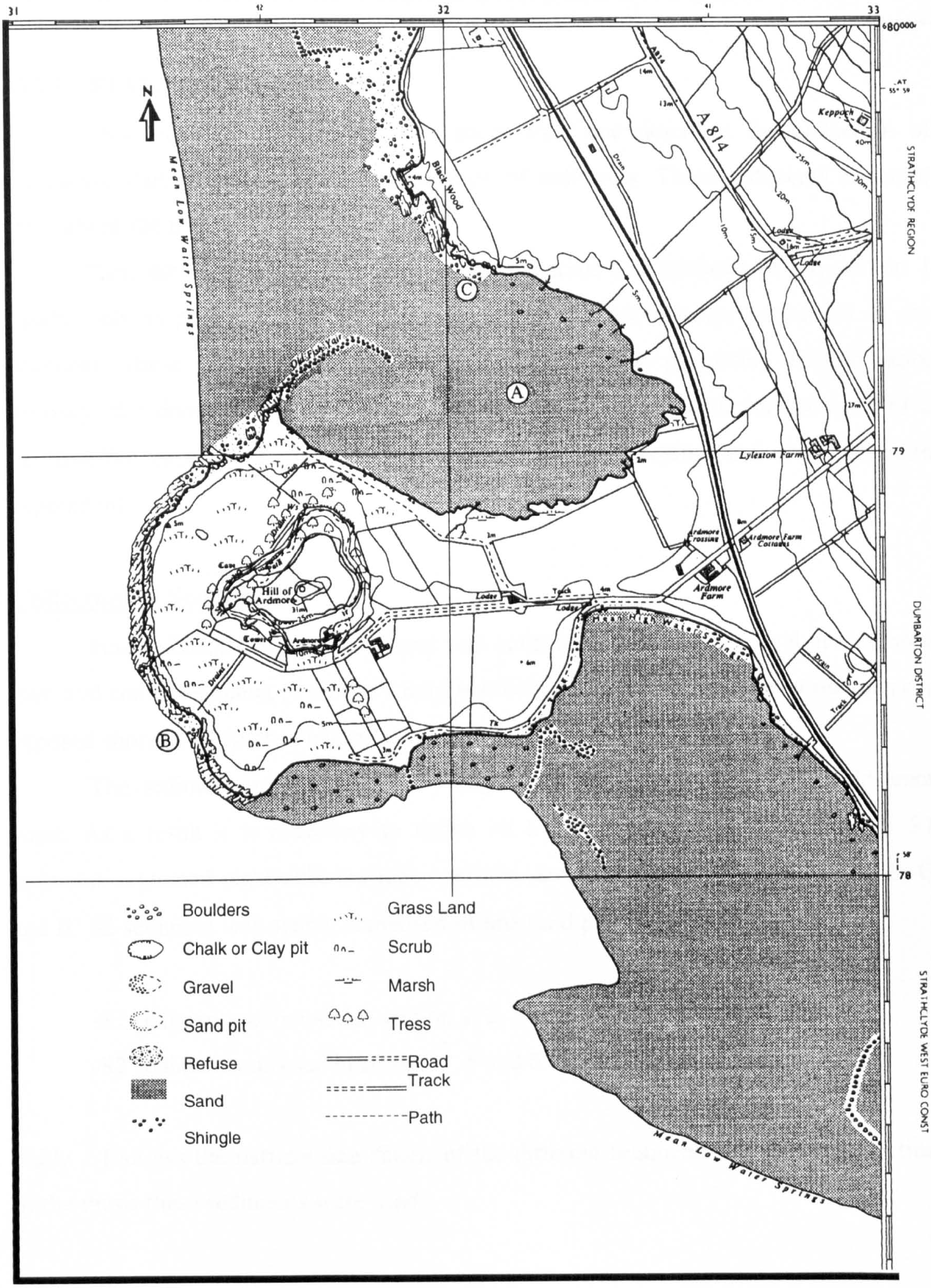


Figure II Map of Ardmore Bay at the Clyde Estuary, Scotland, United Kingdom.

SECTION 1: Geotechnical Properties of Ardmore Bay Sediments

1.1 MATERIALS AND METHODS

This section is divided into five parts. Part one describes the collection of sediments. Part two describes the preparation of sediments. These sediments are used throughout the thesis.

Parts three, four and five describe the materials and methods of the section 1 results only as follows. The third part deals with the geotechnical properties of the sediment. These properties are particle size and the phase properties of void ratio, porosity, dry density, bulk density and specific gravity. The fourth part consists of a permeability experiment. The fifth part consists of a packing and shear strength experiment.

1.1.1 Collection of Sediments

Fine sediment (63 μm to 1 mm) was collected from mid-tide level at Ardmore Bay, and coarse sediment (1 mm to 8 mm) was collected from high-tide level on a nearby exposed shore at Ardmore Peninsula.

The sediment used in laboratory experiments was treated in slightly different ways. As a result it is necessary to define an S1 sediment and an S2 sediment. S1 sediment contained eight different mean particle size of sediments A, B, C, D, E, F, G and H. S2 sediment was mainly composed of fine sand particle size 63 μm to 1 mm.

-S1 sediments were used in section 1, 2, 3 and 4.

-S2 sediment was used in section 1, 5 and 6.

Table 1.1 shows the particle size details of the different sediments and in which section of the thesis these sediments were used.

Table 1.1 Sediment types and sediment classification of the different sediments used in this thesis. S1 sediments were air dried before being used whereas S2 sediment was wet sieved and maintained in water until being used. A = Fine sand (63 µm to 1 mm). B = Coarse sand (1 mm to 2 mm). C = Granules (2 mm to 4 mm). D = Pebbles (4 mm to 8 mm). E = (1:1:1: B:C:D) means that sediment E consists of one part of sediment B, one part of sediment C and one part of sediment D. Sediment F, G and H were prepared by mixing sediment A and sediment E in a proportion of 2:1, 1:1 and 1:2 respectively. Sediment F = (2:1: A:E) means 2 parts of sediment A to 1 part of sediment E.

Sediment Types		Sand				Gravel		Thesis
		Fine sand			Coarse sand	Granules	Pebbles	
		63 µm - 500 µm	63 µm - 710 µm	63 µm - 1 mm	1 mm - 2 mm	2 mm - 4 mm	4 mm - 8 mm	Sections
S1	A	___	___	100 %	___	___	___	1, 2, 3 & 4
	B	___	___	___	100 %	___	___	1, 2 & 3
	C	___	___	___	___	100 %	___	1, 2 & 3
	D	___	___	___	___	___	100 %	1, 2 & 3
	E	___	___	___	33 %	33 %	33 %	1, 3 & 4
	F	___	___	66 %		33 %		1, 3 & 4
	G	___	___	50 %		50 %		1 & 3
	H	___	___	33 %		66 %		1, 3 & 4
S2		___	___	100 %	___	___	___	1
			100 %	___	___	___	___	5
		Used in Exp ✣	___	___	___	___	Used in Exp ✣	6

✣ For detail see section 6.

1.1.2 Preparation of Sediments

S1 Sediments (Section 1, 2, 3 and 4)

Eight different particle sized sediments were prepared as follows. Fine sediment was sieved in fresh water through a 1 mm BS sieve and retained on a 63 µm BS sieve. Coarse sediments were sieved through an 8 mm BS sieve followed by 4 mm, 2 mm and 1 mm BS sieves. The sieved sediments were classified as sediment A (63 µm to 1 mm), sediment B (1 mm to 2 mm), sediment C (2 mm to 4 mm) and sediment D (4 mm to 8 mm).

Sediments A, B, C and D were air dried. Sediments E, F, G and H were prepared by dry mixing sediments A, B, C and D. Sediment E (1 mm to 8 mm) was prepared by mixing one part of sediment B, one part of sediment C and one part of sediment D (1:1:1, B:C:D). Sediment A and sediment E were mixed in a proportion of 2:1 to make sediment F (63 µm to 8 mm), 1:1 to make sediment G (63 µm to 8 mm) and 1:2 to make sediment H (63 µm to 8 mm).

Sediments A, B, C, D, E, F, G and H can be classified as fine sand, coarse sand, granules, pebbles, gravely, sandy/gravely (2:1), sandy-gravely (1:1) and gravely/sandy (2:1) sediments. This classification is based on the metric particle size classification introduced by Wentworth (1922) and the particle size classification devised by Krumbein (1934) using the phi (ϕ) scale (Appendix I: Table 1).

S2 Sediments (Section 1, 5 and 6)

S2 sediment contained only fine sediment which was similar in particle size to sediment A (63 µm to 1 mm - see above) of the S1 sediment. It was wet sieved either in fresh water or in sea water. After wet sieving the sediments were maintained in water until being used in experiments in section 1, 5 and 6.

S2 sediment used in section 1: The sediment was wet sieved manually through a 1 mm BS sieve and retained on a 63 µm BS sieve. After wet sieving the sediment was washed three times with fresh water and allowed to stand for 30 to 45 seconds before decanting off the detrital material. The sediment was than maintained in fresh water until used in the experiments.

S2 sediment used in section 5: The sediment was wet sieved manually through a 710 µm BS sieve and retained on a 63 µm BS sieve. The sieving was done in sea water.

S2 sediment used in section 6: The sediment was wet sieved manually through a 500 µm BS sieve and retained on a 63 µm BS sieve. The sieving was done in sea water.

1.1.3 Geotechnical Properties

Particle Size Analysis

S1 sediments: Approximately 100 gm of air dry sediment from each of the sediment types A, B, C, D, E, F, G and H was analysed by mechanical sieving. The sieves used were: 8 mm (-3 ϕ), 5.6 mm (-2.5 ϕ), 4 mm (-2 ϕ), 2.8 mm (-1.5 ϕ), 2 mm (-1 ϕ), 1.4 mm (-0.5 ϕ), 1 mm (0 ϕ), 710 µm (0.5 ϕ), 500 mm (1 ϕ), 355 µm (1.5 ϕ), 250 µm (2 ϕ), 180 µm (2.5 ϕ), 125 µm (3 ϕ), 90 µm (3.5 ϕ), 63 µm (4 ϕ) and a pan. The sediment retained on each sieve was weighed to an accuracy of 0.01 g. Three replicate sieve analysis of each of the sediments A, B, C, D, E, F, G and H were done. The data was then analysed by using a computer programme developed by Ms M. Kirkham. The computer programme calculation is based on the method of moments, introduced by Krumbein (1934). Parameters for particle size analyses and their formulae are presented in appendix I: Table 2.

S2 sediment: Ten samples were prepared as follows. Samples were dried in an oven overnight. They were gently disaggregated using a pestle and mortar. 100 g samples were dry sieved on a stack of sieves on a mechanical sieve shaker. The sieves used were: 1000 µm (0 ϕ), 500 µm (1 ϕ), 250 µm (2 ϕ), 125 µm (3 ϕ), 63 µm (4 ϕ) and the pan. The sediment on each sieve was weighed to an accuracy of 0.01 gm. The six weights thus obtained for each sample were analysed using a computer programme developed by Ms M. Kirkham.

Coefficient of uniformity (Cu) and of curvature (Cz) of the S1 sediments were calculated as follows. Coefficient of uniformity (Cu) and of curvature (Cz) of the S2 sediments were not calculated for S2 sediment. The particle size D_{10}, D_{30} and D_{60} were taken from the particle size distribution (Fig 1.6). The effective size D_{10} was the particle diameter below which 10% of the sediment weight lay. Similarly D_{30} and D_{60} are the particle diameters below which 30% and 60% of the sediment weight lay. The coefficient of uniformity (Cu) and coefficient of curvature were calculated by the following formulae (Bowels 1978; Smith 1981; Craig 1992).

$$\text{Coefficient of uniformity (Cu)} = \frac{D_{60}}{D_{10}} \qquad \text{---(1.1)}$$

$$\text{Coefficient of Curvature (Cz)} = \frac{{D_{30}}^2}{D_{60} \times D_{10}} \qquad \text{---(1.2)}$$

Phase Relations (Void ratio, Porosity, Dry density, Bulk density, Specific gravity)

The void ratio, porosity, dry density, bulk density and specific gravity of S1 sediments A, B, C, D, E, F, G and H were measured as follows.

A glass container (15 cm × 7.5 cm) was filled with 1000 ml of fresh water. The depth of water (d_1) in the container was recorded (Fig. 1.1a). Approximately 400 ml of known weight (Ws) air dried sediment was added to the water in the container. The sediment was stirred with a metal rod to remove the trapped air bubbles. The depth of sediment + water (d_2) and the depth of sediment (d_3) were than recorded (Fig. 1.1b). These measurements were then used to calculate the void ratio, porosity, dry density, bulk density and specific gravity of sediment. The details are described in Appendix 1.

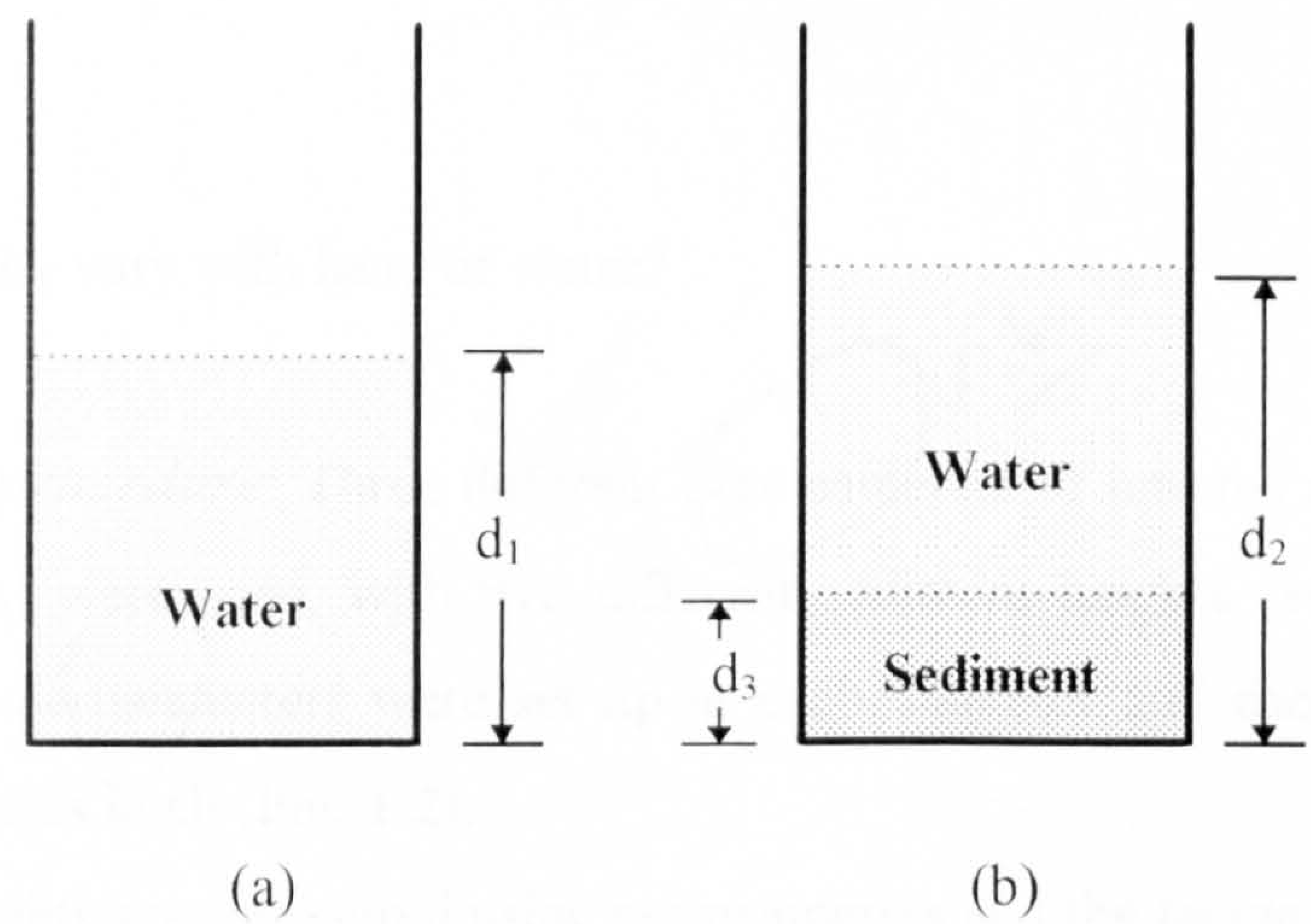


Figure 1.1 S1 sediment phase relationship experiment. a) d_1 = depth of water in the container before adding sediment. b) d_3 = depth of sediment in water and d_2 = depth of (water + sediment) in the container.

1.1.4 Permeability Experiment using S2 Sediment

A permeability experiment was designed to test the effects of diameter of tube, depth of sediment, and head of water on the permeability coefficient. Specifically, the permeability experiment was designed to test the following hypotheses.

Hypothesis 1:

Does permeability vary with diameter of tube?

Hypothesis 2.

Does permeability vary with depth of sediment?

Hypothesis 3:

Does permeability vary with head of water?

Experimental procedure: Three different permeameters of internal diameters (20 mm, 25 mm, 54 mm) were used, with two different sediment heights (100 mm, 200 mm). Three replicate permeameters were set up at each diameter and each sediment height, giving 18 replicates in all (Fig. 1.2).

Permeability was measured using permeameters and the falling-head method (Fig. 1.3) Permeameters consisted of plastic tubing whose bottom end was covered with stainless steel and fibre mesh. Sediment was packed in the permeameter by allowing it to fall freely through water. Sediment height was adjusted to 100 mm (P_1) or 200 mm (P_2). Uniform packing was obtained by tapping the tube ten times on a flat surface. The permeameter was set up as shown in figure 1.3. When the overlying water became clear the depth of water was adjusted to 450 mm above the bottom of the core in both permeameters and permeability was measured by recording the time taken for the level of water to fall successive 50 mm distances. After taking five consecutive readings on P_1 and three consecutive readings on P_2, water was carefully added without disturbing the sediment surface to return it to its original level of 450 mm (see figure 1.3). The process was repeated twice, giving three sets of replicate readings for P_1 and three sets of replicate readings for P_2. After the third set of replicate readings the sediment was removed from the tube, weighed, oven dried and re-weighed.

The permeability coefficient (k) was calculated using the following equation (Smith 1981).

$$k = \frac{L}{t} \times 2.3 \log_{10} \frac{h_1}{h_2} \qquad \text{---(1.12)}$$

Where k = coefficient of permeability (mm. s^{-1}), L = length of sediment (mm), h_1 = initial water level (mm), h_2 = final water level (mm), t = time (seconds) for water level to fall from h_1 to h_2.

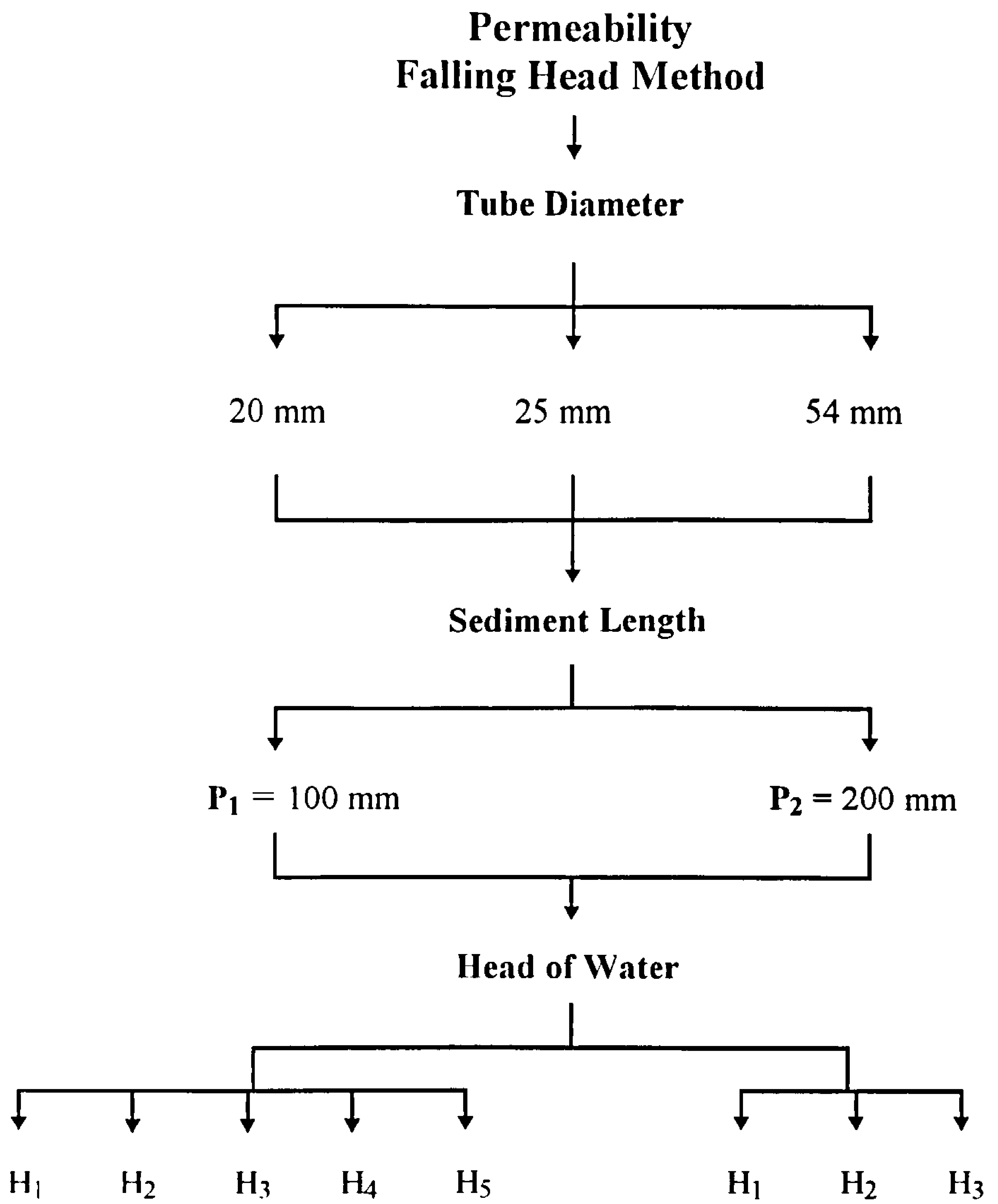


Figure 1.2 Permeability experiment. Permeameter internal tube diameters 20 mm, 25 mm, and 54 mm. S2 sediment packed at 100 mm and 200 mm length in each of the above tubes. H_1 = head of water 450 to 400 mm, H_2 = head of water 400 to 350 mm, H_3 = head of water 350 to 300 mm, H_4 = head of water 300 to 250 mm, H_5 = head of water 250 to 200 mm.

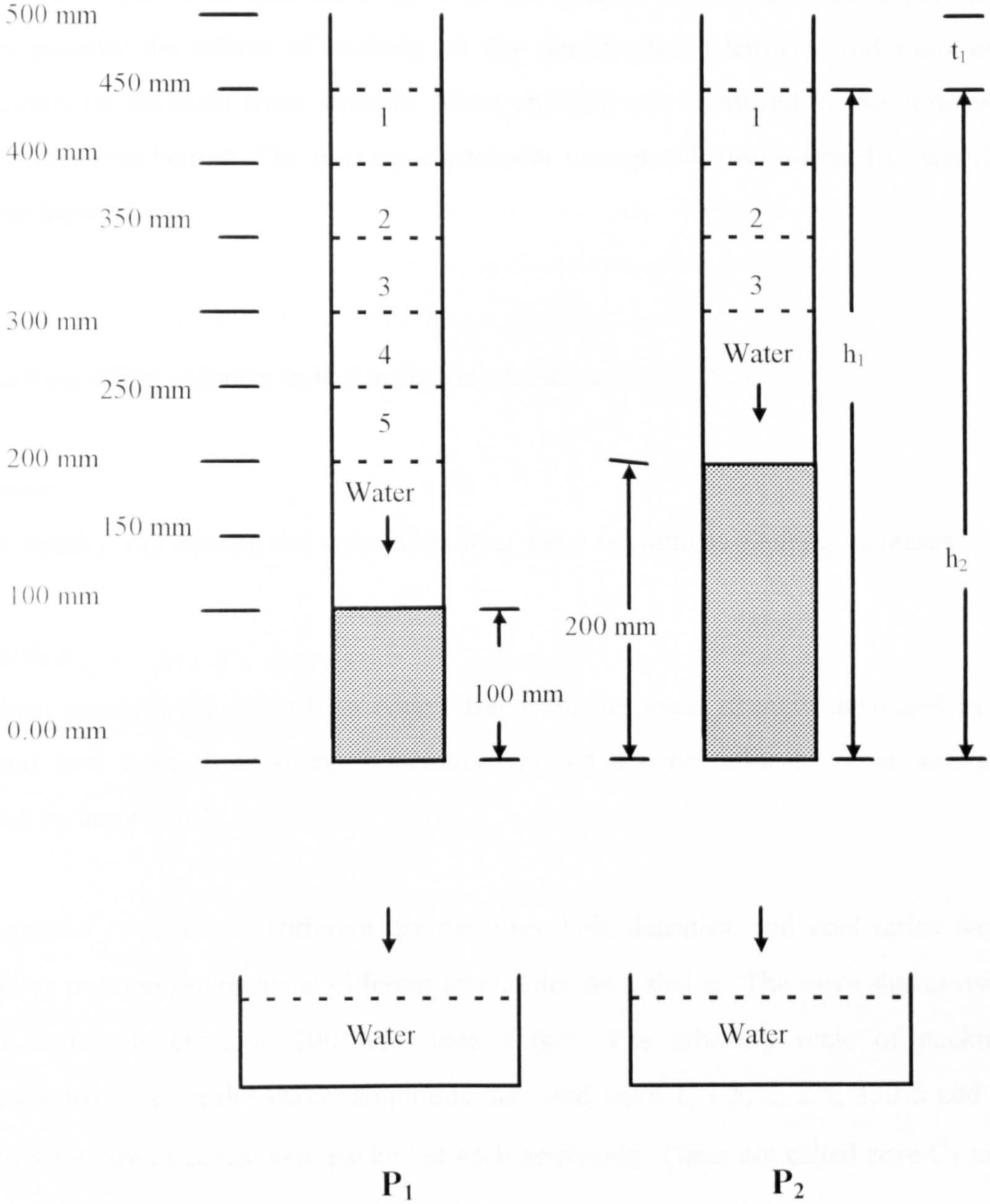


Figure 1.3 Falling head permeameter. P_1 (sediment length L = 100 mm) and P_2 (sediment length L = 200 mm). The level of water was adjusted to h_1 (450 mm). The time (t_1) for water level to fall from head h_1 (450 mm) to h_2 (400 mm) was recorded. After taking three consecutive readings in the case of P_1 and five consecutive readings in the case of P_2, water is carefully added to the tube. The process was repeated twice giving three replicate readings of permeability.

1.1.5 Packing and Shear strength Experiment using S2 Sediment

A packing experiment was designed to quantify the effects of packing on geotechnical properties of sediment (Fig. 1.4). The specific objectives of the experiment were to quantify the effects of packing on dry density, bulk density, void ratio and consequently on sediment shear strength. Shear strength was measured by the cone and vane methods (see below). The packing experiment was specifically designed to test the following hypotheses.

Hypothesis 1:

Does packing effect sediment bulk density, dry density and void ratio?

Hypothesis 2:

Do bulk density, dry density and void ratio affect shear strength as packing increases?

Hypothesis 3:

Does shear strength measured by a cone differ from the shear strength measured by a vane, and how does shear strength measured by small cone differ to shear strength measured by large cone?

Experimental procedure: Different dry densities, bulk densities, and void ratios were obtained by packing sediments at different amplitudes on a shaker. The sieve shaker used was an Endecotts Octagon 200 test sieve shaker. The arbitrary scale of packing amplitudes provided on the shaker amplitude dial used were 1, 1.5, 2, 2.5, 3, 3.5 and 4. Two replicate size of cores were packed at each amplitude. These are called core C_1 and core C_2 (Fig. 1.4). Shear strength was determined with a Geonor fall-cone penetrometer using a small cone (10 g) and a large cone (60 g), and with a Pilcon hand vane tester using a small vane (19 mm) and a large vane (33 mm). Shear strength was measured on C_1 using the 10 gm cone and the 19 mm vane, and on C_2 using the 60 gm cone and the 33 mm vane.

The procedure for taking the shear strength readings on C_1 and C_2 was exactly the same, as follows. Firstly three surface replicate cone readings were taken forming a triangle which avoided the wall and the centre of the core. Secondly one vane measurement was taken in the centre of the core. This procedure insured that neither the cone test nor the vane test were affected by the wall, and that the vane test was not affected by the cone test (Fig. 1.5).

Geonor fall-cone penetrometer: In the laboratory, shear strength of the S2 Sediment was measured by using a Geonor Fall-Cone Penetrometer as follows. A metal cone was vertically positioned with its apex just touching the surface of the sediment. The cone was allowed to fall under its own weight into the sediment. The depth of penetration of the cone into the sediment was measured. Three replicate readings were taken and the shear strength was calculated using the formula given by Hansbo (1957).

$$\tau_f = \frac{k\,Q\,9.81}{h^2} \qquad \text{---(1.13)}$$

Where τ_f = Shear strength in kN m^{-2} or kPa, k = constant depending on the apex angle of cone, Small cone: k_{10} = 0.1514, Large cone: k_{60} = 0.0252, Q = weight of cone in gm, h = penetration of cone in mm.

Pilcon hand vane tester: In the laboratory, shear strength of the S2 Sediment was measured by using a Pilcon Hand Vane Tester as follows. Firstly the vane scale (provided on the torque head of the apparatus) was adjusted to zero. The vane was then driven into the sediment and torque was applied by rotating the torque head in clockwise direction at a constant rate until the sediment cylinder failed. Shear strength was calculated by multiplying the scale readings with the calibration factor on the torque head of the apparatus as follows:

a) Small Vane Shear Strength = Scale reading × 1.346 kN m^{-2} or kPa.

b) Large Vane Shear Strength = Scale reading × 1.145 kN m^{-2} or kPa.

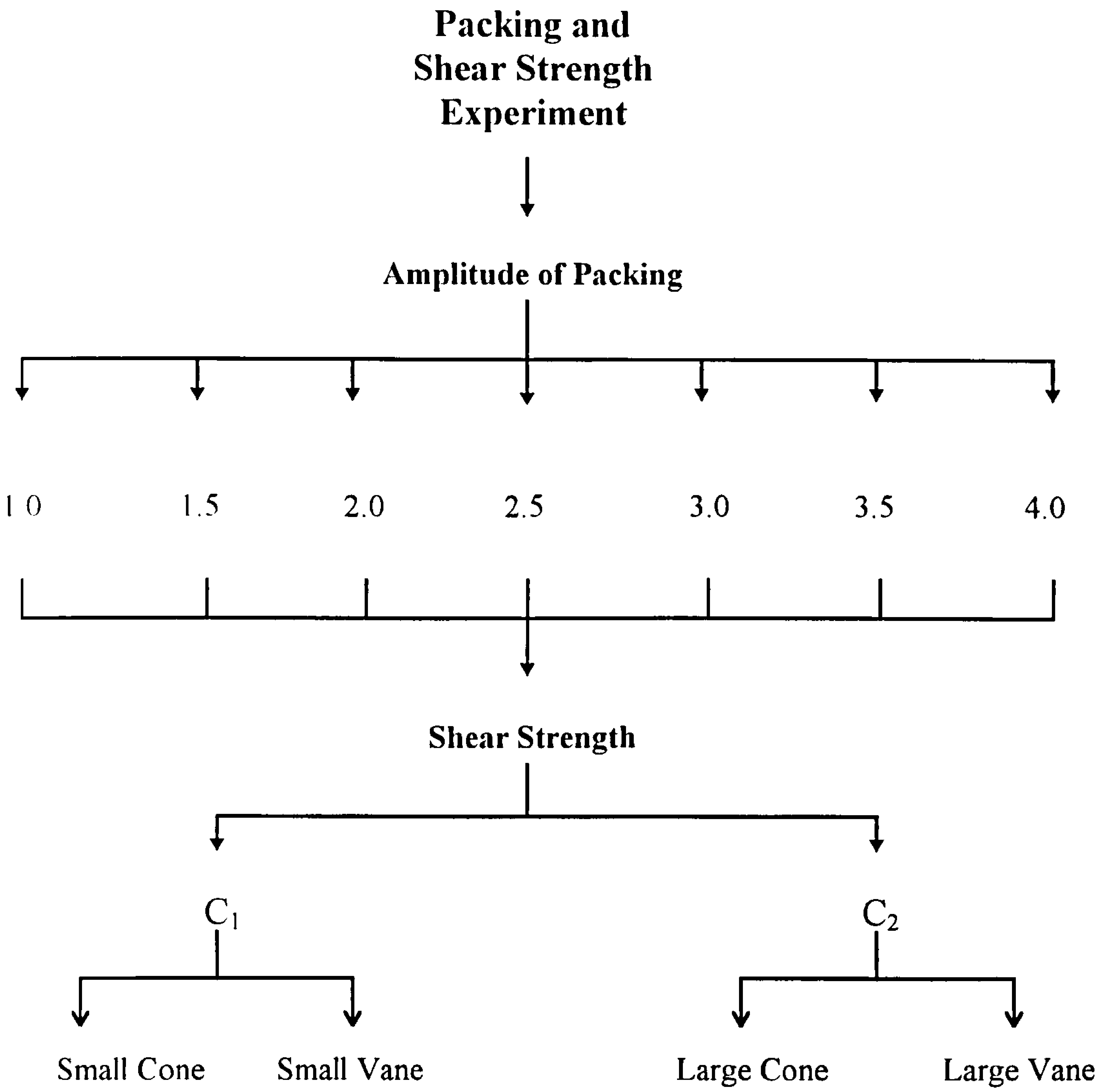


Figure 1.4 Packing and shear strength experimental design. S2 sediment packed at amplitudes 1, 1.5, 2, 2.5, 3, 3.5, and 4. Two replicates were done on each packing amplitude (C_1 and C_2). Shear strength of replicate core of packing C_1 was tested by using a small cone and a small vane and the shear strength of replicate core of packing C_2 was tested by using a large cone and a large vane. Three replicate readings were taken by using cone and one reading by using vane.

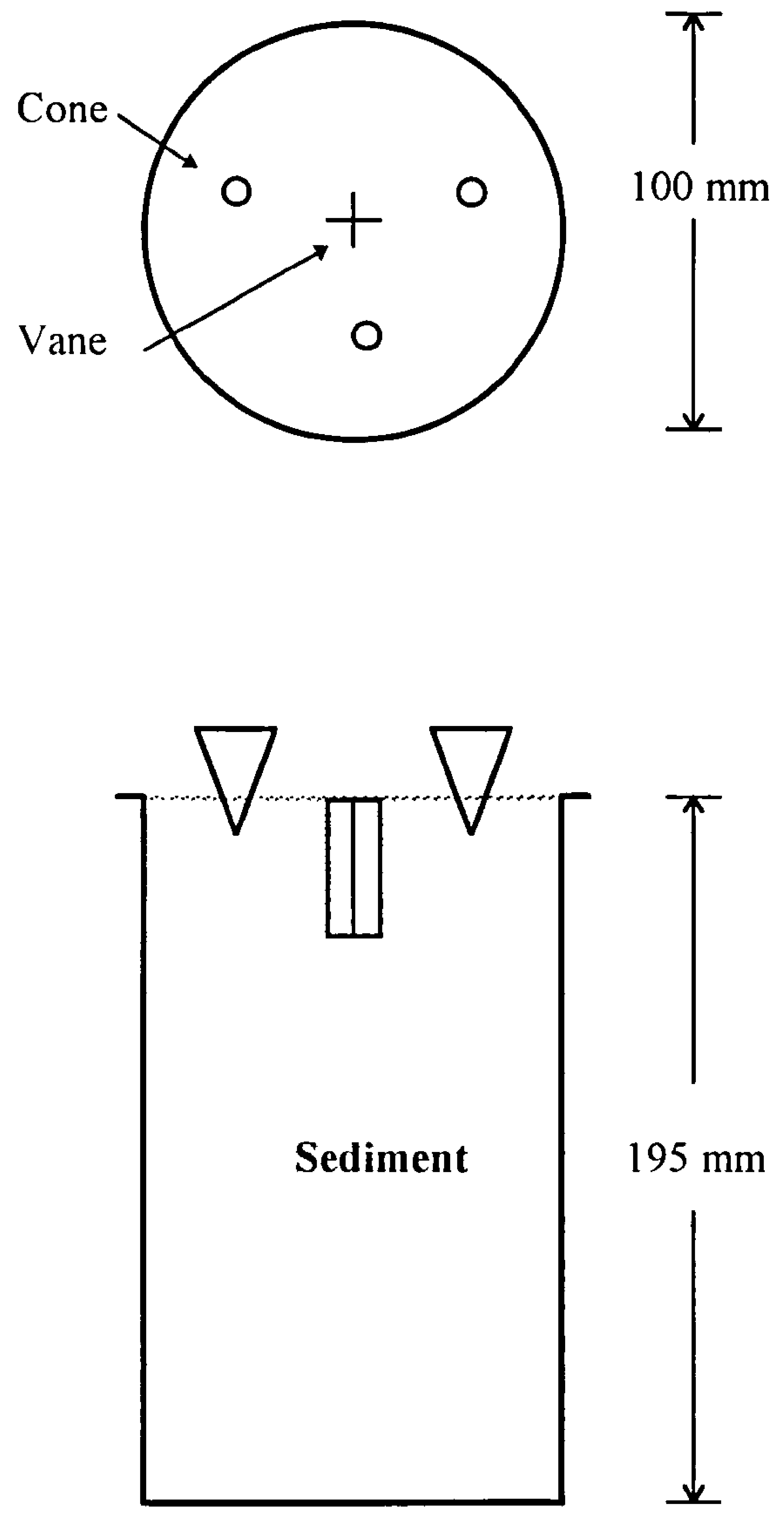


Figure 1.5 Positions of shear strength measurement by cone and vane in S2 sediment. **Top:** plan of cylindrical container. **Bottom:** side elevation of the cylindrical container.

1.2 RESULTS

The results are divided into three parts. The first part (1.2.1) covers the geotechnical properties of sediments consisting of particle size and phase relations (Void ratio, Porosity, Dry density, Bulk density, Specific gravity). The second part (1.2.2) describes the results of the permeability experiment. The third part (1.2.3) describes the results of the packing and shear strength experiment.

1.2.1 Geotechnical Properties

Particle Size Analysis

S1 sediments: The mean data of three replicate readings for particle size analyses was plotted and presented as follows. The percentage weight passed (% weight finer) of sediments A, B, C, D, E, F, G and H was plotted against particle size in phi (ϕ) unit and presented in particle size distribution chart (Fig 1.6). Percentage weight retained against particle size in phi (ϕ) unit plots for each type of sediments are presented in figure 1.7 and 1.8. The results of the particle size analyses are shown in table 1.2, in which the mean particle size, sorting, skewness, kurtosis, coefficient of uniformity and coefficient of curvature.

Sediment A was bimodal and moderately sorted having a sorting coefficient 0.5726. Sediment A was positively skewed having skewness value 0.1931. It was also platykurtic having a kurtosis value of 0.5898. Sediment A was uniform having a coefficient of uniformity Cu = 2.131 (Table 1.2 and Fig. 1.6 and 1.7). (see appendix I for the explanation of positive and negative skewness, and platykurtic and leptokurtic curves)

Sediment B was unimodal and very well sorted having a sorting coefficient 0.1650. Sediment B was very positively skewed having a skewness value of 1.138. It was also very leptokurtic having a kurtosis value 3.188. Sediment B was very uniform having a coefficient of uniformity Cu = 1.292 (Table 1.2 and Fig. 1.6 and 1.7).

Sediment C was unimodal and very well sorted having a sorting coefficient of 02382. Sediment C was negatively skewed having a skewness value of - 0.3183. It was also very platykurtic having a kurtosis value of 1.593. Sediment C was very uniform having a coefficient of uniformity Cu = 1.304 (Table 1.2 and Fig. 1.6 and 1.7).

Sediment D was unimodal and very well sorted having a sorting coefficient of 0.2480. Sediment D was very positively skewed having a skewness value of 0.1282. It was also very platykurtic having a kurtosis value of 1.936. Sediment D was very uniform having a coefficient of uniformity Cu = 1.399 (Table 1.2 and Fig. 1.6 and 1.7).

Sediments E was bimodal whereas sediment F was multimodal. Sediment E and sediment F were very poorly sorted having sorting coefficients of 2.044 and 2.013. Sediments E and F were negatively skewed having skewness values of - 0.2042 and - 0.2152. These were also platykurtic having kurtosis values of 1.034 and 1.391. Sediment E was very uniform having a coefficient of uniformity Cu = 1.919 whereas sediment F was poorly graded having a coefficient of uniformity Cu = 5.267 (Table 1.2 and Fig. 1.6 and 1 8).

Sediment G was multimodal and poorly sorted having a sorting coefficient of 1.975. Sediment G was symmetrical having a skewness value of 0.0368. It was also platykurtic having a kurtosis value of 1.551. Sediment G was poorly graded having a coefficient of uniformity Cu = 13.29 (Table 1.2 and Fig. 1.6 and 1.8).

Sediment H was multimodal and moderately sorted having a sorting coefficient of 0.7427. Sediment H was positively skewed having a skewness value of 0.2160. It was also platykurtic having a kurtosis value of 1.304. Sediment H was poorly graded having a coefficient of uniformity Cu = 15.68 (Table 1.2 and Fig. 1.6 and 1.8).

Table 1.2 Particle size analyses Mean±SD of three replicate readings. A = Fine sand (63 μm to 1 mm), B = Coarse sand (1 mm to 2 mm), C = Granules (2 mm to 4 mm), D = Pebbles (4 mm to 8 mm), E = (1:1:1; B:C:D) means that sediment E consist of one part of sediment B, one part of sediment C and one part of sediment D. Sediment F, G and H were prepared by mixing sediment A and sediment E in a proportion of 2:1, 1:1 and 1:2 respectively. Sediment F = (2:1; A:E) means 2 parts of sediment A to 1 part of sediment E) and so on.

Sediment	Mean Diameter		Sorting	Skewness	Kurtosis	Cu	Cz
	(ϕ)	(mm)					
A	2.176±0.0244	0.2213±0.0038	0.573±0.0044	0.1931±0.0277	0.5898±0.1314	2.131±0.0242	0.8498±0.0490
B	-0.6878±0.0032	1.611±0.0036	0.165±0.0036	1.1383±0.0438	3.188±0.3970	1.292±0.0238	1.021±0.0070
C	-1.424±0.0051	2.684±0.0096	0.238±0.0015	-0.3183±0.0224	1.593±0.0566	1.304±0 0052	0.9267±0.0068
D	-2.532±0.0026	5.784±0.0106	0.248±0.0003	0.1282±0.0099	1.936±0.0051	1.399±0.0651	0.9100±0.0314
E	-1.500±0.0168	2.829±0.0329	2.044±0.0579	-0.2042±0.0254	1.034±0.1328	1.919±0.0794	0.8627±0.0244
F	0.7083±0.0431	0.6122±0.0182	2.013±0.0448	-0.2152±0.0199	1.391±0.0802	5.267±3.1658	0.6475±0.3319
G	0.2267±0.2227	0.8613±0.1299	1.975±0.0080	0.0368±0.0745	1.551±0.0302	13.29±1.0557	0.2608±0.0061
H	-0.2608±0.1309	1.201±0.1060	0.743±0.0220	0.2160±0.0489	1.304±0.0835	15.68±1.5007	0.2816±0.0101

Coefficient of Uniformity : $Cu = D_{60}/D_{10}$ (defined in text). Coefficient of Curvature : $Cz = (D_{30})^2 / (D_{60} \times D_{10})$ (defined in text)
SD = standard deviation of three replicate readings in each case.

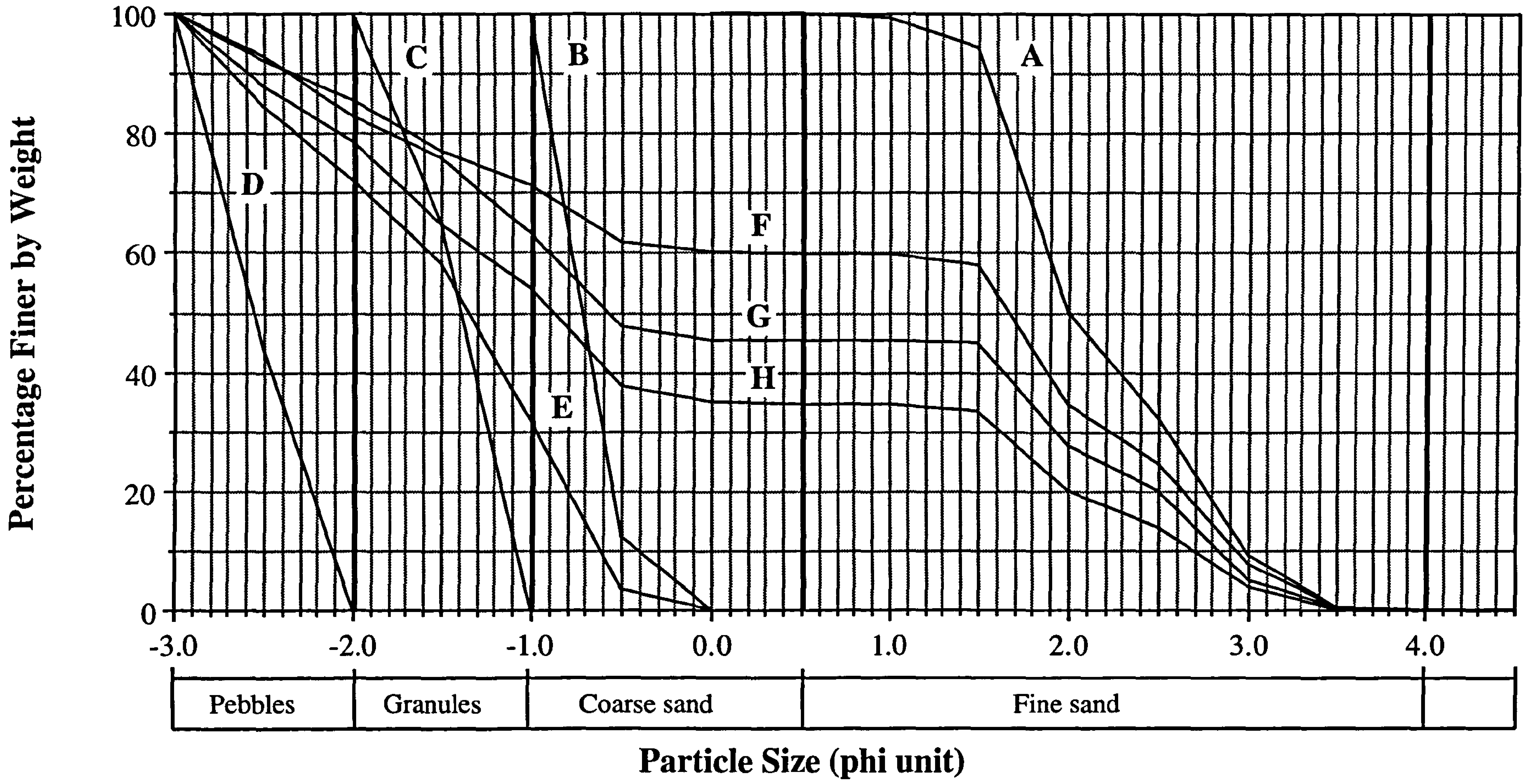


Figure 1.6 Particle size distribution chart of S1 sediment. Mean of three replicate readings of percent finer against particle size in phi (ϕ) unit. A = sediment A (63 μm to 1 mm), B = sediment B (1 mm to 2 mm), C = sediment C (2 mm to 4 mm), D = sediment D (4 mm to 8 mm), E = sediment E (1 mm to 8 mm), F = sediment F (63 μm to 8 mm), G = sediment G (63 μm to 8 mm) and H = sediment H (63 μm to 8 mm).

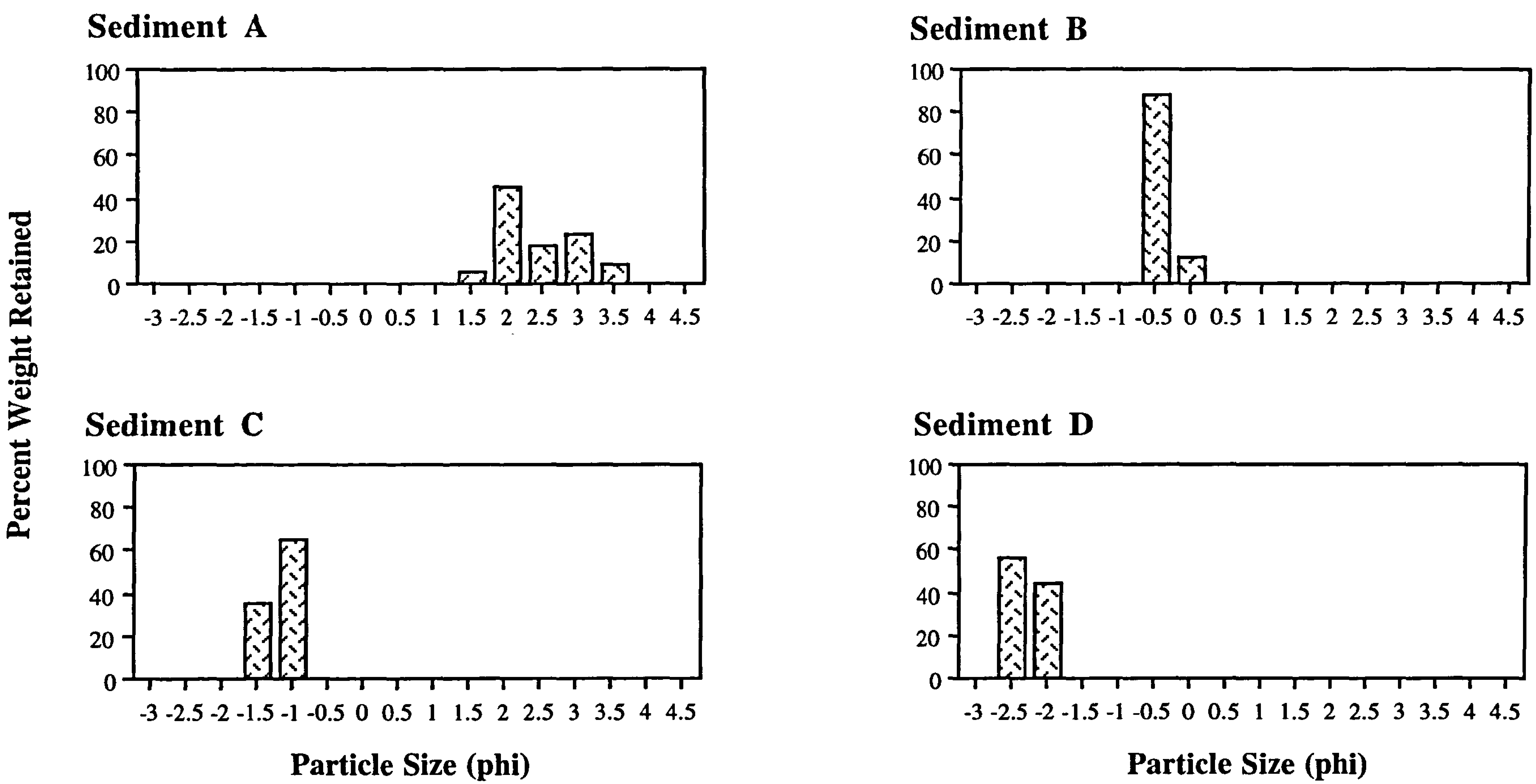


Figure 1.7 Particle size analyses on S1 sediments A, B, C and D. Mean data of three replicate readings. **Top:** right; sediment A (63 μm to 1 mm; 4 ϕ to 0 ϕ), left; sediment B (1 mm to 2 mm; 0 ϕ to -1 ϕ). **Bottom:** right; sediment C (2 mm to 4 mm; -1 ϕ to -2 ϕ), left; sediment D (4 mm to 8 mm; -2 ϕ to -3 ϕ).

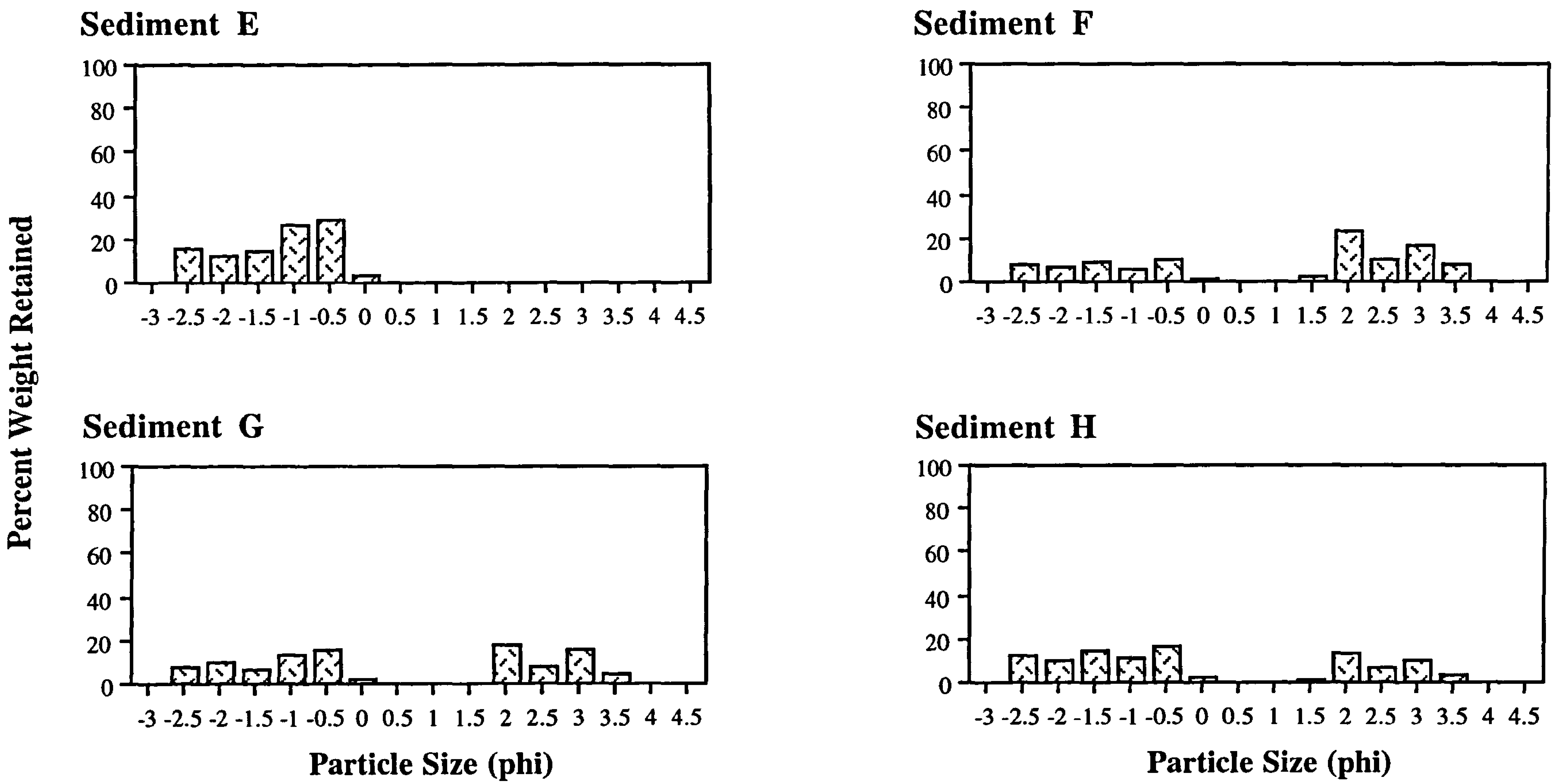


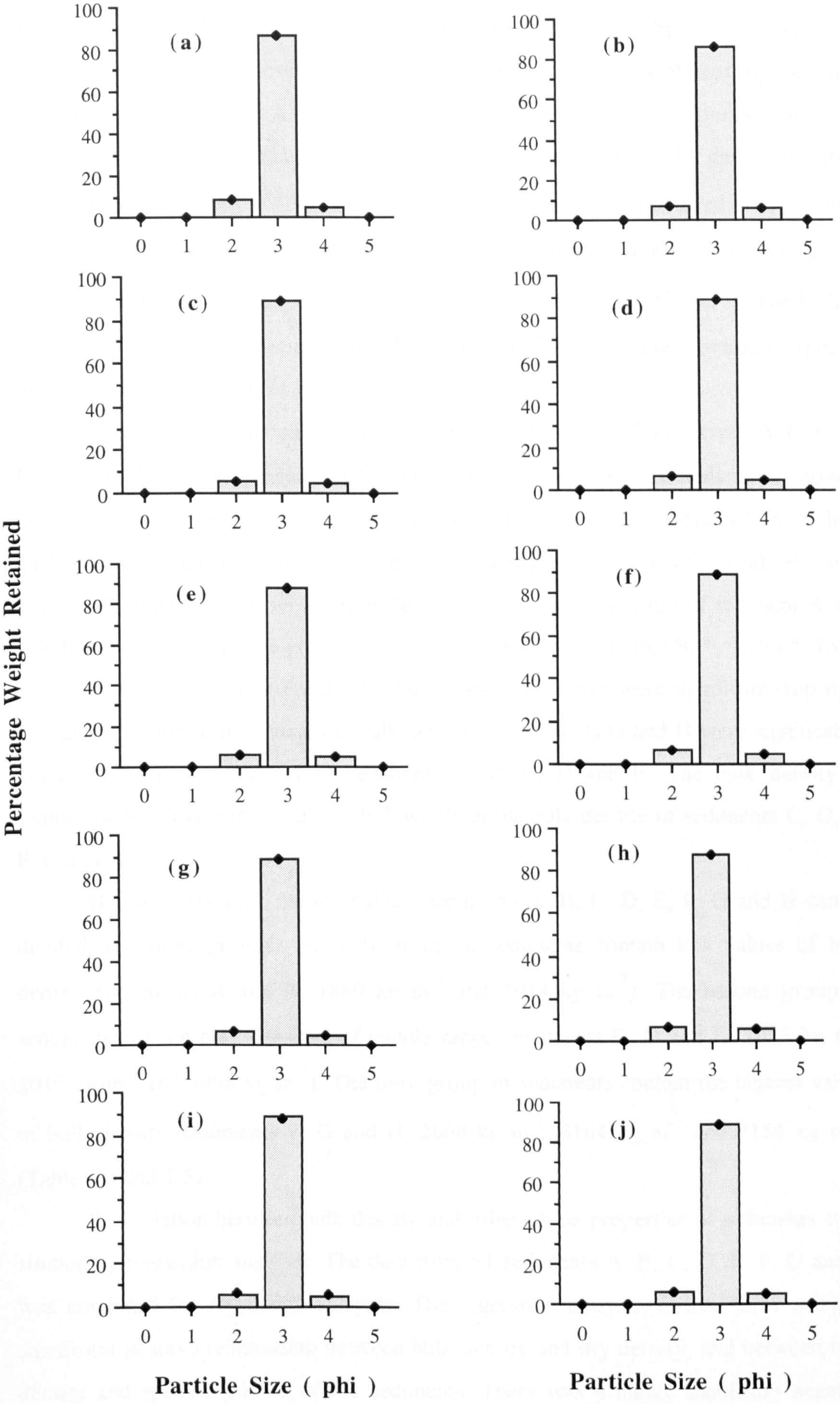
Figure 1.8 Particle size analyses on S1 sediments E, F, G and H. Mean data of three replicate readings. **Top:** right; Sediment E (1 mm to 8 mm; 0 ϕ to -3 ϕ), left; Sediment F (63 μm to 8 mm; 0 ϕ to -3 ϕ). **Bottom:** right; Sediment G (63 μm to 8 mm; 0 ϕ to -3 ϕ), left; Sediment H (63 μm to 8 mm; 0 ϕ to -3 ϕ).

S2 sediment: The grain size parameters obtained by dry sieve analysis on the ten replicate samples of Ardmore sediment (S2) are shown in table 1.3. The results of the analyses show that all the ten replicates were unimodal and well sorted having standard deviation values less than 0.5. The samples were nearly symmetrical and extremely leptokurtic having kurtosis values greater than 3. The frequency distribution curves show a sharp peak having only 5% to 7% grains smaller or greater than the 3.5 ϕ mean grain diameter. Plots of ten replicates are shown in figure 1.9.

Table 1.3 Particle size analyses of ten replicate samples of Ardmore sediment used in permeability and shear strength experiment. Particle size parameters derived from the percentage weight retained on each sieve 1 mm (0ϕ), 500 μm (1ϕ), 250 μm (2ϕ), 125 μm (3ϕ), 63 μm (4ϕ) and on the pan.

Replicate	Mean Size (ϕ)	Sorting	Skewness	Kurtosis
1	3.467	0.3561	-0.2513	4.991
2	3.492	0.3712	-0.3712	4.975
3	3.489	0.3351	-0.1198	6.609
4	3.486	0.3398	-0.1410	6.489
5	3.489	0.3423	-0.1250	6.272
6	3.477	0.3388	-0.2484	6.726
7	3.484	0.3488	-0.2484	6.726
8	3.493	0.3544	-0.1051	5.759
9	3.491	0.3486	-0.0985	6.078
10	3.491	0.3362	-0.1032	6.648
Mean±SD	3.486±0.0082	0.3465±0.0113	-0.1727±0.0897	6.094±0.6525

Figure 1.9 Particle size analyses on S2 sediment. Data from the ten replicates. Sieves used were: 0 ϕ (1 mm), 1 ϕ (500 μm), 2 ϕ (250 μm), 3 ϕ (125 μm), 4 ϕ (63 μm), 5 ϕ (pan).


Percentage Weight Retained
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
0 20 40 60 80 100
0 1 2 3 4 5
Particle Size (phi)
Particle Size (phi)

Phase Relations (Void ratio, Porosity, Dry density, Bulk density, Specific gravity)

The results are presented in table 1.4. The highest values of porosity and void ratio occurred in sediment A (0.4018, 0.6743) and the lowest values of porosity and void ratio occurred in sediment H (0.2808, 0.3943). The highest value of dry density occurred in sediment H (1873 kg m^{-3}) and the lowest value of dry density occurred in sediment A (1487 kg m^{-3}). The highest value of bulk density occurred in sediment G (2164 kg m^{-3}) and the lowest value of bulk density occurred in sediment A (1889 kg m^{-3}). The highest value of specific gravity occurred in sediment G (2.647) and the lowest value of specific gravity occurred in sediment B (2.432).

The differences in bulk density and void ratio between sediment types A, B, C, D, E, F, G and H were statistically analysed by a series of 1×2 one way analyses of variance in which pairs of sediment were compared in turn. The F ratios obtained from these analyses are presented in table 1.5. Out of the twenty eight F ratios for void ratio only five were significant (bottom left triangle of F ratios). The void ratio of sediment A was significantly higher than the void ratios of sediments F, G and H (8.150 *, 9.760 *, 15.79 *). Out of the twenty eight F ratios for bulk density seventeen were significant (top right triangle of F ratios). In general the bulk density of sediments G and H were significantly higher than the bulk density of sediments A, B, C, D and E. The bulk density of sediments A and B were significantly lower than the bulk density of sediments C, D, E, F, G and H.

Based on the bulk density values, sediments A, B, C, D, E, F, G and H can be divided into three groups. The first group of sediments contain low values of bulk density (sediments A and B; 1889 kg m^{-3} and 1914 kg m^{-3}). The second group of sediments contain bulk densities of middle range (sediments C, D and E; 1985 kg m^{-3}, 2010 kg m^{-3} and 1998 kg m^{-3}). The third group of sediments contain the highest values of bulk density (sediments F, G and H; 2068 kg m^{-3}, 2164 kg m^{-3} and 2154 kg m^{-3}) (Table 1.4 and 1.5).

The relation between bulk density and other phase properties of sediments were studied by regression analyses. The data from S1 sediments A, B, C, D, E, F, G and H was combined for regression analyses. The regression analyses results show a highly significant positive relationship between bulk density and dry density, and between bulk density and specific gravity of the sediments. There was a highly significant negative relationship between bulk density and void ratio, and bulk density and porosity (Fig. 1.10). Bulk density was positively correlated with the coefficient of uniformity ($Y = 15 X + 1944$, $F_{1, 23} = 42.75$ $P < 0.001$ ***).

Table 1.4 Geotechnical properties of S1 sediments. Mean±SD of three replicate readings. Sediments, A, B, C, D, E, F, G and H (see table 1 1). Vv = volume of void, Vs = volume of solid, V = total volume, Ws = weight of solid, W = total weight and γ_w = density of water.

Sediment	Porosity n = Vv/V	Void ratio e = Vv/Vs	Dry density γ_d = Ws/V (kg m^{-3})	Bulk density γ_b = W/V (kg m^{-3})	Specific gravity Gs = Ws/(Vs×γ_w)
A	0.4018±0.0290	0.6743±0.0820	1487.0±71.76	1889.0±43.14	2.486
B	0.3618±0.0123	0.5670±0.0303	1552.3±29.77	1914.0±17.35	2.432
C	0.3513±0.0073	0.5417±0.0172	1633.7±18.45	1984.7±11.24	2.518
D	0.3484±0.0245	0.5363±0.0569	1661.3±62.36	2009.7±38.18	2.550
E	0.3575±0.0125	0.5570±0.0300	1640.7±31.94	1998.3±19.09	2.554
F	0.3282±0.0333	0.4910±0.0752	1740.0±86.26	2068.0±53.11	2.590
G	0.2934±0.0544	0.4210±0.1140	1870.7±143.6	2164.0±89.82	2.647
H	0.2808±0.0456	0.3943±0.0904	1872.7±119.1	2153.7±72.95	2.604

Table 1.5 Statistical analyses of the geotechnical properties (bulk density and void ratio) between the sediments A, B, C, D, E, F, G and H. Pairs of sediment compared in turn by 1×2 one way analyses of variance (DF=1, 4 and n=3). Table gives F ratios from these analyses. Top right triangle: bulk density (kg m^{-3}). Lower left triangle. void ratio. Probability 0.05>P>0.01*, 0.01>P>0.001**, P<0.001***.

Sediment	A	B	C	D	E	F	G	H
A		0.8700	13.82 *	13.16 *	16.12 *	20.53 *	22.85 **	29.26 **
B	4.520		35.06 **	15.16 *	32.07 **	22.97 **	22.41 **	30.65 **
C	7.520	1.580		1.180	1.140	7.070	11.78 *	15.73 *
D	5.740	0.680	0.020		0.210	2.390	7.500	9.18 *
E	5.420	0.160	1.590	0.310		4.570	9.770 *	12.73 *
F	8.150 *	2.640	1.290	0.690	1.990		2.540	2.700
G	9.760 *	4.590	3.280	2.460	3.990	0.790		0.020
H	15.79 *	9.830 *	7.690	5.300	8.740 *	2.030	0.100	

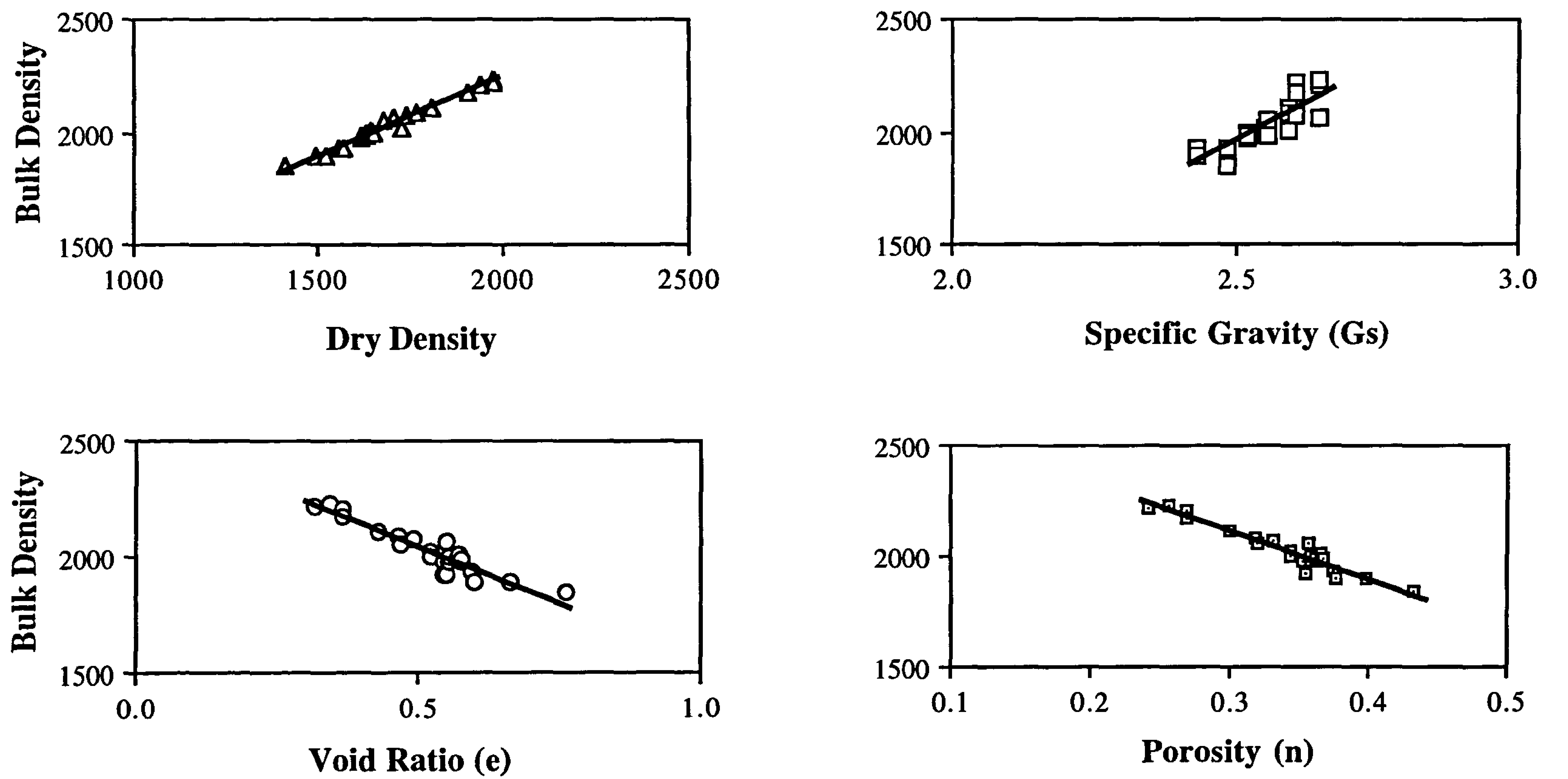


Figure 1.10 Combined data of S1 sediments A, B, C, D, E, F, G and H. **Top**: Left; relation between bulk density (kg m^{-3}) and dry density (kg m^{-3}) of sediments ($Y = 0.702 X + 842$, $F_{1,23} = 2500.3$ $P < 0.001$ ***). Right; relation between bulk density (kg m^{-3}) and specific gravity (Gs) of sediments ($Y = 1369 X - 1465$, $F_{1,23} = 59.33$ $P < 0.001$ ***). **Bottom**: Left; relation between bulk density (kg m^{-3}) and void ratio (e) of sediments ($Y = -970 X + 2530$, $F_{1,23} = 66.63$ $P < 0.001$ ***). Right; relation between bulk density (kg m^{-3}) and porosity (n) of sediments ($Y = -2196 X + 2770$, $F_{1,23} = 213.41$ $P < 0.001$ ***).

1.2.2 Permeability Experiment using S2 Sediment

The results of the permeability experiment are shown in table 1.6. The data were statistically analysed by three-way, two-way and one-way analyses of variance. The three and two way analyses of variance showed highly significant interaction effects (Appendix I: Table 3.1 and 3.4) and so the following statements are based on one-way analyses of variance. The permeability experiment was designed to test three hypotheses as follows (see materials and methods):

(a) *Hypothesis 1* Does permeability vary with diameter of tube?

Six 1 × 3 one way analyses of variance were conducted on the data, three on the P_1 data and three on the P_2 data. The first of the three compared permeability coefficients between the three tube diameters for the 450 mm - 400 mm water head. The second of the three compared permeability coefficients between the three tube diameters the 400 mm - 350 mm water head. The third of the three compared permeability coefficients between the three tube diameters for the 350 mm - 300 mm water head. This was done for the 100 mm sediment depth and for the 200 mm sediment depth. The results of these six 1×3 one way analyses of variance are shown in table 1.7. All three analyses were significant for the 100 mm sediment. Only one of the three analyses was significant for the 200 mm sediment. It can be concluded that permeability decreases significantly with increasing tube diameter for a 100 mm sediment length. The effect is probably not significant for the 200 mm sediment length.

(b) *Hypothesis 2:* Does permeability vary with depth of sediment?

Differences in permeability between the 100 mm sediment length and the 200 mm sediment length were compared by nine 1 × 2 one way analysis of variance, one for each water head drop and each tube diameter. The analyses are shown in table 1.8. All except one of the analyses were statistically significant. This means that in eight out of the nine comparisons the permeability of the 100 mm sediment length was higher than the permeability of the 200 mm sediment length.

(c) *Hypothesis 3*: Does permeability vary with head of water?

Differences in permeability between the different heads of water were tested by six 1×3 one way analysis of variance, three for the 100 mm sediment length and three for the 200 mm sediment length. The analyses were shown in table 1.9. Four out of the six analyses were not significant. This suggests that the permeability does not change dramatically with different water heads. The remaining two analyses were only significant at a probability of 0.05. Furthermore in the first one of these (tube diameter 25 mm, sediment length 200 mm) the permeability fell with decreasing water head, and in the second (tube diameter 54 mm, sediment length 200 mm) the permeability increased and then decreased.

Table 1.6 Permeability experiment. Effect of tube diameter, sediment length and water head on the permeability coefficient (k) (mm. s^{-1}). Mean±SD of three replicate readings at each head.

Tube Diameter (mm)	Head (h_1 - h_2) (mm)	Sediment length (mm).	
		P_1 = 100 mm	P_2 = 200 mm
20	450 - 400	0.1430 ± 0.0044	0.1141 ± 0.0145
	400 - 350	0.1466 ± 0.0028	0.1007 ± 0.0107
	350 - 300	0.1413 ± 0.0034	0.1033 ± 0.0011
25	450 - 400	0.1197 ± 0.0019	0.0941 ± 0.0019
	400 - 350	0.1202 ± 0.0011	0.0950 ± 0.0071
	350 - 300	0.1164 ± 0.0018	0.0901 ± 0.0006
54	450 - 400	0.1045 ± 0.0039	0.0999 ± 0.0011
	400 - 350	0.1082 ± 0.0009	0.1027 ± 0.0010
	350 - 300	0.1049 ± 0.0011	0.1005 ± 0.0006

Table 1.7 Statistical analyses for the differences in the permeability coefficients (k) between the three tube diameters (20 mm, 25 mm and 54 mm). F ratios were obtained by 1×3 one-way analyses of variance comparing three different tube diameters (20 mm/25 mm/54 mm) with 3 replicate readings per cell for sediment length 100 mm (core P_1) and in sediment length 200 mm (core P_2). Summary table from appendix I: table 3.5. Probability: 0 05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***.

Sediment length (mm)	Head (h_1 - h_2) (mm)	DF	F ratio	P
P_1 = 100	450 - 400	2, 6	157.6	< 0.001 ***
	400 - 350	2, 6	558.8	< 0.001 ***
	350 - 300	2, 6	483.3	< 0.001 ***
P_2 = 200	450 - 400	2, 6	4.810	0.057 ns
	400 - 350	2, 6	1.390	0.320 ns
	350 - 300	2, 6	7.860	0.021 *

Table 1.8 Statistical analyses for the differences in the permeability coefficients (k) between the two sediment lengths (core P_1 = 100 mm and core P_2 = 200 mm). F ratios were obtained by 1×2 one-way analyses of variance comparing two different sediment lengths (100 mm/200 mm) with 3 replicate readings per cell for tube diameters 20 mm, 25 mm and 54 mm. Summary table from appendix I: table 3.6 and 3.7. Probability 0.05>P>0.01*, 0.01>P>0.001**, P<0.001***. ns = not significant.

Tube Diameter	Head (h_1 - h_2) (mm)	DF	F ratio	P
20 mm	450 - 400	1, 4	11.02	0.029 *
	400 - 350	1, 4	51.37	0.002 **
	350 - 300	1, 4	348.1	< 0.001 ***
25 mm	450 - 400	1, 4	279.9	< 0.001 ***
	400 - 350	1, 4	470.6	< 0.001 ***
	350 - 300	1, 4	569.3	< 0.001 ***
54 mm	450 - 400	1, 4	3.800	0.123 ns
	400 - 350	1, 4	44.80	0.003 **
	350 - 300	1, 4	36.38	0.004 **

Table 1.9 Statistical analyses for the differences in the permeability coefficients (k) between the three heads of water (H_1 = head of water 450 to 400 mm, H_2 = head of water 400 to 350 mm, H_3 = head of water 350 to 300 mm). F ratios were obtained by 1×3 one-way analyses of variance comparing three different head of water (H_1/ H_2/ H_3) with three replicate readings per cell. Summary table from appendix I: table 3.8.

Tube Diameter	DF	F ratio	P
a) Sediment length 100 mm			
20 mm	2, 6	1.730	0.2550 ns
25 mm	2, 6	4.810	0.0570 ns
54 mm	2, 6	2.040	0.2110 ns
b) Sediment length 200 mm			
20 mm	2, 6	1.390	0.3200 ns
25 mm	2, 6	9.180	0.0150 *
54 mm	2, 6	7.860	0.0210 *

1.2.3 Packing and Shear strength Experiment using S2 Sediment

The results and the analyses of the experiments are shown in table 1.10 to 1.14 and in figures 1.11 to 1.13. The results from the cone penetrometer and the vane test are shown in table 1.10. The effect of packing amplitude on the bulk density, dry density, and on the void ratio is presented in table 1.11. The packing and shear strength experiment was designed to test three hypotheses as follows (see materials and methods):

(a) *Hypothesis 1*: Does packing effect sediment bulk density, dry density and void ratio?

Bulk density and dry density increases as the amplitude increases. The void ratio decreases as the amplitude increases. These effects are shown in table 1.11 and figure 1.11 and statistically analysed in table 1.12. The data were statistically analysed by three 1×7 one way analyses of variance (Table 1.12). Bulk density and dry density significantly increases with increasing amplitude of packing. Void ratio decreased significantly with increasing amplitude of packing.

(b) *Hypothesis 2* :Do bulk density, dry density and void ratio affect shear strength as packing increases?

Shear strength increases with packing amplitude. This is shown by the two highly significant 1×7 one way analyses of variance (Table 1.13). Shear strength increases as bulk density and dry density increases with increased packing density. Shear strength decreases as void ratio increases. These effects are shown in figure 1.12 and were statistically analysed in table 1.13. Shear strength data were statistically analysed by two 1×7 one way analyses of variance. The shear strength significantly increases with increasing amplitude of packing as shown in table 1.14. From the statement above in (a) about the relationship between the amplitude of packing and the bulk density, dry density and void ratio it can be concluded that shear strength increases significantly with increasing bulk density and dry density and that shear strength decreases significantly with increasing void ratio. However the above relationships of shear strength (kN m^{-2}) with bulk density (kg m^{-3}), dry density (kg m^{-3}), void ratio and porosity are non linear (Fig. 1.12).

(c) *Hypothesis 3*: Does shear strength measured by a cone differ from the shear strength measured by a vane, and how does shear strength measured by small cone differ to shear strength measured by large cone?

Shear strength measured by the cone increases with increasing shear strength measured by vane. However the above relationships of shear strength was non linear (Fig. 1.13).

Shear strength measured by the vane was higher than shear strength measured by cone at each amplitude of packing. These effects are shown in table 1.10 and figure 1.14. The mechanism by which the two methods determined shear strength and the shear strength values obtained from two methods at an amplitude of packing 3 are shown in figure 1.14. The cylinder shear strength was determined by using the 19 mm and 33 mm vane at depth 30 mm and 50 mm respectively. The average shear strength was measured by using the 10 gm cone and 60 gm cone at depth 5.73 mm and 10.03 mm respectively. Shear strength of S2 sediment at amplitude of packing 1 to 2.5 was too low to be measured by a small vane and at amplitude of packing 1 to 2 was too low to be measured by a large cone.

Shear strength measured by the large cone was higher than shear strength measured by using the small cone at each amplitude of packing. Differences in shear strength obtained by using large cone and small cone were statistically analysed seven 1 × 2 one-way analyses of variance. In six out of the seven comparisons the shear strength measured by the large cone were significantly higher than shear strength measured by using the small cone (Table 1.14).

Table 1.10 Effect of packing on shear strength. C_1 = replicate core 1 of packing and C_2 = replicate core 2 of packing. Amplitudes 1 to 4 represent amplitudes on the Endecott Octagon sieve shaker (see text).

Amplitude	C_1		C_2	
	Small cone $kN\ m^{-2}$	Small Vane $kN\ m^{-2}$	Large cone $kN\ m^{-2}$	Large Vane $kN\ m^{-2}$
1	0.3536 0.3924 0.3537	NR	0.6046 0.7601 0.5886	NR
1.5	0.3536 0.4636 0.4258	NR	0.7717 0.8476 0.7601	NR
2	0.3924 0.4258 0.5224	NR	0.7601 0.7958 0.7836	NR
2.5	0 4379 0.4773 0.5067	NR	0.7836 0.8083 0.8476	0.458
3	0.8163 0.6561 0.5742	1.211	1.379 1.248 1.324	12.59
3.5	2.155 1.909 2.027	16.15	1.565 1.635 1.969	21.64
4	2.155 1.909 2.815	16.56	9.171 7.508 9.171	22.79

NR = not recorded (shear strength was too low to be measured by a vane)

Table 1.11 Effect of packing on geotechnical parameters (bulk density, dry density and void ratio) Amplitudes 1 to 4 represent measured packing (see text). C_1 = replicate core 1 of packing and C_2 = replicate core 2 of packing.

Amplitude	C_1			C_2		
	Bulk Density $kg\ m^{-3}$	Dry Density $kg\ m^{-3}$	Void Ratio	Bulk Density $kg\ m^{-3}$	Dry Density $kg\ m^{-3}$	Void Ratio
1	1979	1496	0.9373	1970	1489	0.9255
1.5	1983	1506	0.9137	1979	1502	0.9137
2	2003	1531	0.8953	2026	1569	0.8398
2.5	2034	1598	0.7733	2049	1611	0.7834
3	2107	1674	0.7634	2107	1678	0.7535
3.5	2145	1725	0.7246	2142	1719	0.7341
4	2149	1732	0.7152	2152	1735	0.7152

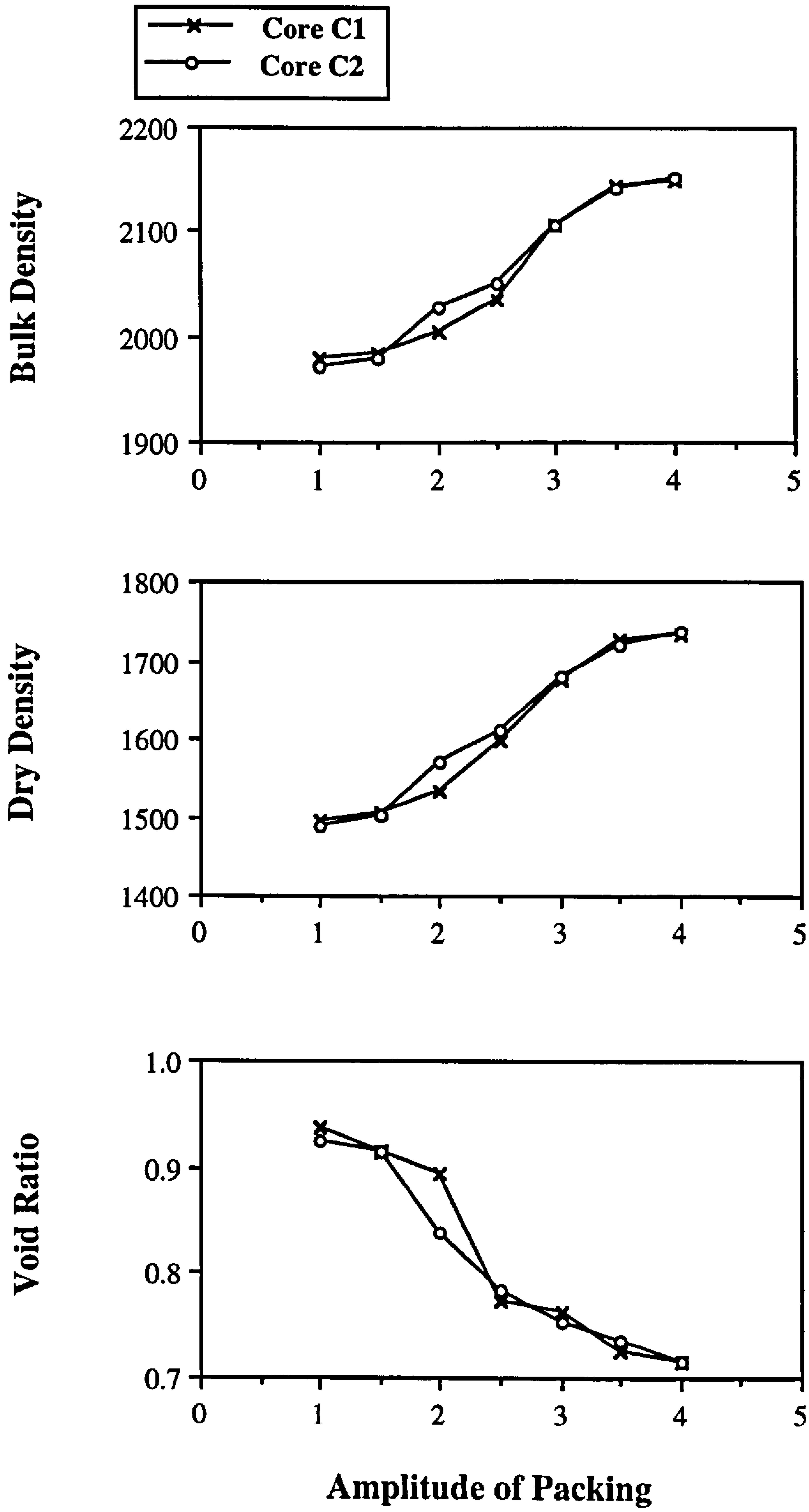


Figure 1.11 S2 sediment. **Top**: Relationship between the amplitude of packing and bulk density (kg m^{-3}). **Middle**: Relationship between the amplitude of packing and dry density (kg m^{-3}). **Bottom**: Relationship between the amplitude of packing and void ratio. Two replicate cores of packing C_1 and C_2 at an each amplitude of packing 1, 1.5, 2, 2.5, 3, 3.5 and 4.

Table 1.12 Statistical analyses for the differences in the geotechnical parameters (bulk density, dry density and void ratio) of S2 sediment between the amplitude (1, 1.5, 2, 2.5, 3, 3.5 and 4) of packing. F ratios were obtained by three 1×7 one-way analyses of variance (geotechnical parameter × seven different amplitude of packing). Summary table from appendix I: table 4.1 (n=2). Probability 0.05>P>0.01*, 0.01>P>0.001**, P<0.001***. ns = not significan.

Parameters	DF	F ratio	P
Bulk Density	6, 7	179.0	< 0.001 ***
Dry Density	6, 7	163.2	< 0.001 ***
Void Ratio	6, 7	63.65	< 0.001 ***

Table 1.13 Statistical analyses for the differences in the shear strength between the amplitude (1, 1.5, 2, 2.5, 3, 3.5 and 4) of packing. Shear strength was measured by using small cone at core C_1 and large cone on core C_2. F ratios were obtained by two 1×7 one-way analyses of variance (shear strength × seven different amplitude of packing). Summary table from appendix I: table 4.2 (n=3).

Shear Strength	DF	F ratio	P
Core C_1	6, 14	56.03	< 0.001 ***
Core C_2	6, 14	179.1	< 0.001 ***

Table 1.14 Relation between the shear strength measured by using the small cone and large cone. F ratios were obtained by seven 1×2 one-way analyses of variance (amplitude at which shear strength was measured × shear strength measured by using the small cone and large cone). Summary table from appendix I: table 4.3 (n=3).

Amplitude	Shear Strength (kN m^{-2})		D F	F ratio
	Small Cone	Large Cone		
1	0.3666±0.0224	0.6511±0.0948	1 4	25.63 **
1.5	0.4143±0.0559	0.7931±0.0475	1 4	79.98 **
2	0.4469±0.4316	0.7798±0.0182	1 4	68.06 **
2.5	0.4739±0.0345	0.8132±0.0323	1 4	154.5 ***
3	0 6822±0.1231	1.317±0.0658	1 4	62.02 **
3.5	2.030±0.1230	1.723±0.216	1 4	0.099 ns
4	2.293±0.4930	8.617±0.960	1 4	105.1 **

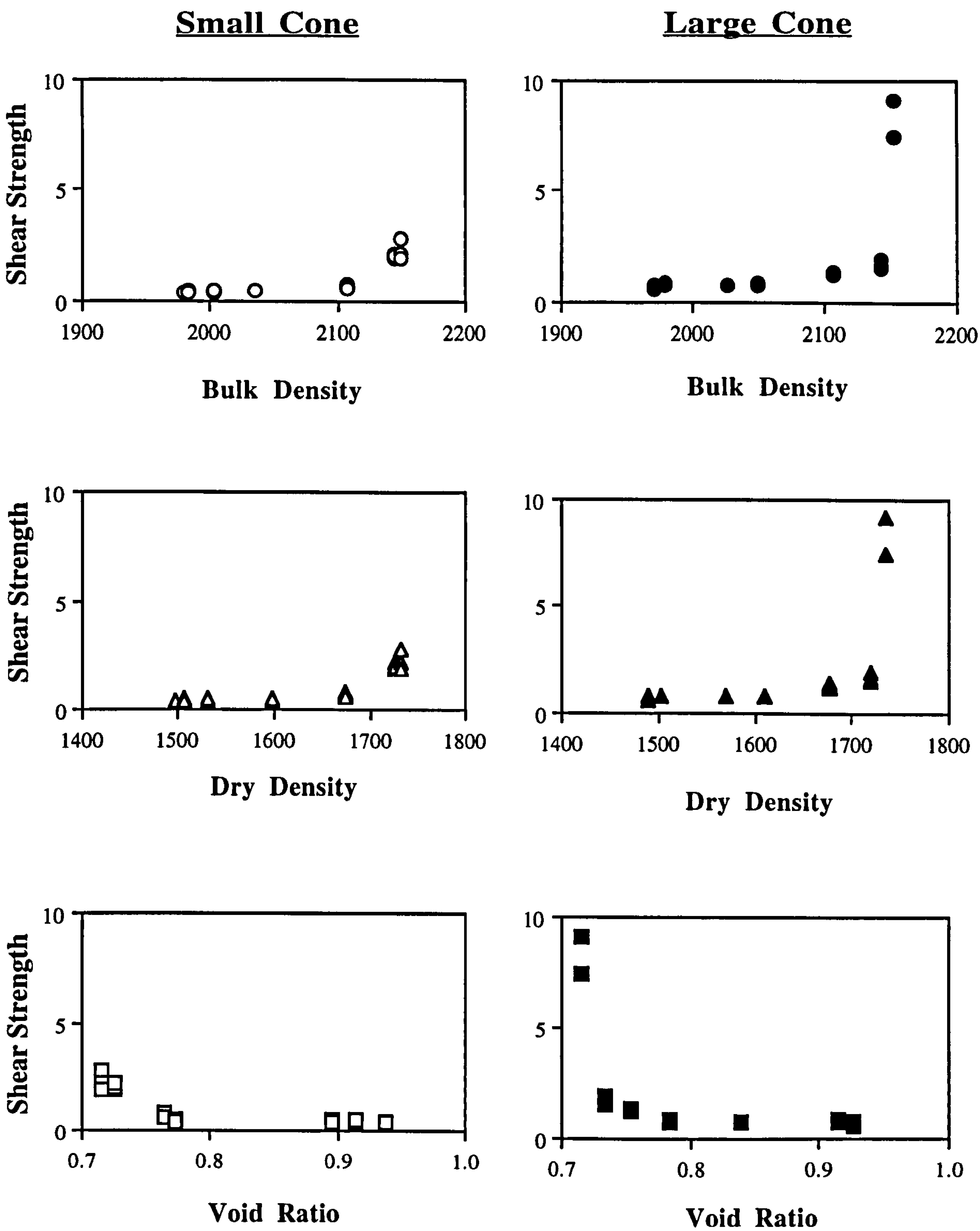


Figure 1.12 Packing experiment. Relation between geotechnical properties of S2 sediment. Left: shear strength measured by using a small cone in core of packing C_1. Right: shear strength measured by using a large cone in core of packing C_2. Top: relationship between shear strength (kN m^{-2}) and dry density (kg m^{-3}). Middle: relationship between shear strength (kN m^{-2}) and bulk density (kg m^{-3}). Bottom: relationship between shear strength (kN m^{-2}) and void ratio.

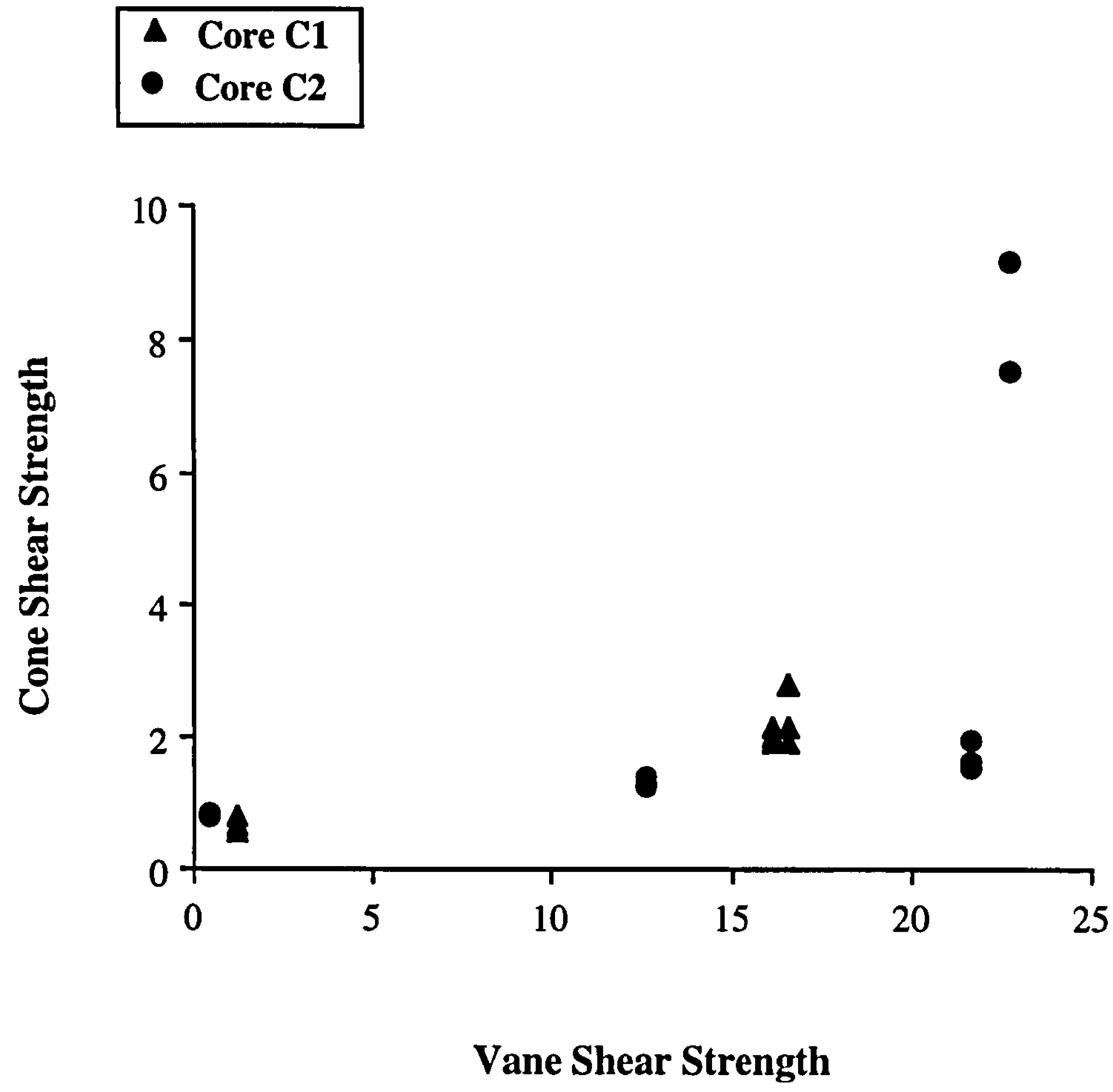


Figure 1.13 Combine data from core of packing C_1 and core of packing C_2. Relation between shear strength measured by using the vane (kg m^{-3}) and shear strength measured by using the cone (kg m^{-3}).

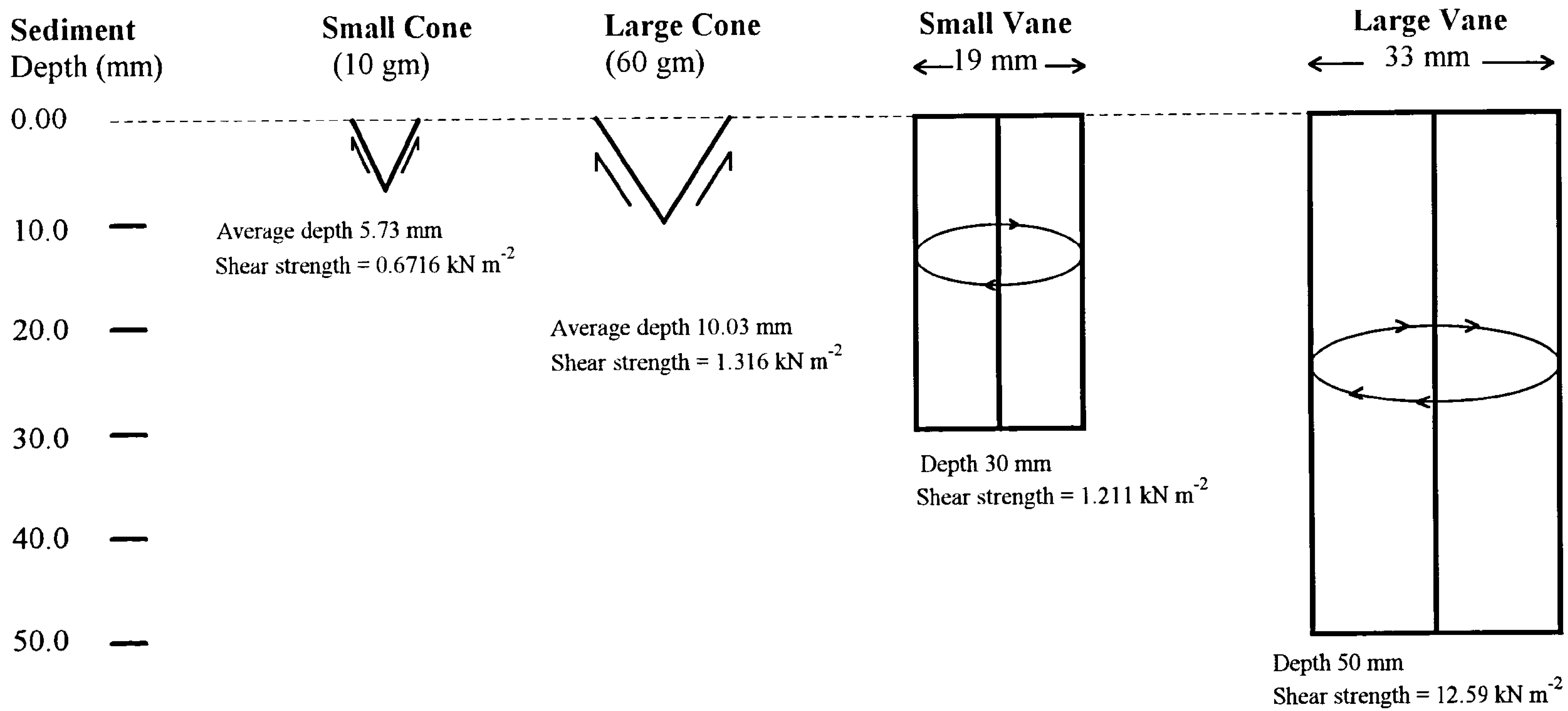


Figure 1.14 Diagram illustrating the depth of penetration of cones and vanes into sediment. Vane penetration are exact where as cone penetration are average for amplitude 3 of packing.

SECTION 2: Effect of Size and Shape of Container and Sediment Types on Avalanching

2.1 MATERIALS AND METHODS

2.1.1 Design of Avalanching Experiment 1

Avalanching experiment 1 was designed to quantify the effects of orientation of container, shape of container, volume of sediment, and particle size on first and second angles of avalanche and angles of repose. The objectives are stated as the following hypotheses.

Hypothesis 1:
Does the orientation of the rectangular container affect the angles of avalanche and angles of repose?

Hypothesis 2:
Does the shape of the container affect angles of avalanche and angles of repose?

Hypothesis 3:
Does the volume of sediment affect angles of avalanche and angles of repose?

Hypothesis 4:
Do the angles of avalanche and angles of repose vary with particle size?

Two different shapes of container were used, one was rectangular (size 15 cm × 7.5 cm, Height = 40 cm) and the other was circular (ID = 9.4 cm) in shape (Fig. 2.1). The rectangular container was first used by placing its width (7.5 cm) parallel to the inclined surface (slope) and then its length (15 cm) was placed parallel to the inclined surface (Fig. 2.2). Two volumes of sediment were used (200 ml and 400 ml). Four sediments of different particle size were used: sediment A (63 μm to 1 mm), sediment B (1 mm to 2 mm), sediment C (2 mm to 4 mm) and sediment D (4 mm to 8 mm). Dry sediments were used throughout. Three replicate readings were taken for each treatment.

(Note: A, B, C and D are the fractions of the S1 sediment described in Section 1.1.2, see table 1.1)

2.1.2 Container and Inclinometer Design

Glass rectangular containers (internal size 15 cm × 7.5 cm, depth 40 cm) in which the sediment was to be avalanched were constructed by bonding 4 mm thick glass sheets with silicone sealant transparent gel. The glass containers were then graduated by sticking a self adhesive transparent scale on the outer walls.

Glass circular containers (internal diameter 9.4 cm) were constructed using 4 mm thick glass tube. The bottom of the glass tube was sealed by bonding a 10 cm diameter circular PVC disc with silicone sealant.

An inclinometer for avalanching the sediments was constructed (Fig. 2.3). It consisted of a lever arm, one end of which rested on a wooden sliding block and the other end of which rested on an Archimedes screw. The glass container was held on the lever arm by a wooden block and retained by a tight length of cord (Fig. 2.3; 3 and 5).

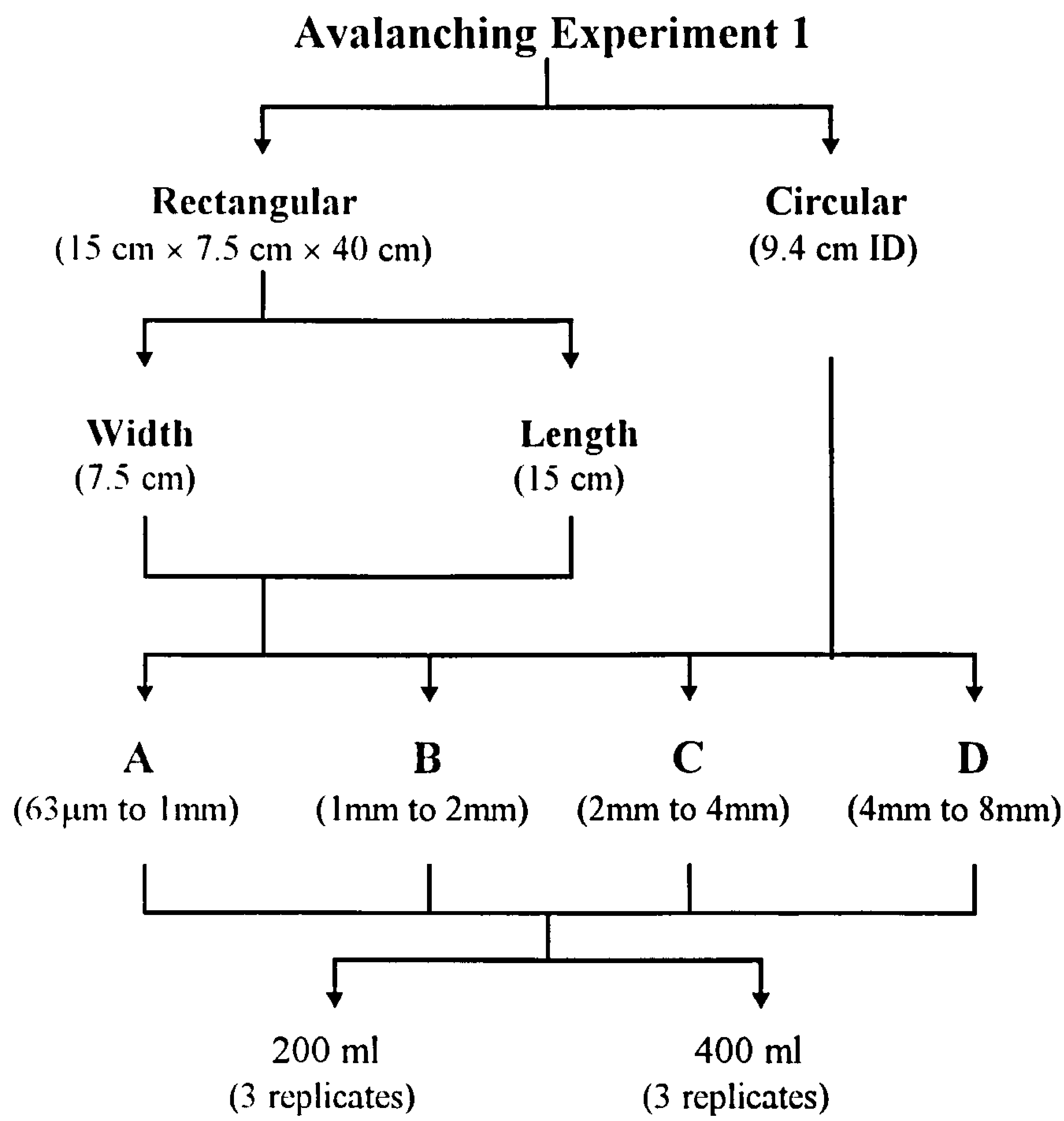


Figure 2.1 Avalanching experiment 1. Rectangular container (size 15 cm × 7.5 cm Height = 40 cm) and circular container (ID = 9.4 cm). The rectangular container first used by placing its width (7.5 cm) parallel to the inclined surface and then its length (15 cm) was placed parallel to the inclined surface. A, B, C and D = S1 sediments A, B, C and D. 200 ml and 400 ml = sediment volume 200 cm^{-3} and sediment volume 400 cm^{-3}. Three replicate readings were taken for each sediment volume.

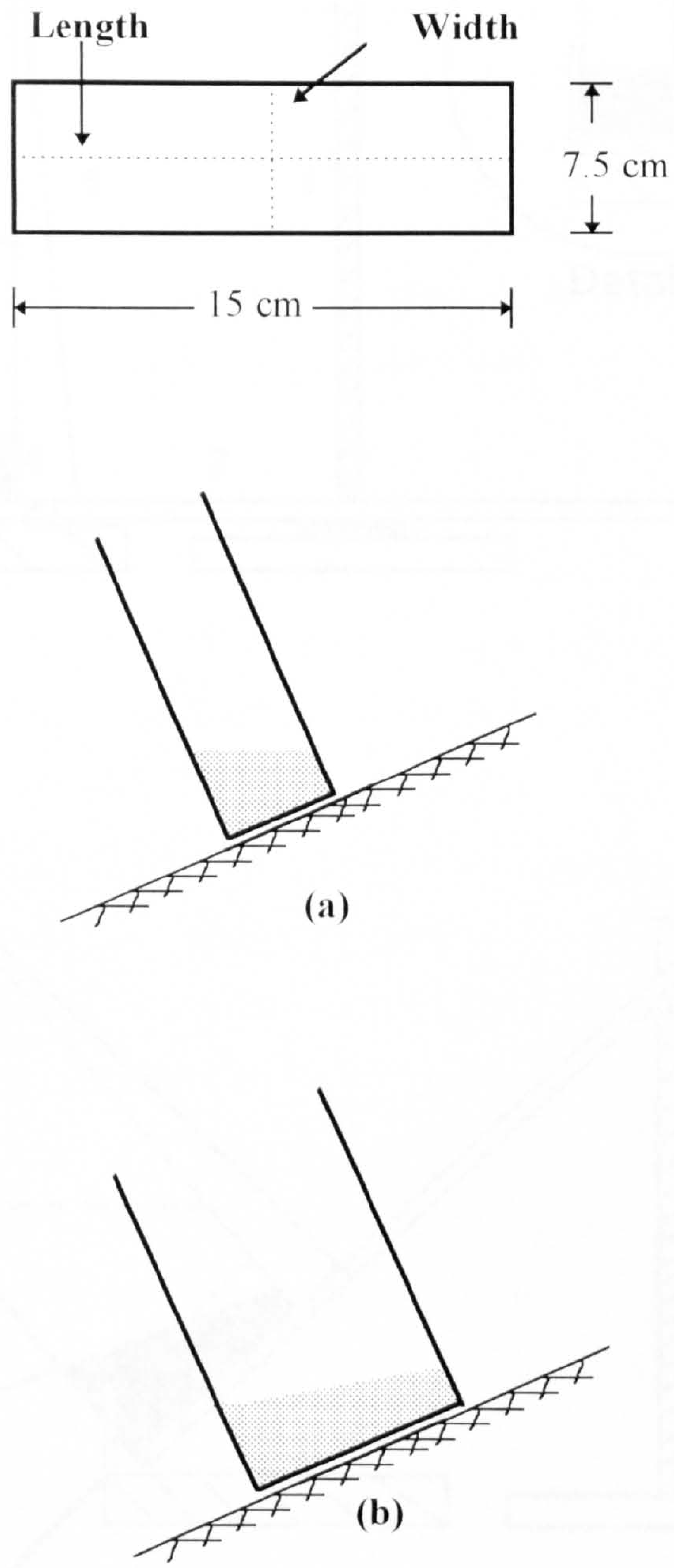


Figure 2.2 Avalanching experiment 1. Rectangular container. a) Rectangular container's width (7.5 cm) parallel to the inclined surface. b) Rectangular container's length (15 cm) parallel to the inclined surface.

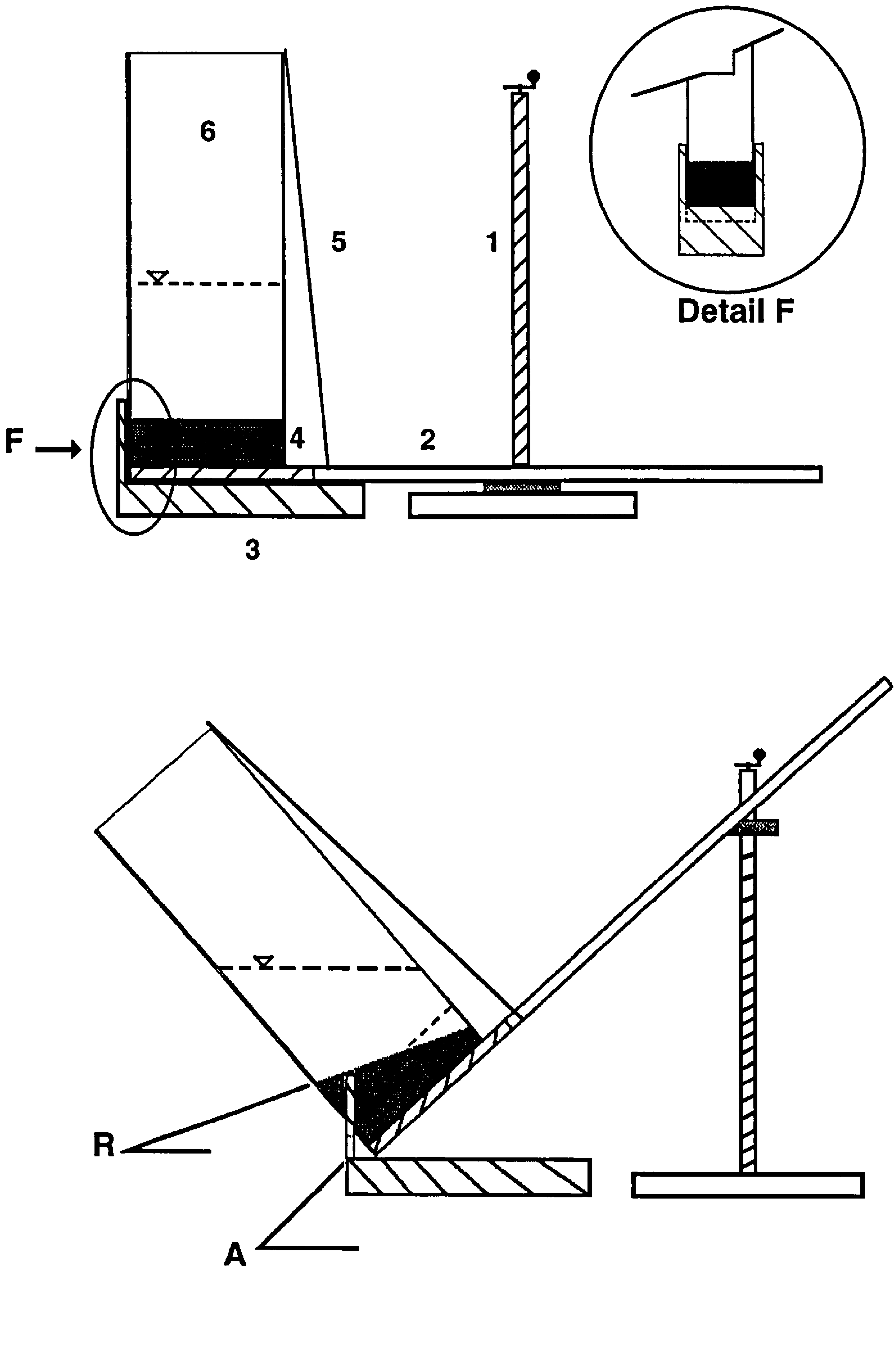


Figure 2.3 Inclinometer design. **Top**: Inclinometer before an avalanche. 1, Archimedes screw; 2, lever arm; 3, U frame and sliding block; 4, container holder; 5, cord; 6, glass container with sediment and water. Detail F = magnified side view of equipment as seen from F. **Bottom**: Inclinometer after an avalanche. A= angle of avalanche. R= angle of repose.

2.1.3 Conduct of Experiment

A total of twenty four sediment containers were set up. These were divided into three main groups each containing eight containers (Fig. 2.1). The first group of eight containers consisted of the rectangular shape container whose width (7.5 cm) was parallel to the inclined surface, the second group consisted of the rectangular shape container whose length (15 cm) was parallel to the inclined surface, and the third group consisted of the circular shaped container. In each of the three main groups two containers were set up for each of the sediment types A, B, C and D. One of these contained 200 ml and the other contained 400 ml of sediment.

The detailed procedure was as follows. A measured volume of dry sediment was added to the container. The sediment in the container was mixed and levelled by a metal rod, and then left to stand for 15 minutes prior to being transfered to the inclinometer. The sediment in the container was avalanched and the first angle of avalanche (A_1) and the first angle of repose (R_1) were then recorded. The angle of avalanche is the angle at which the slope begins to avalanche. The inclination of the slope after an avalanche, once avalanching has ceased in known as the angle of repose (see figure 2.3). The sediment in the container was then avalanched a second time, and the second angle of avalanche (A_2), second angle of repose (R_2) were measured. The container was then taken off the inclinometer, and the sediment mixed and levelled, and left to stand for 15 minutes as previously. The container was then put back on the inclinometer and a second set of readings were taken. This process was repeated a third time. Three replicate sets of readings were therefore obtained.

2.1.4 Avalanching Procedure

At the end of the designated time of 15 minutes, the depth of the sediment was recorded. This was done at three points along the length of the container and at one point along the width of the container. This gave eight readings in total. The container was then carefully transferred to the inclinometer (Fig. 2.3). The inclinometer was then gently raised at a rate of 0.5 to 0.8 degrees per second until avalanching occurred. This was done by turning the Archimedes screw on which the lever arm rested. The first angle of avalanche (A_1) and the first angle of repose (R_1) were then recorded using a protractor that read to an accuracy of 0.1°. The duration of the first avalanche (T_1) in seconds, and the depth (mm) of sediment after the avalanche were also recorded. The depth was recorded at the same six positions along the lengths of the container as previously. It was not possible to record the two depths along the widths of the container because they were obscured by the supports of the container. The sediment in the container was then avalanched a second time, and the second angle of avalanche (A_2), second angle of repose (R_2), depths of sediment and the duration of second avalanche (T_2) were recorded. A corrected value A_2' for the second angle of avalanche was calculated by using the following relationship $A_2'=(A_2-A_1)+R_1$. This is the accepted procedure for calculating the true second angle of avalanche (see Meadows *et al.* 1994). From here on, the second angle of avalanche refers to the true corrected second angle of avalanche (A_2').

The factor of safety and angle of dilatation after an avalanche were calculated as follows (For detail see appendix II):

$$\text{Factor of Safety} = \frac{\text{Tan (A)}}{\text{Tan (R)}} \qquad \text{---(2.1)}$$

$$\text{Angle of Dilatation} = A - R \qquad \text{---(2.2)}$$

Where A = angle of avalanche, R = angle of repose

2.2 RESULTS

The results and the analyses of avalanching experiment 1 are shown in table 2.1 to table 2.11. The mean±SD values of the three replicate readings for first angles of avalanche (A_1) and first angles of repose (R_1) are presented in table 2.1 and the mean±SD values of three replicate readings for the second angles of avalanche (A_2') and second angles of repose (R_2) are presented in table 2.2. The statistical analyses on angles of avalanche and repose are shown in table 2.3 to table 2.10.

Factors of safety were calculated from the first angles of avalanche (A_1) and repose (R_1), and from the second angles of avalanche (A_2') and repose (R_2) and mean±SD data of the three replicate readings for factors of safety are presented in table 2.11.

With this background the results described below are divided into four parts. The first part (2.2.1) deals with hypothesis 1, the second part (2.2.2) deals with hypothesis 2, the third part (2.2.3) deals with hypothesis 3, and the fourth part (2.2.4) deals with hypothesis 4.

2.2.1 Hypothesis 1: Does the orientation of the rectangular container affect the angles of avalanche and angles of repose?

(a) *First angles of avalanche (A_1) and first angles of repose (R_1)*

The results are shown in table 2.1 and were statistically analysed in table 2.3. The data were statistically analysed by sixteen 1×2 one-way analyses of variance. Eight one-way analyses of variance were conducted on the angles of avalanche, and eight one-way analyses of variance were conducted on the angles of repose. In each of the two sets of eight one-way analyses of variance, four analyses were conducted on the 200 ml sediment data, and four analyses were conducted on 400 ml sediment data. Out of the eight F ratios for angles of avalanche, five were highly significant (Table 2.3 column 4). Out of the eight F ratios for the angles of repose, four were significant (Table 2.3 column 7). All the comparisons for the angles of avalanche and repose in sediments B and C were significant (Table 2.3 rows 2, 3, 6 and 7). The comparisons for the angles of avalanche and for the angles of repose in sediment A were not significant.

These results show that higher angles of avalanche and higher angles of repose occurred with the length (15 cm) parallel to the inclined surface than with the width (7.5 cm) parallel to the inclined surface (Table 2.1, Table 2.3 rows 2, 3, 4, 6 and 7).

(b) *Second angles of avalanche (A_2') and second angles of repose (R_2)*

The results are shown in table 2.2 and were statistically analysed by sixteen 1×2 one-way analyses of variance in the same way as the first angles of avalanche and repose (see Table 2.4). All the eight F ratios for the second angles of avalanche were not significant (Table 2.4 column 4). Out of the eight F ratios for the second angles of repose, only three were significant (Table 2.4 column 7). In the three significant comparisons the angles of repose with the length (15 cm) parallel to the inclined surface were higher than with the width (7.5 cm) parallel to the inclined surface (Table 2.2 Table 2.4; column 7 rows 2, 6 and 7).

These results show that the orientation of the rectangular container does not affect the second angles of avalanche (A_2') and has a minor effect on the second angles of repose (R_2).

2.2.2 Hypothesis 2: Does the shape of the container affect angles of avalanche and angles of repose?

(a) *First angles of avalanche (A_1) and first angles of repose (R_1)*

The results are shown in table 2.1 and were statistically analysed in table 2.5. The data were statistically analysed by thirty two 1×2 one-way analyses of variance. In sixteen of these analyses, the rectangular container's width parallel to the inclined surface was compared with the circular container, and in sixteen of them the rectangular container's length parallel to the inclined surface was compared with the circular container. In each of the two sets of sixteen one-way analyses of variance, eight analyses were done on the angles of avalanche, and eight analyses were done on angles of repose. Four analyses were done on the 200 ml sediment, and four analyses were done on the 400 ml sediment.

Out of the sixteen F ratios for angles of avalanche, five were significant (Table 2.5 column 4). Out of the sixteen F ratios of angles for repose nine were significant (Table 2.5 column 7).

A careful inspection of the statistically significant differences in the angles of avalanche and angles of repose in tables 2.1 and 2.5 show that in every case: (i) the angles of avalanche and repose are highest when the length (15 cm) of the rectangular container is parallel to the inclined surface. (ii) the angles of avalanche and repose are intermediate in the circular container (ID = 9.4 cm). (iii) the angles of avalanche and repose are lowest when the width (7.5 cm) of the rectangular container is parallel to the inclined surface.

(b) *Second angles of avalanche (A_2') and second angles of repose (R_2)*

The results are shown in table 2.2 and were statistically analysed by thirty two 1×2 one-way analyses of variance in the same way as the first angles of avalanche and repose (see Table 2.6). Out of sixteen F ratios for second angles of avalanche, five were significant (Table 2.6 column 4). Out of sixteen F ratios for second angles of repose, six were significant (Table 2.6 column 7).

A careful inspection of the statistically significant differences in the second angles of avalanche (A_2') and the angles of repose (R_2) in tables 2.2 and 2.6 shows that the second angles of avalanche and repose are highest in the circular container, intermediate when the length (15 cm) of the rectangular container is parallel to the inclined surface, and lowest when the width (7.5 cm) of the rectangular container is parallel to the inclined surface.

Table 2.1 Avalanching experiment 1 First angles of avalanche (A_1) and first angles of repose (R_1) Rectangular container's width (7 5 cm) parallel to the inclined surface, rectangular container's length (15 cm) parallel to the inclined surface and circular container (ID = 9 4 cm). Mean ± SD of three replicate readings.

Sediment Types	Volume (ml)	Angle of Avalanche (A_1)			Angle of Repose (R_1)		
		Rectangular		Circular	Rectangular		Circular
		Width	Length		Width	Length	
A	200	37.67±0.289	36.83±2.021	37.50±0.500	30.67±2.309	31.67±1.528	34.33±1.155
	400	37.83±1.443	35.33±1.528	36.83±0.764	30.67±0.577	32.00±1.000	33.17±0.764
B	200	39.67±0.577	43.00±0.500	42.33±0.289	31.50±.500	35.17±1.041	34.83±0.289
	400	40.17±0.289	42.83±.289	40.83±0.764	32.17±.0.764	36.00±0.500	34.00±0.500
C	200	40.67±0.577	43.67±.289	43.67±0.577	32.00±.500	35.17±0.764	33.00±1.000
	400	39.67±0.577	42.33±0.577	42.33±0.577	32.33±1.528	36.00±0.000	32.17±0.289
D	200	43.50±0.000	46.50±0.866	43.67±0.764	34.50±0.500	33.83±1.756	38.00±0.00
	400	43.50±0.500	43.83±1.041	44.17±0.764	33.67±1.528	35.67±1.528	37.67±0.577

S1 sediments A, B, C and D are as follows (see table 1.1 in section 1). sediment A = Fine sand (63 µm to 1 mm), sediment B = Coarse sand (1 mm to 2 mm), sediment C = Granules (2 mm to 4 mm) and sediment D = Pebbles (4 mm to 8 mm).

Table 2.2 Avalanching experiment 1. Second corrected angles of avalanche (A_2') and second angles of repose (R_2) Rectangular container's width (7.5 cm) parallel to the inclined surface, rectangular container's length (15 cm) parallel to the inclined surface and circular container. Mean ± SD of three replicate readings.

Sediment Types	Volume (ml)	Second Angle of Avalanche (A_2')			Second Angle of Repose (R_2)		
		Rectangular		Circular	Rectangular		Circular
		Width	Length		Width	Length	
A	200	35.00±1.500	36.67±1.893	37.67±0.577	32.67±0.764	33.00±1.000	32.67±1.607
	400	34.17±1.258	35.00±1.723	37.17±1.041	31.17±1.258	32.00±1.000	34.67±0.577
B	200	38.17±0.289	39.17±1.443	40.33±1.041	32.17±0.289	34.00±0.500	35.67±0.577
	400	40.00±1.000	40.00±0.500	41.17±0.764	32.50±0.866	34.67±0.289	34.83±0.289
C	200	39.50±0.000	39.00±1.000	38.67±0.577	31.50±0.500	33.83±1.607	33.33±1.528
	400	39.17±1.258	40.17±1.041	40.50±1.000	32.00±0.000	34.67±0.577	33.83±0.289
D	200	41.33±1.041	41.83±1.893	46.33±1.155	35.33±2.082	35.17±2.021	32.50±3.122
	400	40.33±1.893	42.67±1.893	43.33±1.041	34.33±2.082	37.33±2.517	35.00±1.000

For S1 sediments A, B, C and D see table 1.1 and figure 2.1.

Table 2.3 Avalanching experiment 1. Statistical analyses for the effects of orientation of the rectangular container (rectangular container's width (7.5 cm) parallel to the inclined surface, rectangular container's length (15 cm) parallel to the inclined surface) on first angle of avalanche (A_1) and on first angles of repose (R_1).

Factors	A_1			R_1		
	DF	F ratio	Probability	DF	F ratio	Probability
Width / Length						
a) <u>Sediment volume 200 ml</u>						
A	1, 4	0.500	0.519	1, 4	0.390	0.566
B	1, 4	57.14	0.002 **	1, 4	30.25	0.005 **
C	1, 4	64.80	0.001 **	1, 4	36.10	0.004 **
D	1, 4	36.00	0.004 **	1, 4	0.400	0.561
b) <u>Sediment volume 400 ml</u>						
A	1, 4	4.250	0.108	1, 4	4.000	0.116
B	1, 4	128.0	<0.001 ***	1, 4	52.90	0.002 **
C	1, 4	32.00	0.005 **	1, 4	17.29	0.014 *
D	1, 4	0.250	0.643	1, 4	2.570	0.184

Table gives F ratios and probability values obtained from sixteen 1×2 one-way analyses comparing rectangular container's width (7.5 cm) parallel to the inclined surface and rectangular container's length (15 cm) parallel to the inclined surface (n=3). a) eight for sediments volume 200 ml. b) eight for sediments volume 400 ml. Probability: 0 05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***. For S1 sediments A, B, C and D see table 1.1 and figure 2.1.

Table 2.4 Avalanching experiment 1. Statistical analyses for the effects of orientation of the rectangular container (rectangular container's width (7.5 cm) parallel to the inclined surface, rectangular container's length (15 cm) parallel to the inclined surface) on second angles of Avalanche (A_2') and on second angles of repose (R_2).

Factors	A_2'			R_2		
	DF	F ratio	Probability	DF	F ratio	Probability
Width / Length						
a) <u>Sediment volume 200 ml</u>						
A	1, 4	1.430	0.289	1, 4	0.210	0.670
B	1, 4	1.380	0.305	1, 4	30.25	0.005 **
C	1, 4	0.750	0.435	1, 4	5.760	0.074
D	1, 4	0.160	0.709	1, 4	0.010	0.926
b) <u>Sediment volume 400 ml</u>						
A	1, 4	0.450	0.537	1, 4	0.810	0.420
B	1, 4	0.000	1.000	1, 4	16.90	0.015 *
C	1, 4	1.120	0.349	1, 4	64.00	0.001 **
D	1, 4	2.280	0.206	1, 4	2.530	0.187

Table gives F ratios and probability values obtained from sixteen 1×2 one-way analyses comparing rectangular container's width (7.5 cm) parallel to the inclined surface and rectangular container's length (15 cm) parallel to the inclined surface (n=3). a) eight for sediments volume 200 ml. b) eight for sediments volume 400 ml. Probability: $0.05>P>0.01$ *; $0.01>P>0.001$ **; $P<0.001$ ***. For S1 sediments A, B, C and D see table 1.1 and figure 2.1.

Table 2.5 Avalanching experiment 1. Statistical analyses for the effects of shape of the containers (rectangular container's width (7.5 cm) parallel to the inclined surface, rectangular container's length (15 cm) parallel to the inclined surface and circular container) on first angle of avalanche (A_1) and on first angles of repose (R_1).

Factors	A_1			R_1		
	DF	F ratio	Probability	DF	F ratio	Probability
1. Rectangular container's Width / Circular container						
a) <u>Sediment volume 200 ml</u>						
A	1, 4	0.250	0.643	1, 4	6.050	0.070
B	1, 4	72.25	0.001 **	1, 4	100.0	0.001 **
C	1, 4	40.50	0.003 **	1, 4	2.400	0.196
D	1, 4	0.140	0.725	1, 4	147.0	<0.001 ***
b) <u>Sediment volume 400 ml</u>						
A	1, 4	1.120	0.349	1, 4	20.45	0.011 *
B	1, 4	2.000	0.230	1, 4	12.10	0.025 *
C	1, 4	32.00	0.005 **	1, 4	0.030	0.862
D	1, 4	1.600	0.275	1, 4	18.00	0.013 *
2. Rectangular container's Length / Circular container						
a) <u>Sediment volume 200 ml</u>						
A	1, 4	0.310	0.609	1, 4	5.820	0.073
B	1, 4	3.000	0.158	1, 4	0.290	0.621
C	1, 4	0.000	1.000	1, 4	8.890	0.041 *
D	1, 4	18.06	0.013 *	1, 4	16.89	0.015 *
b) <u>Sediment volume 400 ml</u>						
A	1, 4	2.310	0.203	1, 4	2.580	0.184
B	1, 4	18.00	0.013 *	1, 4	24.00	0.008 **
C	1, 4	0.000	1.000	1, 4	529.0	<0.001 ***
D	1, 4	0.200	0.678	1, 4	4.500	0.101

Table gives F ratios and probability values obtained from one-way analyses of variance. 1) sixteen 1×2 one-way analyses comparing rectangular container's width (7.5 cm) parallel to the inclined surface and circular container (ID = 9.4 cm). 2) sixteen 1×2 one-way analyses comparing rectangular container's length (15 cm) parallel to the inclined surface and circular container (n=3). Probability: $0.05>P>0.01$ *; $0.01>P>0.001$ **; $P<0.001$ ***. For S1 sediments A, B, C and D see table 1.1 and figure 2.1.

Table 2.6 Avalanching experiment 1. Statistical analyses for the effects of shape of the containers (rectangular container's width (7.5 cm) parallel to the inclined surface, rectangular container's length (15 cm) parallel to the inclined surface and circular container on second angles of Avalanche (A_2') and on second angles of repose (R_2).

Factors	A_2'			R_2		
	DF	F ratio	Probability	DF	F ratio	Probability
1. Rectangular container's Width / Circular						
a) Sediment volume 200 ml						
A	1, 4	8.260	0.045 *	1, 4	0.000	1.000
B	1, 4	18.00	0.013 *	1, 4	88.20	0.001 **
C	1, 4	6.250	0.067	1, 4	3.900	0.119
D	1, 4	31.03	0.005 **	1, 4	1.710	0.261
b) Sediment volume 400 ml						
A	1, 4	10.12	0.033 *	1, 4	19.17	0.012 *
B	1, 4	2.58	0.184	1, 4	19.60	0.011 *
C	1, 4	2.060	0.224	1, 4	121.0	<0.001 ***
D	1, 4	5.790	0.074	1, 4	0.250	0.643
2. Rectangular container's Length / Circular						
a) Sediment volume 200 ml						
A	1, 4	0.770	0.431	1, 4	0.090	0.776
B	1, 4	1.120	0.349	1, 4	14.29	0.019 *
C	1, 4	0.250	0.643	1, 4	0.150	0.716
D	1, 4	12.36	0.025 *	1, 4	1.540	0.282
b) Sediment volume 400 ml						
A	1, 4	3.450	0.137	1, 4	16.00	0.016 *
B	1, 4	4.900	0.091	1, 4	0.500	0.519
C	1, 4	0.160	0.710	1, 4	5.000	0.089
D	1, 4	0.290	0.621	1, 4	2.230	0.210

Table gives F ratios and probability values obtained from one-way analyses of variance. 1) sixteen 1×2 one-way analyses comparing rectangular container's width (7.5 cm) parallel to the inclined surface and circular container (ID = 9.4 cm). 2) sixteen 1×2 one-way analyses comparing rectangular container's length (15 cm) parallel to the inclined surface and circular container (n=3). Probability: $0.05>P>0.01$ *; $0.01>P>0.001$ **; $P<0.001$ ***. For S1 sediments A, B, C and D see table 1.1 and figure 2.1.

2.2.3 Hypothesis 3: Does the volume of sediment affect angles of avalanche and the angles of repose?

(a) *First angles of avalanche (A_1) and first angles of repose (R_1)*

The results are presented in table 2.1 and were statistically analysed in table 2.7. The data was statistically analysed by twenty four 1×2 one-way analyses of variance. Twelve one-way analyses of variance were conducted on the angles of avalanche, and twelve one-way analyses of variance were conducted on the angles of repose. In each of the twelve one-way analyses of variance, four analyses were done on the data obtained with the rectangular container's width parallel to the inclined surface, four analyses were done on the data obtained with the rectangular container's length parallel to the inclined surface, and four analyses were done on the data obtained with the circular container. Out of the twelve comparisons for angles of avalanche, nine were not significant (Table 2.7 column 4). In the three significant comparisons the 200 ml volume had higher angles of avalanche than the 400 ml volume (Table 2.1 Table 2.7 rows 7, 8 and 10). All the twelve comparisons for angles of repose were not significant (Table 2.7 column 7).

From the above results, it can be concluded that the volume of sediment does not have a major effect on the first angles of avalanche and has no effect on the first angles of repose.

(b) *Second angles of avalanche (A_2') and second angles of repose (R_2)*

The results are shown in table 2.2 and were statistically analysed by thirty two 1×2 one-way analyses of variance variance in the same way as the first angles of avalanche and repose (see Table 2.8). All the twenty four comparisons for the second angles of avalanche and the second angles of repose were not significant (Table 2.8 column 4 and column 7). Hence the volume of the sediment does not affect second angles of avalanche (A_2') and second angles of repose (R_2).

2.2.4 Hypothesis 4: Do the angles of avalanche and angles of repose vary with particle size?

(a) *First angles of avalanche (A_1) and first angles of repose (R_1)*

The data were statistically analysed by twelve 1×4 one-way analyses of variance (Table 2.9) These were divided into two sets of six. Six one-way analyses of variance were conducted on the angles of avalanche, and six one-way analyses of variance were conducted on the angles of repose. Out of each of the six, three analyses were done on data obtained with the 200 ml sediment volume, and three analyses were done on data obtained with the 400 ml sediment volume. All the six F ratios for angles of avalanche were highly significant (Table 2.9 column 4). Out of the six F ratios for angles of repose five were significant (Table 2.9 column 7).

This means that the first angles of avalanche and first angles repose vary with grain size. The results broadly show that angles of avalanche and angles of repose increase with increase in particle size. Table 2.1 shows that the highest angles of avalanche and highest angles of repose occurred in coarsest sediment D (46.50°, 38.00°) and the lowest angles of avalanche and lowest angles of repose occurred in finest sediment A (35.33°, 30.67°).

(b) *Second angles of avalanche (A_2') and second angles of repose (R_2)*

The results are shown in table 2.2 and were statistically analysed by thirty two 1×2 one-way analyses of variance in the same way as the first angles of avalanche and repose (see Table 2.10). All the six comparisons for the second angles of avalanche were significant (Table 2.10 column 4). Out of the six comparisons for the second angles of repose (R_2) two were significant (Table 2.10 column 7). Inspection of the results in table 2.2 shows that the second angles of avalanche (A_2') and the second angle of repose (R_2) increase broadly with the increase in particle size.

(c) Factor of Safety

The results in table 2.11 show that the factor of safety increases with the increase in angle of avalanche and decreases with the increase in angle of repose. Figure 2.4 shows a strong positive linear relationship between the factors of safety and angles of avalanche, and a strong negative relationship between the factors of safety and angles of repose.

Table 2.7 Avalanching experiment 1. Statistical analyses for the effects of sediment volumes (200 ml and 400 ml) on first angles of avalanche (A_1) and on first angles of repose (R_1).

Factors		A_1			R_1	
	DF	F ratio	Probability	DF	F ratio	Probability
Volume (200 ml / 400 ml)						
a) Rectangular container's width parallel to the inclined surface						
A	1, 4	0.040	0.854	1, 4	0.000	1.000
B	1, 4	1.800	0.251	1, 4	1.600	0.275
C	1, 4	4.500	0.101	1, 4	0.130	0.738
D	1, 4	0.000	1.000	1, 4	0.810	0.420
b) Rectangular container's length parallel to the inclined surface						
A	1, 4	1.050	0.363	1, 4	0.100	0.768
B	1, 4	0.250	0.643	1, 4	1.560	0.279
C	1, 4	12.80	0.023 *	1, 4	3.570	0.132
D	1, 4	11.64	0.027 *	1, 4	1.860	0.244
c) Circular container						
A	1, 4	1.600	0.275	1, 4	2.13	0.218
B	1, 4	10.12	0.033 *	1, 4	6.25	0.067
C	1, 4	8.000	0.047	1, 4	1.92	0.238
D	1, 4	0.640	0.468	1, 4	1.00	0.374

Table gives F ratios and probability values obtained from twenty four 1×2 one-way analyses comparing sediments volume 200 ml and sediments volume 400 ml (n=3). a) four analyses for rectangular container's width (7.5 cm) parallel to the inclined surface. b) four analyses for rectangular container's length (15 cm) parallel to the inclined surface. c) four analyses for circular container (ID = 9.4 cm). Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***. For S1 sediments A, B, C and D see table 1.1 and figure 2.1.

Table 2.8 Avalanching experiment 1. Statistical analyses for the effects of sediment volumes (200 ml and 400 ml) on second angles of Avalanche (A_2') and on second angles of repose (R_2).

Factors	A_2'			R_2		
	DF	F ratio	Probability	DF	F ratio	Probability
Volume (200 ml / 400 ml)						
a) Rectangular container's width parallel to the inclined surface						
A	1, 4	0.540	0.502	1, 4	3.120	0.152
B	1, 4	9.310	0.038	1, 4	0.400	0.561
C	1, 4	0.210	0.670	1, 4	3.000	0.158
D	1, 4	0.640	0.468	1, 4	0.350	0.588
b) Rectangular container's length parallel to the inclined surface						
A	1, 4	1.270	0.323	1, 4	1.500	0.288
B	1, 4	0.890	0.398	1, 4	4.000	0.116
C	1, 4	1.960	0.234	1, 4	0.710	0.446
D	1, 4	0.290	0.618	1, 4	1.350	0.310
c) Circular container						
A	1, 4	0.53	0.507	1, 4	4.11	0.112
B	1, 4	1.25	0.326	1, 4	5.00	0.089
C	1, 4	7.56	0.051	1, 4	0.31	0.607
D	1, 4	11.17	0.029	1, 4	1.74	0.257

Table gives F ratios and probability values obtained from twenty four 1×2 one-way analyses comparing sediments volume 200 ml and sediments volume 400 ml (n=3). a) four analyses for rectangular container's width (7.5 cm) parallel to the inclined surface. b) four analyses for rectangular container's length (15 cm) parallel to the inclined surface. c) four analyses for circular container (ID = 9.4 cm). Probability: $0.05>P>0.01$ *; $0.01>P>0.001$ **; $P<0.001$ ***. For S1 sediments A, B, C and D see table 1.1 and figure 2.1.

Table 2.9 Avalanching experiment 1. Statistical analyses for the effects of sediment types (sediment A = 63 µm to 1 mm, sediment B = 1 mm to 2 mm, sediment C = 2 mm to 4 mm and sediment D = 4 mm to 8 mm) on first angle of avalanche (A_1) and on first angles of repose (R_1) between the

Factors	A_1			R_1		
	DF	F ratio	Probability	DF	F ratio	Probability
Sediment types (A/B/C/D)						
a) Sediment volume 200 ml						
width	3, 8	94.33	<0.001***	3, 8	5.370	0.026 *
length	3, 8	38.49	<0.001***	3, 8	4.620	0.037 *
circular	3, 8	82.38	<0.001***	3, 8	22.29	<0.001***
b) Sediment volume 400 ml						
width	3, 8	24.35	<0.001***	3, 8	3.240	0.082
length	3, 8	47.22	<0.001***	3, 8	12.74	0.002 **
circular	3, 8	56.04	<0.001***	3, 8	55.20	<0.001***

Table gives F ratios and probability values obtained from twelve 1×4 one-way analyses comparing four sediments A, B, C and D (n=3). a) six for sediments volume 200 ml. b) six for sediments volume 400 ml. Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***. For S1 sediments A, B, C and D see table 1.1 and figure 2.1.

Table 2.10 Avalanching experiment 1. Statistical analyses for the effects of sediment types (sediment A = 63 μm to 1 mm, sediment B = 1 mm to 2 mm, sediment C = 2 mm to 4 mm and sediment D = 4 mm to 8 mm) on second angles of Avalanche (A_2') and on second angles of repose (R_2).

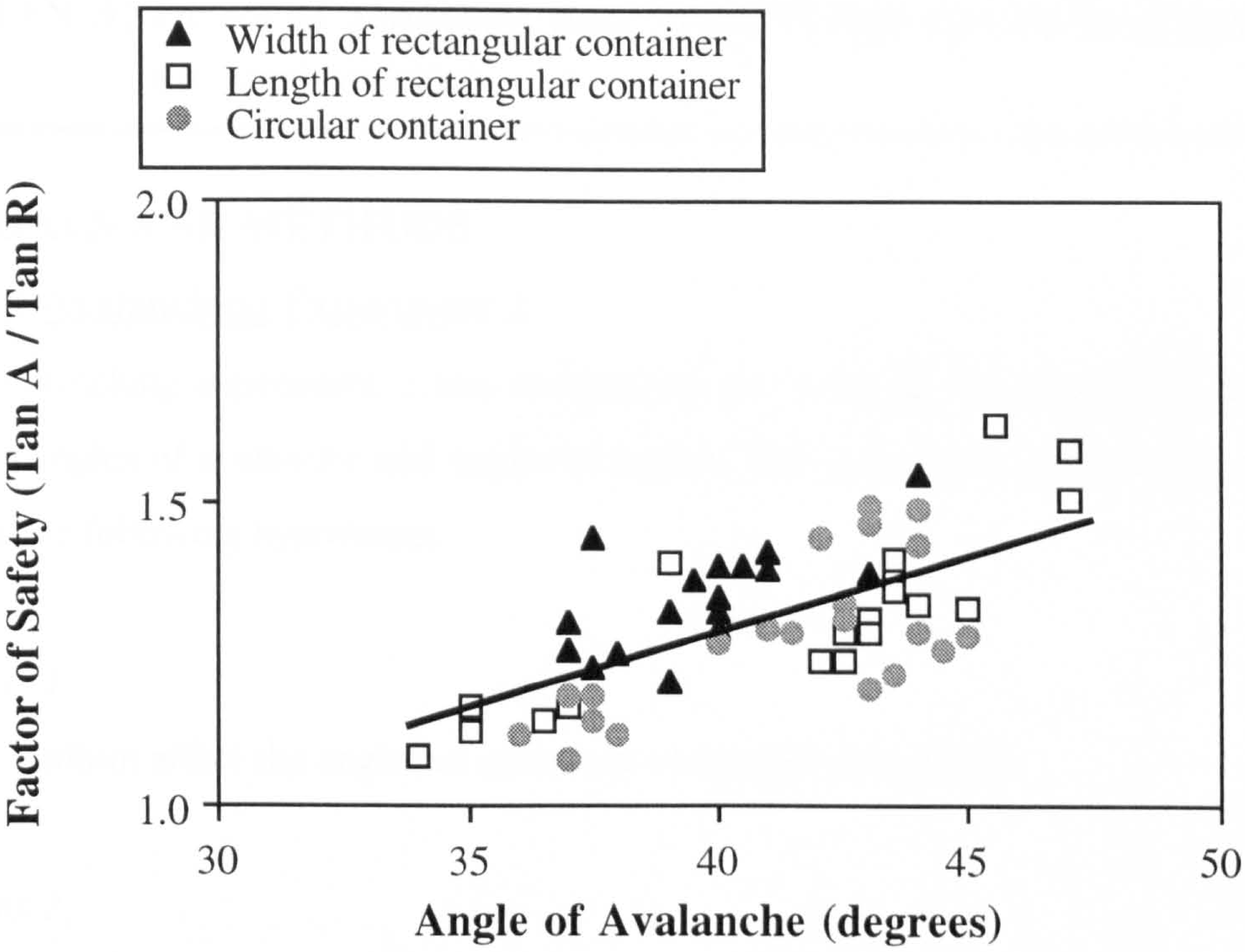
Factors	A_2'			R_2		
	DF	F ratio	Probability	DF	F ratio	Probability
Sediment types (A/B/C/D)						
a) Sediment volume 200 ml						
width	3, 8	25.04	<0.001***	3, 8	6.460	0.016 *
length	3, 8	5.220	0.027 *	3, 8	1.210	0.368
circular	3, 8	58.63	<0.001***	3, 8	1.710	0.242
b) Sediment volume 400 ml						
width	3, 8	12.80	0.002 **	3, 8	3.230	0.082
length	3, 8	15.65	0.001***	3, 8	7.340	0.011 *
circular	3, 8	20.88	<0.001***	3, 8	2.150	0.172

Table gives F ratios and probability values obtained from twelve 1×4 one-way analyses comparing four sediments A, B, C and D (n=3). a) six for sediments volume 200 ml. b) six for sediments volume 400 ml. Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***. For S1 sediments A, B, C and D see table 1.1 and figure 2.1.

Table 2.11 Avalanching experiment 1 Factor of safety of first avalanche (F_1) and factor of safety of second avalanche (F_2). Rectangular container's width (7.5 cm) parallel to the inclined surface, rectangular container's length (15 cm) parallel to the inclined surface and circular container. Mean ± SD of three replicate readings.

Sediment Types	Volume (ml)	F_1 = Tan (A_1) / Tan (R_1)			F_2 = Tan (A_2') / Tan (R_2).		
		Rectangular		Circular	Rectangular		Circular
		Width	Length		Width	Length	
A	200	1.307±0 118	1.221±0.158	1.125±0.054	1.093±0.047	1.148±0.085	1.206±0.060
	400	1.310±0 059	1.135±0.048	1.147±0.033	1.124±0.064	1.124±0.110	1.096±0.020
B	200	1.353±0.039	1.325±0.071	1.317±0.014	1.250±0.001	1.209±0.066	1.177±0.056
	400	1.343±0.051	1.276±0.035	1.281±0.012	1.319±0.087	1.214±0.034	1.257±0.025
C	200	1.376±0.053	1.355±0.026	1.470±0.033	1.345±0.027	1.209±0.037	1.220±0.093
	400	1.313±0.101	1.254±0.025	1.449±0.013	1.304±0.059	1.221±0.058	1.275±0.047
D	200	1.381±0.026	1.574±0.065	1.222±0.033	1.244±0.104	1.280±0.185	1.653±0.153
	400	1.428±0.103	1.339±0.063	1.259±0.038	1.253±0.187	1.211±0.076	1.350±0.099

For S1 sediments A, B, C and D see table 1.1 and figure 2.1.



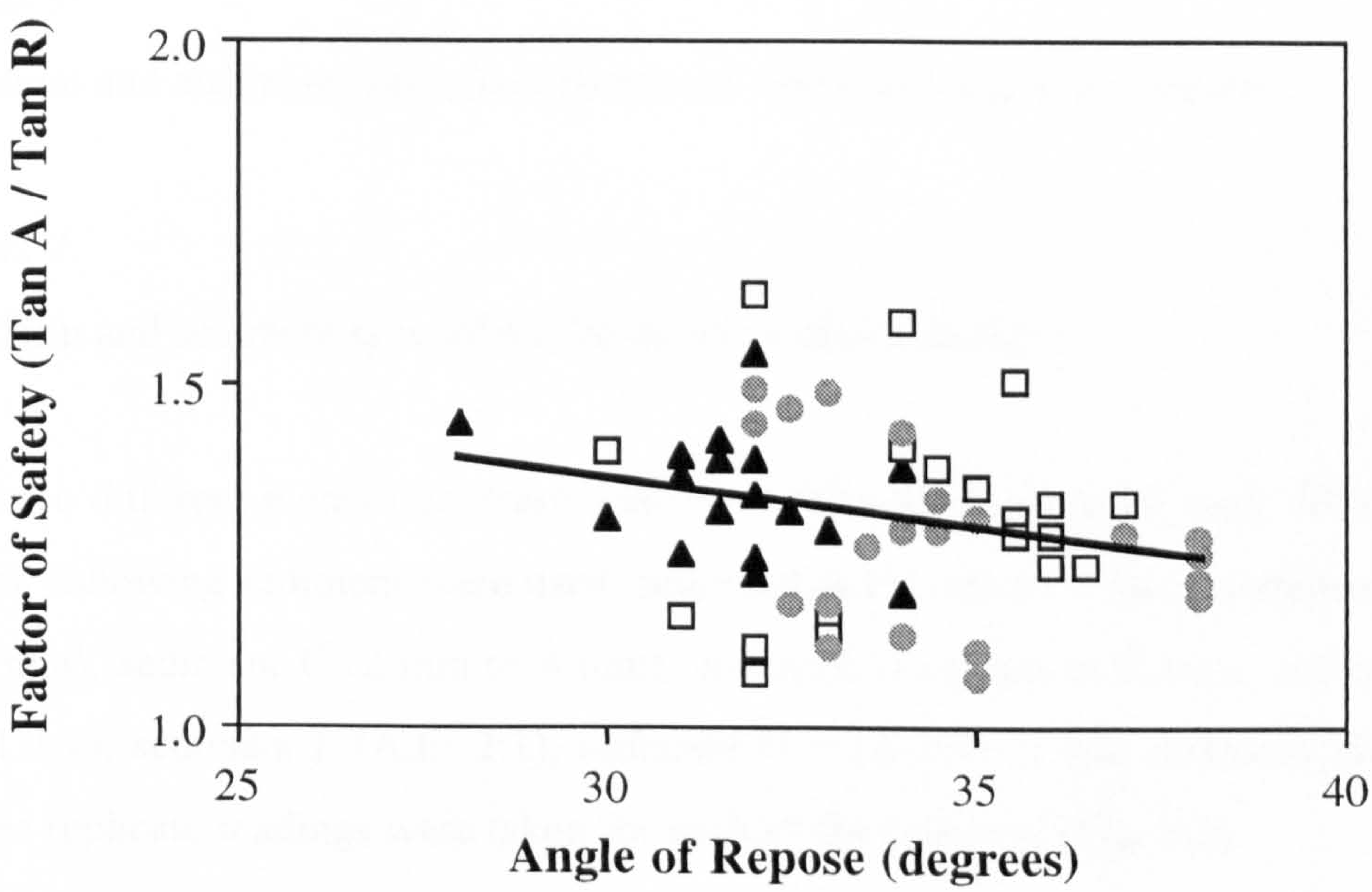


Figure 2.4 Data from avalanching experiment 1. **Top:** relationship between the factor of safety and first angle of avalanche (y = 0.0251 x + 0.282, $F_{1,70}$ = 48.34 P<0.001 ***). **Bottom:** relationship between the factor of safety and first angle of repose (y = - 0.0137 x + 1.780, $F_{1,70}$ = 4.94 P=0.029 *). Width of rectangular ontainer (7.5 cm) parallel to the inclined surface. Length of rectangular container (15 cm) parallel to the inclined surface. Circular container (ID = 9.4 cm) on the inclined surface.

SECTION 3: Effect of Medium: Air, Fresh Water and 50 % Glycerol on Avalanching

3.1 MATERIALS AND METHODS

3.1.1 Design of Avalanching Experiment 2

Avalanching experiment 2 was designed to test whether the supporting medium affects the angles of avalanche and angles of repose. The experiment design allowed me to answer the following hypotheses.

Hypothesis 1:

Does the medium affect the angles of avalanche and angles of repose?

Hypothesis 2:

Do the angles of avalanche and angles of repose vary with particle size?

Hypothesis 3

Does medium and sediment type affect factors of safety and angles of dilatation?

Hypothesis 4:

Does medium and sediment type affect the duration of avalanche?

Three different media (air, fresh water and 50% glycerol) were used. 400 ml of each of the following sediment were used: sediment A (63 μm to 1 mm), sediment B (1 mm to 2 mm), sediment C (2 mm to 4 mm), sediment D (4 mm to 8 mm), sediment E (B:C:D; 1:1:1), sediment F (A:E: 2:1), sediment G = (A:E; 1:1) and sediment H (A:E; 1:2). Three replicate readings were taken for each of the sediment (Fig. 3.1).

(Note A, B, C, D, E, F, G and H are the fractions of the S1 sediment described in section I, see table 1.1)

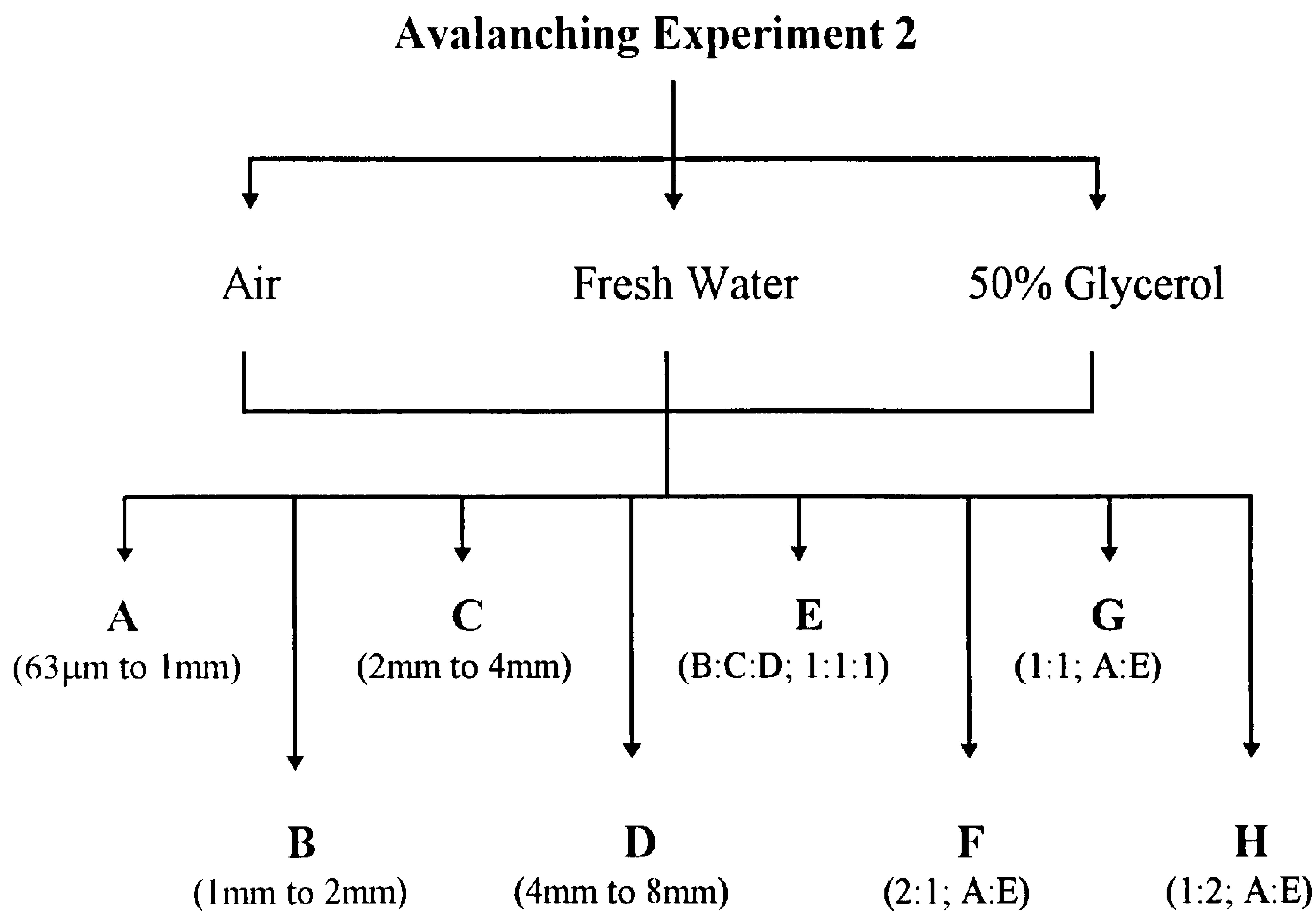


Figure 3.1 Avalanching experiment 2. Three different media: air, fresh water and 50% glycerol. S1 sediments: sediment A = Fine sand (63 µm to 1 mm), sediment B = Coarse sand (1 mm to 2 mm), sediment C = Granules (2 mm to 4 mm), sediment D = Pebbles (4 mm to 8 mm), sediment E = (1:1:1 ; B:C:D) means sediment E contain of one part of sediment B, one part of sediment C and one part of sediment D. Sediments F, G and H were prepared by mixing sediment A and sediment E in a proportion of 1:2, 1:1 and 2:1. Sediment F = (2:1; A:E) contain 2 parts of sediment A to 1 part of sediment E and so on.

3.1.2 Conduct of Avalanching Experiment 2

Twenty four rectangular glass containers (size 15 cm × 7.5 cm, Height = 40 cm) were set up. These were divided into three groups each containing eight containers, one for each of the eight sediments A, B, C, D, E, F, G and H. The first group of eight containers contained sediments in air, the second group contained sediments in fresh water and the third group contained sediments in 50% glycerol. The detailed procedure was as follows:

Medium 1 (Air): 400 ml of dry sediment was added to the container. Sediment in the container was mixed and levelled using a metal rod. The container was then left to stand for 15 minutes before being avalanched.

Medium 2 (Fresh water): The container was first filled with approximately 1000 ml fresh water. 400 ml dry sediment was then added to the water in the container. Sediment in the water was mixed using a metal rod to remove air bubbles. The sediment in the container was allowed to soak in the water over night. Next day the sediment in the container was again mixed and left to stand for 15 minutes before being avalanched.

Medium 3 (50% glycerol: 100% glycerol diluted with fresh water): The experiment was set up in exactly the same way as the experiment in fresh water.

The inclinometer used to avalanche the container is explained in figure 2.3. The procedure of avalanching the container was similar to the avalanching described in 2.1.4.

In each of the above three media, three replicate sets of readings were taken as in 2.1.3 and 2.1.4. The duration of first avalanche (T_1) and the duration of second avalanche (T_2) in seconds were also recorded. This was done by using a stop watch.

3.2 RESULTS

The results and statistical analyses of avalanching experiment 2 are shown in tables 3.1 to 3.15.

The mean±SD values of the three replicates for the first angles of avalanche (A_1) and first angles of repose (R_1) are presented in table 3.1 and the mean±SD values of three replicates for the second angles of avalanche (A_2') and second angles of repose (R_2) are presented in table 3.2. The statistical analyses of the angles of avalanche and repose are shown in table 3.3 to table 3.9.

The mean±SD values of three replicate readings for factors safety in the first avalanche (F_1) and for factors safety in the second avalanche (F_2) are presented in table 3.10. The mean±SD values of three replicate readings for angles of dilatation in the first avalanche (D_1) and angles of dilatation in the second avalanche (D_2) are presented in table 3.11. Statistical analyses on factors of safety are shown in table 3.12 column 2, 3 and 4 and in table 3.13. Statistical analyses on the angles of dilatation are shown in table 3.12 column 5, 6 and 7.

The mean±SD values of three replicate readings for the duration of the first avalanche (T_1) and for the duration for second avalanche (T_2) are presented in table 3.14. Statistical analyses on the duration of avalanche are shown in table 3.15.

With this background, the results are divided into four parts. Part one (3.2.1) describes the results of testing hypothesis one. Part two (3.2.2) describes the results of testing hypothesis two. Part two also contains a comparison of the first and second angles of avalanche and repose. Part three (3.2.3) describes the results of testing hypothesis three Part four (3.2.4) describes the results of testing hypothesis four.

3.2.1 Hypothesis 1: Does the medium affect angles of avalanche and angles of repose?

(a) *First angle of avalanche (A_1) and first angle of repose (R_1)*

The data are shown in table 3.1 and are statistically analysed in table 3.3. The differences between the three media: air / fresh water and fresh water / 50% glycerol were statistically analysed as follows. Firstly sediments in air were compared with the sediments in fresh water by sixteen 1×2 one-way analyses of variance. Secondly the sediments in fresh water were compared with the sediments in 50% glycerol by sixteen 1×2 one-way analyses of variance. In each of the two sets of sixteen one-way analyses of variance, eight analyses were conducted on the angles of avalanche, and eight analyses were conducted on the angles of repose.

Eight out of the sixteen comparisons for the angles of avalanche were significant (Table 3.3 column 4). Seven out of the sixteen comparisons for the angles of repose were significant (Table 3.3 column 7). However, there was no consistent relationship between these significant results. For example in the air / fresh water comparison, two of the angles of avalanche in air were significantly higher than those in fresh water, and two in fresh water were significantly higher than those in air. The same was broadly true for angles of repose. There are therefore no consistent differences in the first angles of avalanche and the first angles of repose in air, fresh water and 50% glycerol.

(b) *Second angle of avalanche (A_2') and second angle of repose (R_2)*

The data for the second angles of avalanche (A_2') and second angles of repose (R_2) are presented in table 3.2 and were statistically analysed in exactly the same way as the first angles of avalanche (A_1) and first angles of repose (R_1) in table 3.4.

Second angles of avalanche: Two out of the eight comparisons of the second angles of avalanche in air and fresh water were significant (Table 3.4a, column 4). In both cases, the second angles of avalanche in air were higher than the second angles of avalanche in water. Three out of the eight comparisons of the second angles of avalanche in fresh water and 50% glycerol were significant (Table 3.4b, column 4). In two out of the three, the second angles of avalanche in fresh water were significantly higher than those in 50%

glycerol, while in the third the second angle of avalanche was significantly higher in 50% glycerol than in fresh water.

Second angles of repose: Four out of the eight comparisons of the second angles of repose in air and fresh water were significant (Table 3.4a, column 7). In three, the second angles of repose in fresh water were significantly higher than those in air, and in one the second angle of repose was significantly higher in air than in fresh water. Two out of the eight comparisons of the second angles of repose in fresh water and 50% glycerol were significant (Table 3.4b, column 7). In one, the second angle of repose in fresh water was significantly higher than in 50% glycerol, and in other the second angle of repose was significantly higher in 50% glycerol than in fresh water

From the above significant results, it can be concluded that the second angles of avalanche (A_2') were higher in air than in fresh water, and in 50% glycerol in one case. The second angles of repose (R_2) in fresh water were mostly higher than in air.

Table 3.1 Avalanching experiment 2 Effects of medium on first angles of avalanche (A_1) and first angles of repose (R_1) Mean ± SD of three replicate readings.

Sediment Type	First Angle of Avalanche (A_1)			First Angle of Repose (R_1)		
	Air	Fresh water	50% Glycerol	Air	Fresh water	50% Glycerol
A	37.83±1.443	38.00±0.000	38.67±1.155	30.67±0.577	32.00±0.500	31.67±1.528
B	39.17±0.289	38.17±0.289	40.50±0.500	31.17±0.764	33.17±0.289	33.00±0.866
C	39.67±0.577	39.67±0.577	40.67±0.577	32.33±1.528	35.83±0.764	33.33±0.577
D	43.50±0.500	43.83±0.289	43.67±0.289	33.67±1.528	35.00±0.000	38.50±0.500
E	38.83±0.577	41.00±0.500	39.67±0.289	34.50±0.866	35.17±0.577	34.33±0.289
F	40.17±0.289	38.50±0.000	41.17±0.289	35.00±1.323	33.83±0.289	30.33±0.577
G	38.17±0.289	38.50±0.00	40.33±0.577	34.33±1.258	35.00±0.000	32.50±0.500
H	38.67±0.577	39.83±0.289	40.17±1.041	35.33±0.577	33.50±0.000	33.17±0.764

S1 sediments A, B, C, D, E, F, G and H are as follows (see table 1.1 in section 1). Sediment A = Fine sand (63 μm to 1 mm), sediment B = Coarse sand (1 mm to 2 mm), sediment C = Granules (2 mm to 4 mm), sediment D = Pebbles (4 mm to 8 mm), sediment E = (1:1:1; B:C:D) means that sediment E consist of one part of sediment B, one part of sediment C and one part of sediment D. Sediments F, G and H were prepared by mixing sediment A and sediment E in a proportion of 2:1, 1:1 and 1:2. Sediment F = (2:1; A:E) means 2 parts of sediment A to 1 part of sediment E and so on.

Table 3.2 Avalanching experiment 2. Avalanching experiment 2. Effects of medium on second angles of avalanche (A_2') and second angles of repose (R_2). Mean ± SD of three replicate readings.

Sediment Type	Second corrected true Angle of Avalanche (A_2')			Second Angle of Repose (R_2)		
	Air	Fresh water	50% Glycerol	Air	Fresh water	50% Glycerol
A	34.17±1.258	36.17±1.607	37.33±2.082	31.17±1.258	32.17±0.289	32.67±1.155
B	39.00±1.000	38.33±0.289	37.17±0.764	31.50±0.866	32.50±0.500	33.17±0.764
C	39.17±1.258	40.33±0.577	39.00±0.866	32.00±0.000	33.17±0.577	34.67±0.577
D	40.33±1.893	42.00±0.500	43.83±1.443	34.33±2.082	34.83±0.764	35.33±0.577
E	39.00±0.500	40.50±0.866	39.33±0.289	34.50±0.000	35.17±0.289	35.33±0.289
F	40.17±0.289	37.50±0.500	35.50±1.000	35.30±1.803	33.50±1.000	33.17±0.289
G	39.33±1.155	39.00±0.000	37.50±0.500	35.00±0.000	35.83±0.289	34.17±0.289
H	40.33±0.577	37.17±0.289	39.17±0.764	34.67±0.577	33.50±0.000	34.00±0.500

For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1.

Table 3.3 Avalanching experiment 2. Statistical analyses of the differences in first angles of avalanche (A_1) and in first angles of repose (R_1) between the medium (air / fresh water and fresh water / 50% glycerol).

Factors	A_1			R_1		
	DF	F ratio	Probability	DF	F ratio	Probability
a) Air / Fresh water						
A	1, 4	0.040	0.851	1, 4	9.140	0.039
B	1, 4	18.00	0.013 *	1, 4	18.00	0.013 *
C	1, 4	0.000	1.000	1, 4	12.60	0.024 *
D	1, 4	1.000	0.374	1, 4	2.290	0.205
E	1, 4	24.14	0.008 **	1, 4	1.230	0.329
F	1, 4	100.0	0.001 **	1, 4	2.230	0.210
G	1, 4	4.000	0.116	1, 4	0.840	0.411
H	1, 4	9.800	0.035 *	1, 4	30.25	0.005 **
b) Fresh water / 50% Glycerol						
A	1, 4	1.000	0.374	1, 4	0.130	0.738
B	1, 4	49.00	0.002 **	1, 4	0.100	0.768
C	1, 4	4.500	0.101	1, 4	20.45	0.011 *
D	1, 4	0.500	0.519	1, 4	147.0	<0.001 ***
E	1, 4	16.00	0.016 *	1, 4	5.000	0.089
F	1, 4	256.0	<0.001 ***	1, 4	88.20	0.001 **
G	1, 4	30.25	0.005 **	1, 4	75.00	0.001 **
H	1, 4	0.290	0.621	1, 4	0.570	0.492

Table gives F ratios and probability values obtained from one-way analyses of variance. a) sixteen 1×2 analyses comparing sediments in air and the sediments in fresh water, eight for first angles of avalanche (A_1) and eight for first angles of repose (R_1). b) sixteen 1×2 analyses comparing sediments in fresh water and the sediments in 50% glycerol, eight for first angles of avalanche (A_1) and eight for first angles of repose (R_1). Probability: $0.05>P>0.01$ *; $0.01>P>0.001$ **; $P<0.001$ ***. For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1.

Table 3.4 Avalanching experiment 2. Statistical analyses of the differences in second corrected true angles of avalanche (A_2') and in second angles of repose (R_2) between the medium (air / fresh water and fresh water / 50% glycerol).

Factors	A_2'			R_2		
	DF	F ratio	Probability	DF	F ratio	Probability
a) Air / Fresh water						
A	1, 4	2.880	0.165	1, 4	1.800	0.251
B	1, 4	1.230	0.329	1, 4	3.000	0.158
C	1, 4	2.130	2.180	1, 4	12.25	0.025 *
D	1, 4	2.170	0.214	1, 4	0.150	0.716
E	1, 4	6 750	0.060	1, 4	16.00	0.016 *
F	1, 4	64.00	0.001 **	1, 4	2.820	0.168
G	1, 4	0.250	0.643	1, 4	25.00	0.007 **
H	1, 4	72.20	0.001 **	1, 4	12.25	0.025 *
b) Fresh water / 50% Glycerol						
A	1, 4	0.590	0.485	1, 4	0.530	0.507
B	1, 4	6.120	0.069	1, 4	1.600	0.275
C	1, 4	4.920	0.091	1, 4	10.12	0.033 *
D	1, 4	4.320	0.106	1, 4	0.820	0.417
E	1, 4	4.900	0.091	1, 4	0.500	0.519
F	1, 4	9.600	0.036 *	1, 4	0.310	0.609
G	1, 4	27.00	0.007 **	1, 4	50.00	0.002 **
H	1, 4	18.00	0.013 *	1, 4	3.000	0.158

Table gives F ratios and probability values obtained from one-way analyses of variance. a) sixteen 1×2 analyses comparing sediments in air and the sediments in fresh water, eight for second angles of avalanche (A_2') and eight for second angles of repose (R_2). b) sixteen 1×2 analyses comparing sediments in fresh water and the sediments in 50% glycerol, eight for second angles of avalanche (A_2') and eight for second angles of repose (R_2). Probability: $0.05>P>0.01$ *; $0.01>P>0.001$ **; $P<0.001$ ***. For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1.

3.2.2 Hypothesis 2: Do the angles of avalanche and angles of repose vary with particle size?

(a) *First angle of avalanche (A_1) and first angle of repose (R_2)*

The data were statistically analysed by six 1×8 one-way analyses of variance (Table 3 5). Three one-way analyses of variance were done on the angles of avalanche and three one-way analyses of variance were done on the angles of repose.

All the six F ratios for first angles of avalanche and first angles of repose were highly significant (Table 3.5a rows 1, 2 and 3).

Differences between the sediments A, B, C, D, E, F, G and H were further analysed by comparing the pairs of sediments in turn by fifty six 1×2 one-way analyses of variance (Table 3.6). These detailed pairwise comparisons were only done for the data obtained from sediments in air, not for sediments in water and 50% glycerol. Out of the fifty six one-way analyses of variance on sediments in air, twenty eight were done on angles of avalanche (top right triangle of table 3.6) and twenty eight were done on angles of repose (bottom left triangle of table 3.6).

Thirteen out of the twenty eight comparisons for the first angles of avalanche, and ten out of the twenty eight comparisons for the first angles of repose, were significant. A detailed inspection of the statistical comparisons in table 3.6 together with the data in table 3.1 column 2 reveal a number of important points. In the well sorted sediments A, B, C and D, the highest angles of avalanche occurred in the coarsest sediment (sediment D) and the lowest angles of avalanche occurred in the finest sediment (sediment A) (A<B<C<D). However in the poorly sorted sediments E, F, G and H, made up of a mix of A to D, the highest angles of avalanche occurred in the sediment containing the greatest percentage of fine sediment (sediment F). The same is generally true for the angles of repose (A<B<C<D).

The relationship between the mean particle size of sediments A to H and the first angles of avalanche and angles of repose was further investigated by regression analyses. Figure 3.2 shows that there is a strong positive linear relationship between the first angles of avalanche and mean particle size and also between the first angles of repose and mean particle size. This means that the angles of avalanche and angles of repose increase with increasing mean particle size, and substantiates the results of the previous statistical analyses (3.2.2 (a)).

(b) *Second angle of avalanche (A_2') and second angle of repose (R_2)*

The data for the second angles of avalanche (A_2') and second angles of repose (R_2) are presented in table 3.2 and were statistically analysed the same way as the data of the first angles of avalanche (A_1) and first angles of repose (R_1) (Table 3.7).

The results of the statistical analyses for the second angles of avalanche and repose were broadly similar to results of the statistical analyses on the first angles of avalanche and repose. The second angles of avalanche and second angles of repose in air were higher in coarser sediments and lower in finer sediments.

Table 3.5 Avalanching experiment 2. Statistical analyses of the differences in angles of avalanche and in angles of repose between the sediment types (A, B, C, D, E, F, G and H).

Factors	Angle of Avalanche			Angle of Repose		
	DF	F ratio	Probability	DF	F ratio	Probability
Sediment types (A/B/C/D/E/F/G/H)						
a) First angle of avalanche (A_1) and first angle of repose (R_1)						
Air	7, 16	21.32	<0.001 ***	7, 16	7.560	<0.001***
Water	7, 16	110.7	<0.001 ***	7, 16	29.35	<0.001***
50% Glycerol	7, 16	13.98	<0.001 ***	7, 16	28.10	<0.001 ***
b) Second angle of avalanche (A_2') and second angle of repose (R_2)						
Air	7, 16	9.980	<0.001 ***	7, 16	7.010	<0.001***
Water	7, 16	21.35	<0.001 ***	7, 16	17.02	<0.001***
50% Glycerol	7, 16	15.21	<0.001 ***	7, 16	7.970	<0.001 ***

Table gives F ratios and probability values obtained from one-way analyses of variance. a) six 1×8 analyses comparing eight sediments A, B, C, D, E, F, G and H, three for first angles of avalanche (A_1) and three for first angles of repose (R_1). b) three 1×8 analyses comparing S1 sediments A, B, C, D, E, F, G and H, three for second angles of avalanche (A_2') and three for second angles of repose (R_2). Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***. For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1.

Table 3.6 Avalanching experiment 2. S1 sediment in air. Pairs of S1 sediments A, B, C, D , E, F, G and H were compared in turn by 1×2 one-way analyses of variance (DF=1, 4 and n=3). The table gives F ratios from these analyses. Upper right triangle: first angles of avalanche (A_1). Lower left triangle: first angles of repose (R_1). Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***.

Sediment Types	A	B	C	D	E	F	G	H
A		2.460	4.170	41.29 **	1.240	7.540	0.150	0.860
B	0.820		1.800	169.0 ***	0.800	18.00 *	18.00 *	1.800
C	3.120	1.400		75.57 **	3.120	1.800	16.20 *	4.500
D	10.12 *	6.430	1.140		112.0 ***	100.0 **	256.0 ***	120.1 ***
E	40.69 **	25.00 **	4.570	0.680		12.80 *	3.200	0.130
F	27.04 **	18.89 *	5.220	1.310	0.300		72.00 **	16.20 *
G	21.04 *	13.88 *	3.060	0.340	0.040	0.400		1.800
H	98.00 **	56.82 **	10.12 *	3.120	1.920	0.160	1.570	

For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1.

Table 3.7 Avalanching experiment 2. S1 sediment in air. Pairs of S1 sediments A, B, C, D , E, F, G and H were compared in turn by 1×2 one-way analyses of variance (DF=1, 4 and n=3). The table gives F ratios from these analyses. Upper right triangle: second angles of avalanche (A_2'). Lower left triangle: second angles of repose (R_2). For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1. Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***.

Sediment Types	A	B	C	D	E	F	G	H
A		27.13 **	23.68 **	22.08 **	38.23 **	64.80 **	27.46 **	59.52 **
B	0.140		0.030	1.160	0.000	3.770	0.140	4.000
C	1.320	1.000		0.790	0.050	1.800	0.030	2.130
D	5.080	4.740	3.770		1.390	0.020	0.610	0.000
E	21.05 *	36.00 **	✦	0.020		12.25 *	0.210	9.140
F	11.66 *	12.00 *	11.31 *	0.540	0.920		1.470	0.200
G	27.84 **	49.00 **	✦	0.310	✦	0.230		1.800
H	19.17 *	27.77 **	64.00 **	0.070	0.250	0.580	1.000	

✦ There is no difference between the replicate values for angles of repose of sediments C, E and G (see table 3.2 column 4). Therefore angles of repose of sediments C, E and G can not be compared with each other.

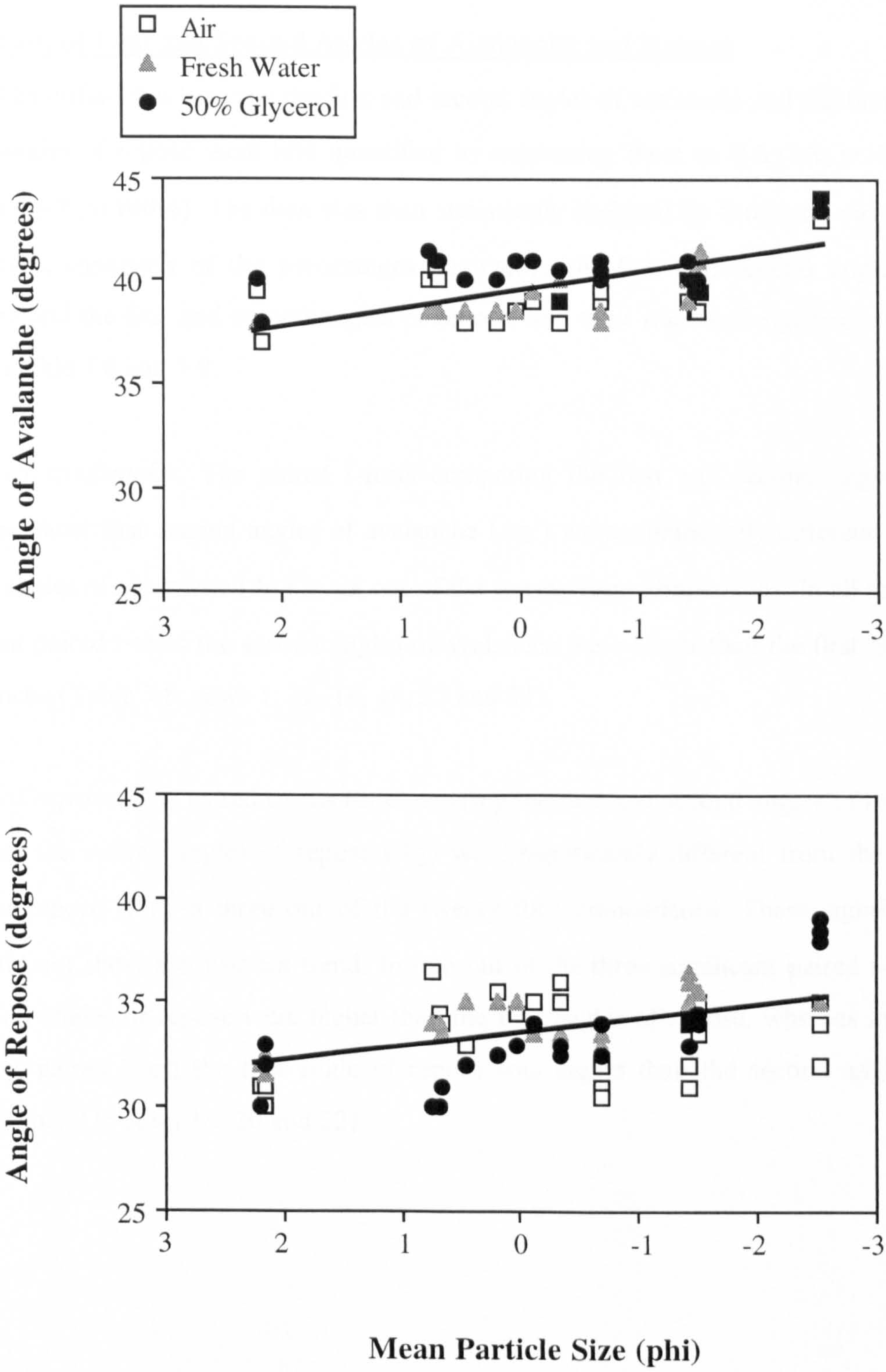


Figure 3.2 Data from avalanching experiment 2. **Top:** relationship between the first angle avalanche and particle mean size in phi (ϕ) unit ($y = -0.851x + 39.60$, $F_{1,70} = 55.24$ $P<0.001$ ***). **Bottom:** relationship between the first angle of repose and mean particle size in phi (ϕ) units ($y = -0.758x + 33.33$, $F_{1,70} = 29.24$ $P<0.001$ ***). Sediments in air, fresh water and 50% glycerol.

(c) Comparison of First and Second Angles of Avalanche and Repose

The differences between the first and second angles of avalanche and the first and second angles of repose were first quantified by expressing them as $((A_2'/A_1)\times 100\%)$ and as $((R_2/R_1)\times 100\%)$. The data was then statistically analysed by Student's paired t-tests. The comparison of the percentages comparing the first and second angles of avalanche and the first and second angles of repose, and their statistical significance are shown in table 3 8 and 3.9.

Angles of avalanche: The paired t-tests comparing the first and second angles of avalanche show that second angles of avalanche (A_2') were significantly different from the first angles of avalanche (A_1) in six out of the twenty four comparisons. In all the six significant paired t-tests the second angles of avalanche were lower than the first angles of avalanche (Table 3.8 rows 1, 12, 14, 18, 22 and 23).

Angles of repose: The paired t-tests for comparing the first and second angles of repose show that the second angles of repose (R_2) were significantly different from the first angles of repose (R_1) in three out of the twenty four comparisons. These significant results did not show a consistent trend. In two out of the three significant paired t-tests the second angles of repose were higher than the first angles of repose, whereas in one significant paired t-test the first angle of repose was higher than the second angle of repose (Table 3.9 rows 16, 20 and 22).

Table 3.8 Avalanching experiment 2. Comparison of first angles of avalanche (A_1) and second angles of avalanche (A_2') by Student's paired t-test (DF=1, Fisher and Yates 1963). Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***.

Sediment	$(A_2' / A_1) \times 100$			Student's t	Probability
	Rep. 1	Rep. 2	Rep. 3		
1) Sediment in Air					
A	89.87	91.89	89.20	11.00	0.0082 **
B	102.6	96.20	100.0	0.230	0.840
C	95.00	103.8	97.50	0.480	0.680
D	97.70	91.86	88.64	2.710	0.110
E	102.6	101.3	97.47	-0.280	0.810
F	100.0	100.0	100.0	Values are identical	
G	100.0	105.3	103.9	-1.940	0.190
H	105.3	105.1	102.6	-5.000	0.038
2) Sediment in Fresh Water					
A	92.11	100.0	93.42	1.980	0.190
B	101.3	100.0	100.0	-1.000	0.420
C	105.1	100.0	100.0	-1.000	0.420
D	95.40	95.46	96.59	0.650	0.580
E	100.0	101.2	95.18	3.460	0.074
F	96.10	97.40	98.70	11.00	0.0082 **
G	101.3	101.3	101.3	Values are identical	
H	92.50	92.50	94.94	8.000	0.015 *
3) Sediment in 50% Glycerol					
A	57.50	102.6	100.0	0.720	0.550
B	92.68	91.25	91.36	20.00	0.003 **
C	92.68	96.34	98.75	2.290	0.150
D	98.85	104.6	97.73	-0.180	0.870
E	97.50	100.0	100.0	1.000	0.420
F	89.02	83.13	86.59	7.800	0.016 *
G	92.50	95.00	91.46	6.430	0.023 *
H	96.30	98.72	97.56	3.460	0.074

For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1.

Table 3.9 Avalanching experiment 2. Comparison of first angles of repose (R_1) and second angles of repose (R_2) by Student's paired t-test (DF=1, Fisher and Yates 1963). Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***.

Sediment	$(R_2 / R_1) \times 100$			Student's t	Probability
	Rep. 1	Rep. 2	Rep. 3		
1) Sediment in Air					
A	100.0	104.8	100.0	-1.000	0.420
B	96.88	106.6	100.0	0.230	0.740
C	103.2	94.12	100.0	0.380	0.740
D	91.43	102.9	112.5	-0.330	0.770
E	98.57	98.57	103.0	0.000	1.000
F	98.53	101.4	104.4	-0.870	0.480
G	106.1	98.59	101.5	-0.920	0.460
H	97.14	97.22	100.0	2.000	0.180
2) Sediment in Fresh Water					
A	101.6	98.46	101.6	-0.500	0.670
B	98.49	96.97	98.51	4.000	0.057
C	91.78	92.86	93.06	-1.000	0.420
D	101.4	100.0	97.14	0.380	0.740
E	100.0	98.59	101.4	0.000	1.000
F	97.02	98.53	101.5	0.760	0.530
G	102.9	101.4	102.9	-5.000	0.038 *
H	100.0	100.0	100.0	Values are identical	
3) Sediment in 50% Glycerol					
A	113.3	96.97	100.0	-0.650	0.580
B	95.59	101.5	104.6	-0.190	0.870
C	106.1	100.0	106.1	-2.000	0.180
D	92.11	89.74	93.51	7.180	0.019 *
E	102.9	102.9	102.9	Values are identical	
F	106.5	111.7	110.0	-0.643	0.023 *
G	107.8	104.6	103.0	-3.780	0.063
H	103.0	106.2	98.53	-1.150	0.370

For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1.

3.2.3 Hypothesis 3: Does medium and sediment type affect factors of safety and angles of dilatation?

The factor of safety values are shown in table 3.10 and angle of dilatation values are shown in table 3.11. Their statistical analyses are shown in table 3.12.

Two out of the eight comparisons of the factors of safety between air and fresh water were significant (Table 3.12a column 2, 3 & 4). In one comparison, the factor of safety in air was significantly higher than in fresh water, whereas in the other comparison the factor of safety in fresh water was significantly higher than in air.

Five out of the eight comparisons of the factors of safety between fresh water and 50% glycerol were significant (Table 3.12b column 2, 3 & 4). In four comparisons, the factors of safety in 50% glycerol were significantly higher than in fresh water, whereas in one comparison the factor of safety in fresh water was significantly higher than in 50% glycerol (Table 3.10).

The same is true for the comparisons of angles of dilatation (Table 3.11 and Table 3.12 columns 5, 6 & 7).

The above results show that there is no difference in the factors of safety in air and fresh water, but that in some cases the factor of safety is greater in 50% glycerol than in fresh water.

Table 3.10 Avalanching experiment 2. Effects of medium on factors of safety in first angle of avalanche (F_1) and in second avalanche (F_2). Mean ± SD of three replicate readings.

Sediment Type	$F_1 = Tan (A_1) / Tan (R_1)$			$F_2 = Tan (A_2') / Tan (R_2)$.		
	Air	Fresh water	50% Glycerol	Air	Fresh water	50% Glycerol
A	1.310±0.059	1.250±0.025	1.302±0.133	1.124±0.064	1.164±0.078	1.195±0.138
B	1.348±0.052	1.203±0.001	1.316±0.026	1.323±0.088	1.241±0.014	1.161±0.058
C	1.313±0.101	1.149±0.052	1.307±0.028	1.304±0.059	1.300±0.027	1.172±0.053
D	1.428±0.103	1.371±0.014	1.200±0.025	1.253±0.187	1.295±0.060	1.356±0.088
E	1.172±0.063	1.234±0.047	1.214±0.026	1.178±0.021	1.212±0.033	1.156±0.000
F	1.207±0.063	1.187±0.013	1.495±0.044	1.186±0.076	1.160±0.023	1.092±0.051
G	1.152±0.054	1.136±0.000	1.333±0.014	1.171±0.047	1.122±0.012	1.131±0.032
H	1.129±0.023	1.260±0.013	1.292±0.022	1.228±0.026	1.145±0.012	1.209±0.056

For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1.

Table 3.11 Avalanching experiment 2. Effects of medium on angles of dilatation in first avalanche (D_1) and in second avalanche (D_2). Mean ± SD of three replicate readings.

Sediment Type	$D_1 = A_1 - R_1$			$D_2 = A_2' - R_2$		
	Air	Fresh water	50% Glycerol	Air	Fresh water	50% Glycerol
A	7.167±1.258	6.000±0.500	7.000±2.646	3.000±1.500	4.000±1.803	3.820±3.215
B	8.000±1.000	5.000±0.000	7.500±0.500	7.500±1.803	5.833±0.289	4.000±1.323
C	7.333±2.082	3.833±1.258	7.333±0.577	7.167±1.258	7.167±0.577	4.333±1.258
D	9.833±1.893	8.833±0.289	5.167±0.577	6.000±3.969	7.167±1.258	8.500±1.803
E	4.333±1.443	5.833±1.041	5.333±0.577	4.500±0.500	5.333±0.764	4.000±0.000
F	5.167±1.443	4.667±0.289	10.83±0.764	4.667±1.756	4.000±0.289	2.333±1.258
G	3.833±1.258	3.500±0.000	7.833±0.289	4.333±1.155	3.167±0.289	3.333±0.764
H	3.333±0.577	6.333±0.289	7.000±0.500	5.667±0.577	3.667±0.289	5.167±1.258

For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1.

Table 3.12 Avalanching experiment 2. Statistical analyses of the differences between the media in factors of safety of first avalanche (F_1), and between the media in angles of dilatation in first avalanche (D_1). a) comparisons of air and fresh water. b) comparisons of fresh water and 50% glycerol. Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***.

Factors	F_1 = Tan (A_1) / Tan (R_1)			$D_1 = A_1 - R_1$		
	DF	F ratio	Probability	DF	F ratio	Probability
Medium						
a) Air / Fresh water						
A	1, 4	2.630	0.180	1, 4	2.230	0.210
B	1, 4	23.78	0.008 **	1, 4	27.00	0.007 **
C	1, 4	6.280	0.066	1, 4	6.210	0.067
D	1, 4	0.900	0.397	1, 4	0.820	0.417
E	1, 4	1.870	0.243	1, 4	2.130	0.218
F	1, 4	0.300	0.615	1, 4	0.350	0.588
G	1, 4	0.250	0.643	1, 4	0.210	0.670
H	1, 4	71.54	0.001 **	1, 4	64.80	0.001 **
b) Fresh water / 50% Glycerol						
A	1, 4	0.440	0.544	1, 4	0.410	0.555
B	1, 4	56.53	0.002 **	1, 4	75.00	0.001 **
C	1, 4	21.20	0.010 *	1, 4	19.17	0.012 *
D	1, 4	110.0	<0.001 ***	1, 4	96.80	0.001 **
E	1, 4	0.430	0.547	1, 4	0.530	0.507
F	1, 4	137.6	<0.001 ***	1, 4	171.1	<0.001 ***
G	1, 4	594.0	<0.001 ***	1, 4	676.0	<0.001 ***
H	1, 4	4.420	0.103	1, 4	4.000	0.116

For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1.

The relationship between the factors of safety and the angles of avalanche and angles of repose was further investigated by using regression analyses. Figure 3.3 shows that there is a strong positive linear relationship between the factors of safety and the angles of avalanche and a strong negative relationship between the factors of safety and the angles of repose

The relationship between the factor of safety and angle of avalanche was then investigated in detail by eight regression analyses, one for each sediment A, B, C, D, E, F, G and H. The regression lines for the relationship between the factors of safety and angles of avalanche were significant in five sediments: A, E, F, G and H (Fig. 3.4 and 3.5). The slopes of the five significant regression lines were then compared by F ratios (Snedecor and Cochran 1980 pp 435). Seven out of the ten comparisons were significant (Table 3.13 column 1 and 2). There were no significant differences between the slopes of the three sediments F, G and H (Table 3.13 column 1 and 2 rows 8, 9 and 10). The highest slope was shown by sediment F (0.105, Fig. 3.5). The lowest slope was shown by sediment E (0.0387, Fig. 3.5).

In the same way, eight regression analyses were conducted on the relationship between the factor of safety and angle of repose one on each of the eight sediments (Fig. 3 6 and 3.7) Seven out of the eight regression lines were significant. These were for sediments A, B, C, D, F, G and H (Fig. 3.7). The slopes of the seven significant regression lines were then compared by F ratios (Table 3.13 column 3 and 4). Eleven out of the twenty one comparisons were significant. The slope of sediment B was not significantly different from the slopes of sediments C, F, G and H (Table 3.13 column 3 and 4 rows 7, 9, 10 and 11). The differences between the slopes of the three sediments F, G and H were also not significant (Table 3.13 column 3 and 4 rows 19, 20 and 21). The highest slope was shown by sediment G (0.0708, Fig. 3.7). The lowest slope was shown by sediment E (0.0358, Fig. 3.7).

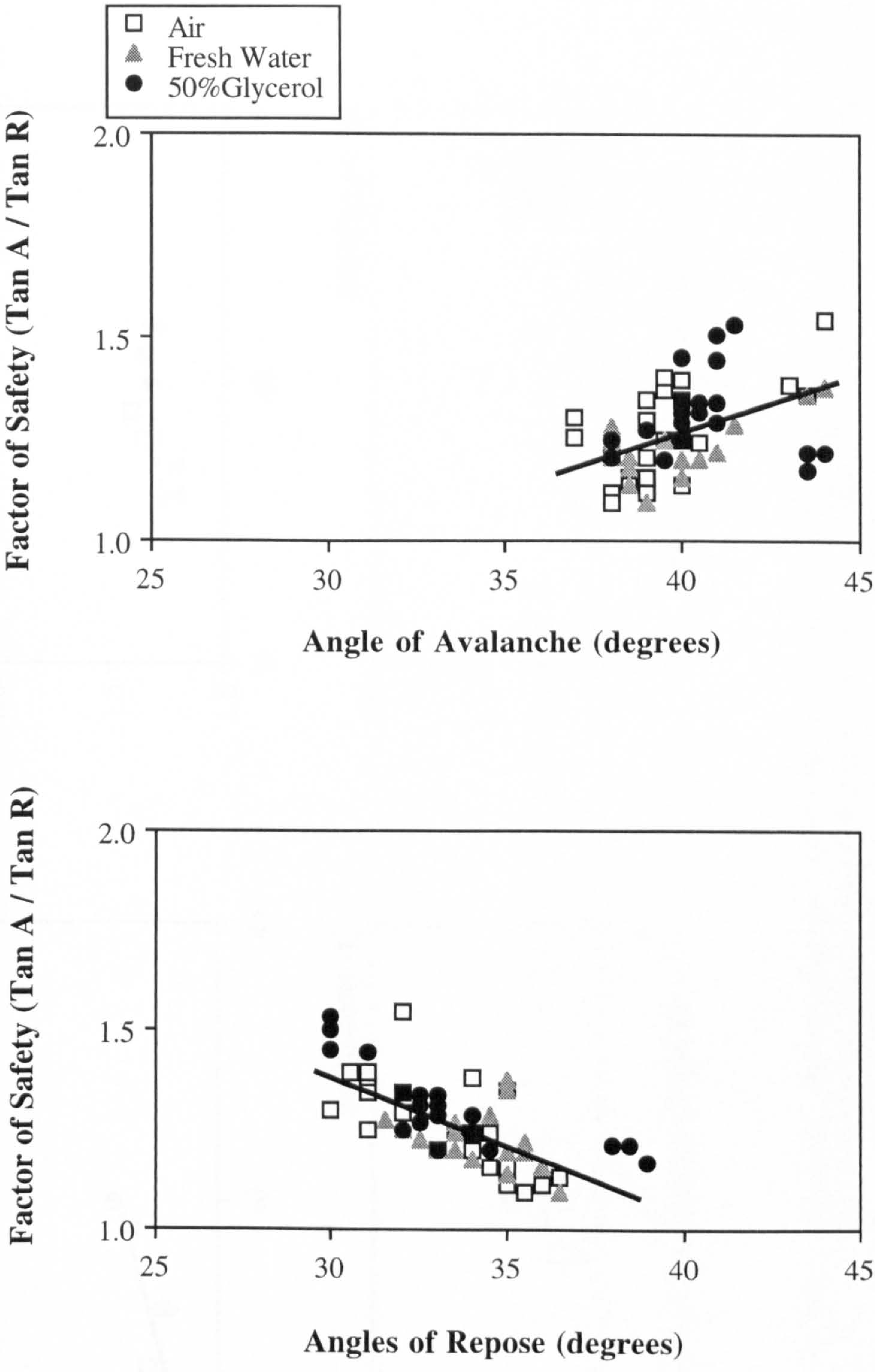


Figure 3.3 Combined data from avalanching experiment 2. **Top:** relationship between the factor of safety and first angle avalanche ($y = 0.0287\ x + 0.117$, $F_{1,70} = 22.96$ $P<0.001$ ***). **Bottom:** relationship between the factor of safety and first angle of repose ($y = -\ 0.0349\ x + 2.440$, $F_{1,70} = 53.23$ $P<0.001$ ***).

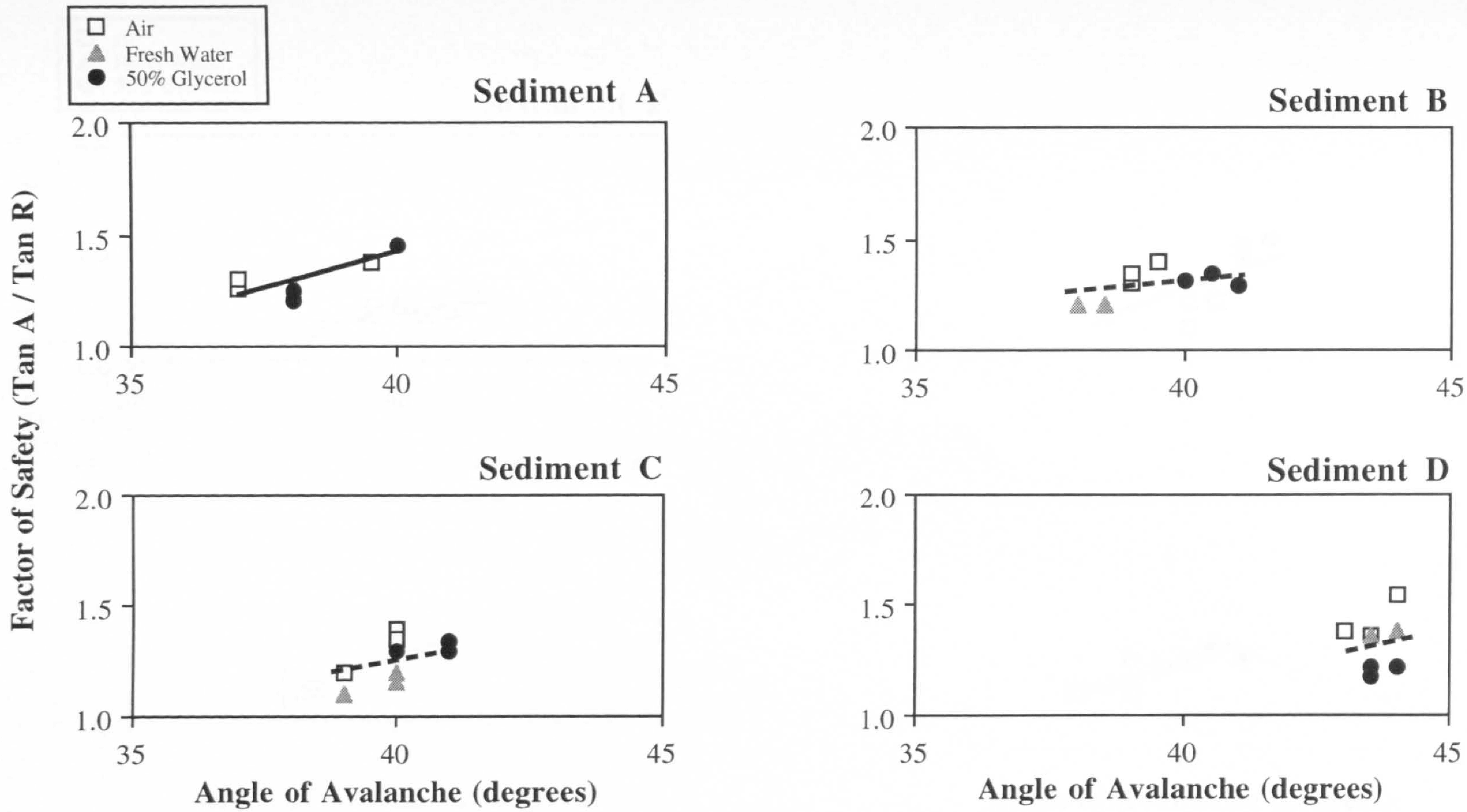


Figure 3.4 Data from avalanching experiment 2. Relationship between the factors of safety and first angle of avalanche. **Top:** left; sediment A data ($y = 0.0592x - 0.972$, $F_{1,7} = 9.000$ $P=0.020$ *). right; sediment B data ($y = 0.0417x - 0.348$, $F_{1,7} = 4.27$ $P=0.078$ ns). **Bottom:** left; sediment C data ($y = 0.0833x - 2.07$, $F_{1,7} = 3.760$ $P=0.094$ ns). right; sediment D data ($y = 0.067x - 1.61$, $F_{1,7} = 0.310$ $P=0.594$ ns). ns = not significant regression line indicated by a dotted line.

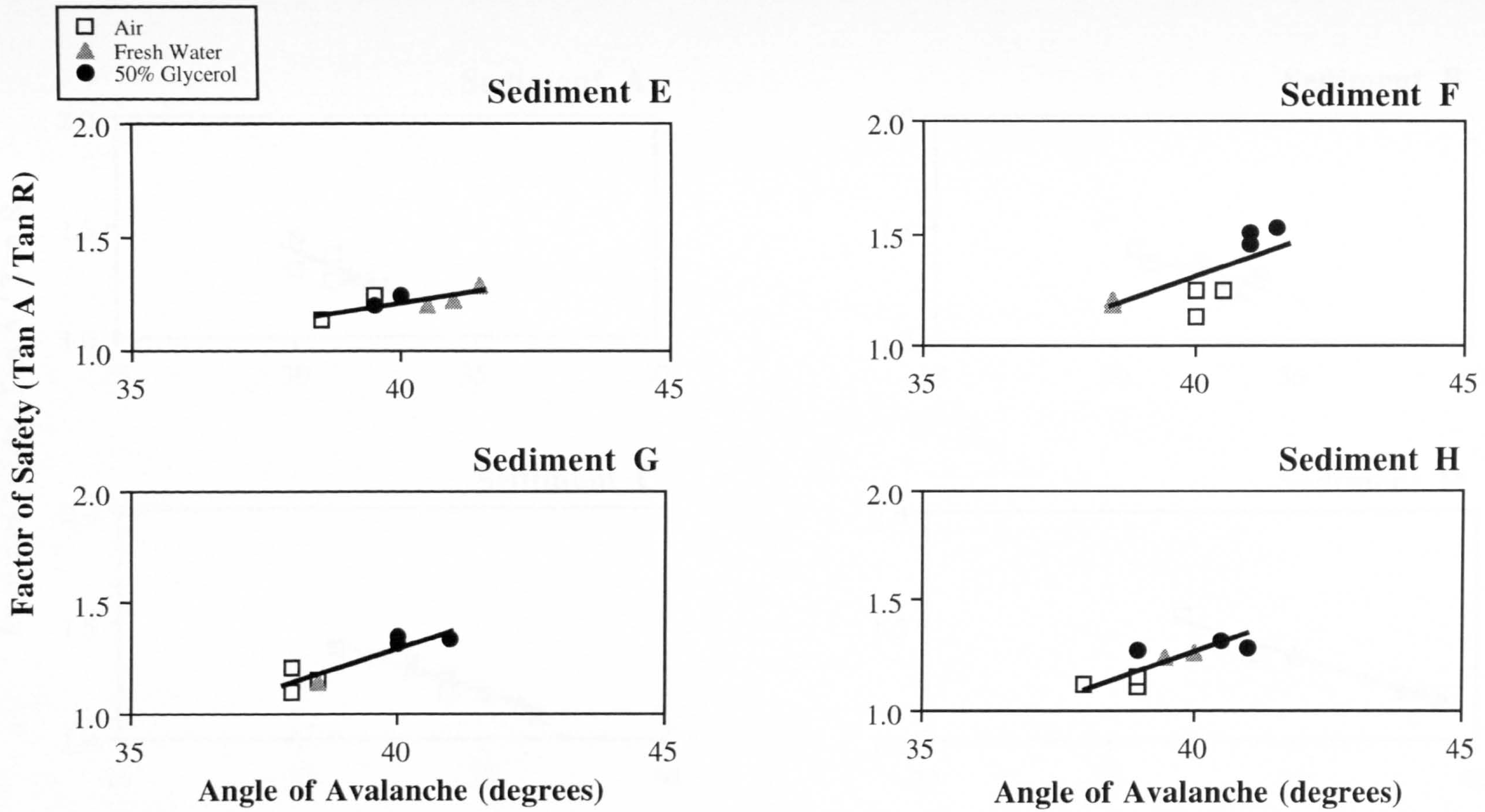


Figure 3.5 Data from avalanching experiment 2. Relationship between the factors of safety and first angle of avalanche. **Top:** left; sediment E data ($y = 0.0387x - 0.334$, $F_{1,7} = 12.82$ $P=0.009$ **). right; sediment F data ($y = 0.105x - 2.910$, $F_{1,7} = 13.10$ $P=0.009$ **). **Bottom:** left; sediment G data ($y = 0.0842x - 2.080$, $F_{1,7} = 30.89$ $P<0.001$ ***). right; sediment H data ($y = 0.0681x - 1.470$, $F_{1,7} = 13.73$ $P=0.008$ **).

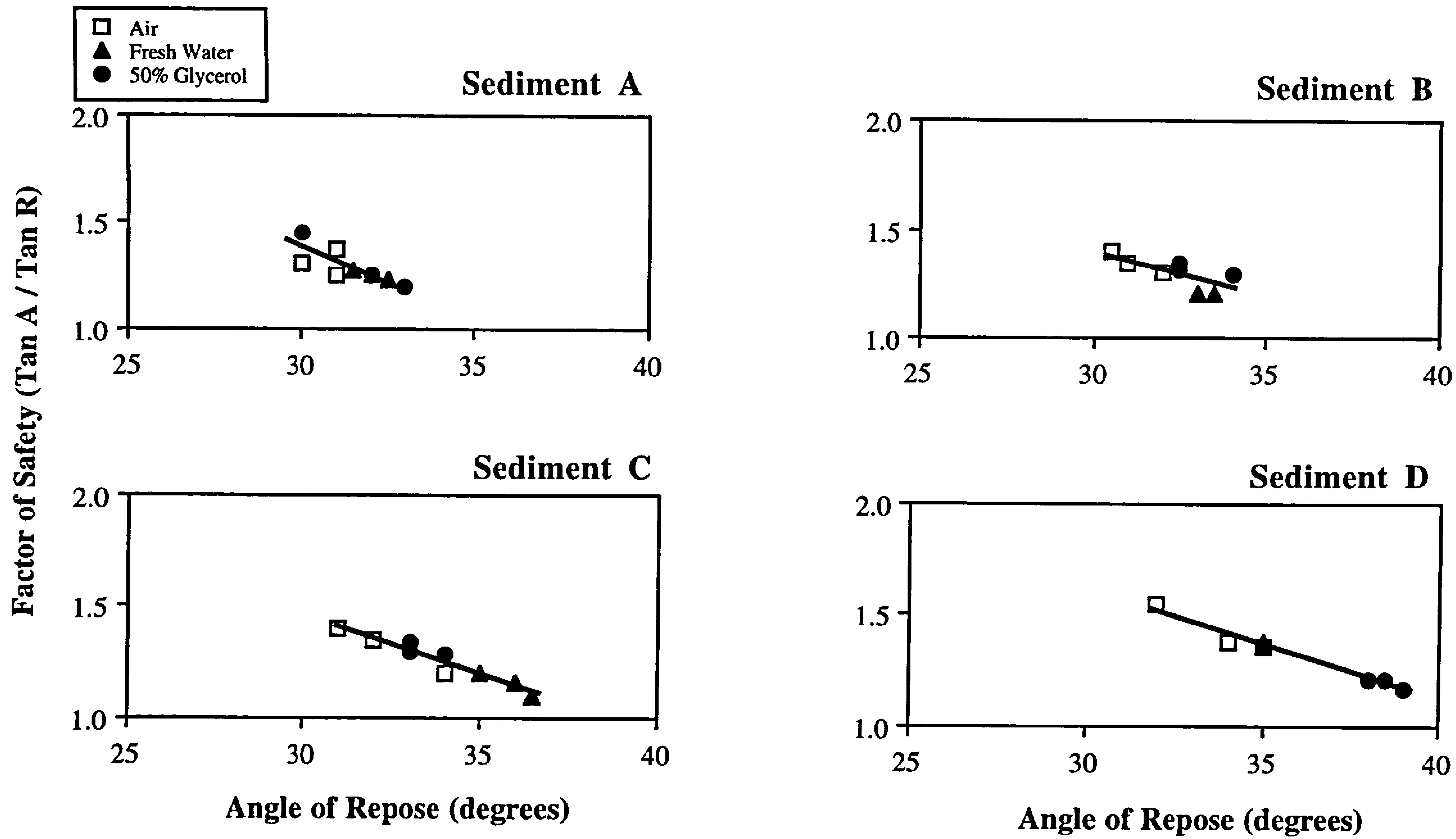


Figure 3.6 Data from avalanching experiment 2. Relationship between the factors of safety and first angle of repose. **Top:** left; sediment A data ($y = -0.0603x + 3.180$, $F_{1,7} = 12.21$ $P=0.010$ *). right; sediment B data ($y = -0.0475x + 2.83$, $F_{1,7} = 8.740$ $P=0.021$ *). **Bottom:** left; sediment C data ($y = -0.0530x + 3.050$, $F_{1,7} = 81.15$ $P<0.001$ ***). right; sediment D data ($y = -0.0494x + 3.10$, $F_{1,7} = 244.3$ $P<0.001$ ***).

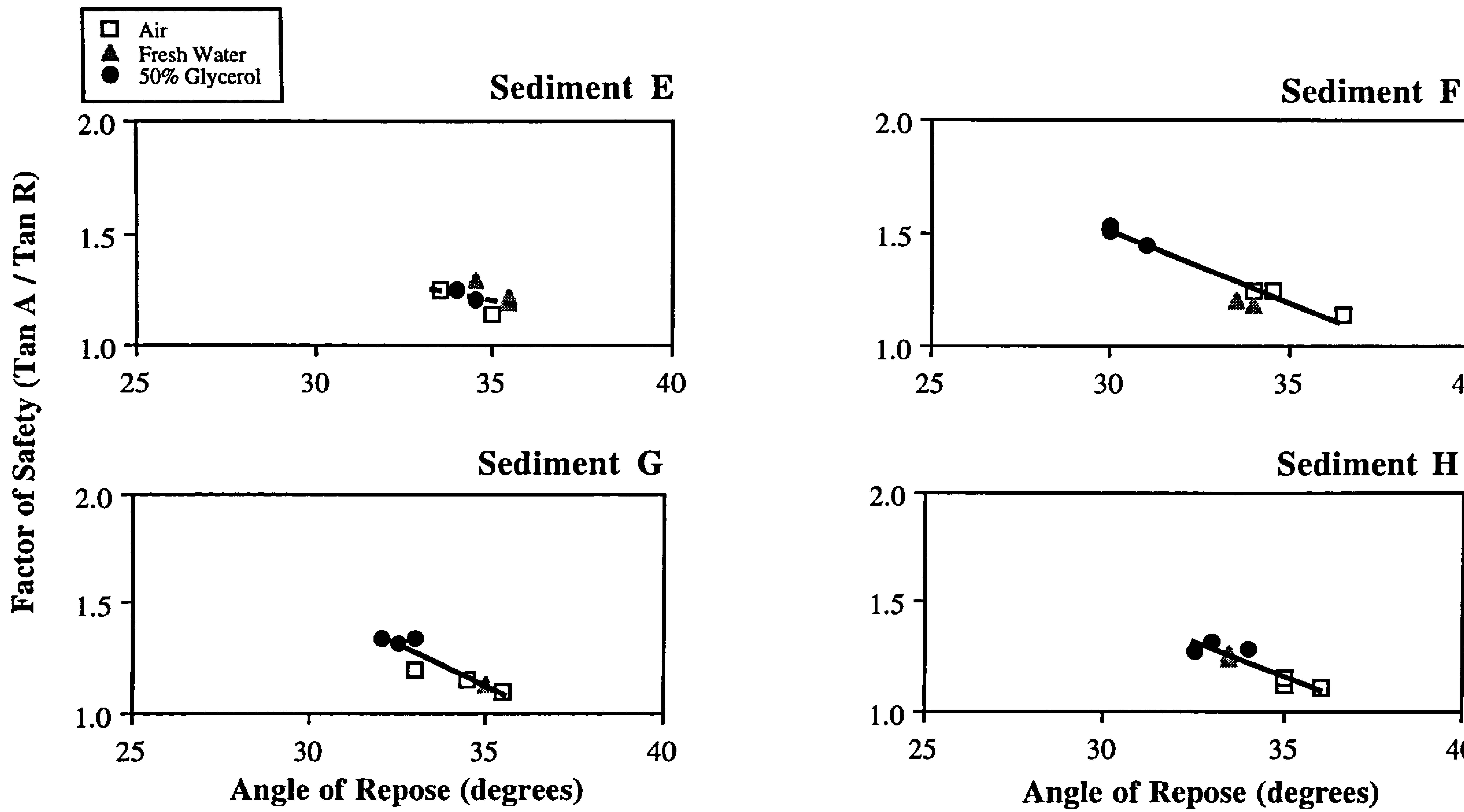


Figure 3.7 Data from avalanching experiment 2. Relationship between the factors of safety and first angle of repose. **Top:** left; sediment E data (y = - 0.0358 x + 2.450, $F_{1,7}$ = 2.070 P=0.193 ns). right; sediment F data (y = - 0.0659 x + 3.480, $F_{1,7}$ = 67.91 P<0.001 ***). **Bottom:** left; sediment G data (y = - 0.0708 x + 3.610, $F_{1,7}$ = 50.71 P<0.001 ***). right; sediment H data (y = - 0.0610 x + 3.300, $F_{1,7}$ = 26.29 P<0.001 ***). ns = not significant regression line indicated by a dotted line.

Table 3.13 Comparisons of slopes of significant regression lines. Part I. Factor of safety against angle of avalanche. Part II. Factor of safety against angle of repose. Pairs of regression equations were compared in turn. Table gives the F ratio values obtained from these comparisons (Snedecor and Cochran 1980 pp 435). Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***.

Factor of safety against angle of avalanche		Factor of safety against angle of repose	
Comparison	$F_{1,14}$	Comparison	$F_{1,14}$
A/E	33.56 ***	A/B	4.387
A/F	10.11 *	A/C	14.86 **
A/G	30.28 ***	A/D	80.30 ***
A/H	23.19 ***	A/F	18.16 ***
E/F	9.683 *	A/G	7.733 *
E/G	12.75 **	A/H	7.772 *
E/H	5.135 *	B/C	3.218
F/G	0.381	B/D	64.21 ***
F/H	1.784	B/F	4.551
G/H	1.428	B/G	1.700
		B/H	1.183
		C/D	163.6 ***
		C/F	1.685
		C/G	9.835 *
		C/H	1.988
		D/F	82.32 ***
		D/G	205.6 ***
		D/H	149.0 ***
		F/G	2.000
		F/H	0.253
		G/H	2.237

For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1.

3.2.4 <u>Hypothesis 4</u>: Does medium and sediment type affect the duration of avalanche?

The duration (seconds) of the first avalanche (T_1) and the duration of the second avalanche (T_2) are shown in table 3.14. The statistical analyses for the duration of avalanche were divided into two parts (Table 3.15). In part one, the differences in the duration between the three media: air / fresh water and fresh water / 50% glycerol are analysed, and in part two the differences in the duration of avalanche between the eight sediments A, B, C, D, E, F, G and H are analysed.

Part one: The differences in the duration of avalanche between the three media: air / fresh water and fresh water / 50% glycerol were statistically analysed as follows. Firstly sediments in air were compared with the sediments in fresh water by sixteen 1×2 one-way analyses of variance. Secondly the sediments in fresh water were compared with the sediments in 50% glycerol by sixteen 1×2 one-way analyses of variance. In each of the two sets of sixteen one-way analyses of variance, eight analyses were done on the duration of the first avalanche (T_1), and eight analyses were done on the duration of the second avalanche (T_2).

All the eight comparisons for the duration of the first avalanche between air and fresh water were significant and all the eight comparisons for the duration of the second avalanche between air and fresh water were significant (Table 3.15 rows 1 to 8). In all of these sixteen significant comparisons (T_1 & T_2), an inspection of the data in table 3.15 showed that the duration of the avalanches in water was longer than the duration of the avalanches in air.

Seven out of the eight comparisons for the duration of the first avalanche between fresh water and 50% glycerol were significant, and six out of the eight comparisons for the duration of the second avalanche between water and 50% glycerol were significant (Table 3.15 rows 9 to 16). In all these thirteen significant comparisons, the duration of the avalanches in 50% glycerol was longer than the duration of the avalanche in water. The longest duration of avalanche occurred in 50% glycerol (80.18 seconds, Table 3.14) and the shortest duration of avalanche occurred in air (0.50 seconds, Table 3.14).

Part two: The differences in the duration of avalanche between the eight sediments A, B, C, D, E, F, G and H were statistically analysed by six 1×8 one-way analyses of variance. Three one-way analyses of variance were done on the duration of the first avalanche (T_1) between the sediments - one for the air data, one for the water data, and one for the 50% glycerol data. The same was done for the duration of the second avalanche (T_2).

All the six 1×8 one-way analyses of variance were significant (Table 3.15 rows 17, 18 and 19) In the well sorted sediments A, B, C and D the highest duration of avalanche occurred in the finest sediment (sediment A) and the lowest duration of avalanche occurred in coarsest sediment (sediment D). In the poorly sorted sediments E, F, G and H, made up of a mix of A to D, the longest duration of avalanche occurred in the sediment containing the greatest percentage of fine sediment (sediment F) in most cases (Table 3.14).

The relationship between duration of the first avalanche and the mean particle size of sediments A to H was further investigated in the three media: air, fresh water and 50% glycerol. This was done by regression analysis. Figure 3.8 shows that there is a strong negative linear relationship between the duration of avalanche and mean particle size. This relationship is more obvious and highly significant in fresh water ($y = 4.89\ x + 9.49$, $F_{1,22} = 93.34$ $P<0.001$ ***) and very highly significant in 50% glycerol ($y = 20.5\ x + 35\ 2$, $F_{1,22} = 69.23$ $P<0.001$ ***).

Table 3.14 Avalanching experiment 2. Effects of medium on duration of first avalanche (T_1) and duration of second avalanche (T_2).

Sediment Type	Duration of first avalanche (T_1) (seconds)			Duration of second avalanche (T_2) (seconds)		
	Air	Fresh water	50% Glycerol	Air	Fresh water	50% Glycerol
A	1.833±0.176	20.03±0.693	80.18±2.581	1.733±0.379	19.90±5.425	68.70±6.689
B	0.933±0.076	1.900±0.050	3.133±0.126	0.750±0.050	1 567±0.115	3.033±0.058
C	0.933±0.126	1.367±0.189	1.967±0.115	0.867±0.029	1.633±0.176	2.067±0.058
D	0.783±0.029	1.333±0.126	2.167±0.379	0.833±0.076	1.283±0.161	1.550±0.132
E	0.567±0.076	1.167±0.029	1.583±0.382	0.633±0.076	1.233±0.104	1.550±0.304
F	0.500±0.050	18.97±0.954	79.80±5.806	0.567±0.076	18.12±2.973	60.17±6.914
G	0.550±0.050	9.917±0.355	33.97±4.865	0.517±0.058	7.600±0.781	33.93±2.980
H	0.567±0.029	5.117±0.592	11.42±1.941	0.617±0.029	4.650±0.229	12.50±4.264

For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1.

Table 3.15 Avalanching experiment 2. Statistical analyses of the differences in duration of first avalanche (T_1) and in the duration of second avalanche (T_2) between the I) medium (air / fresh water and fresh water / 50% glycerol) and between the II) sediment types (A, B, C, D, E, F, G and H). Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***

Factors	T_1			T_2		
	DF	F ratio	Probability	DF	F ratio	Probability
Part I: Medium						
a) Air / Fresh water						
A	1, 4	1942.1	<0.001 ***	1, 4	33.48	0.004 **
B	1, 4	336.4	<0.001 ***	1, 4	126.4	<0.001 ***
C	1, 4	10.90	0.030 *	1, 4	55.68	0.002 **
D	1, 4	54.45	0.002**	1, 4	19.18	0.012 *
E	1, 4	162.0	<0.001 ***	1, 4	64.80	0.001 **
F	1, 4	1120.1	<0.001 ***	1, 4	104.5	0.001 **
G	1, 4	2050.9	<0.001 ***	1, 4	245.4	<0.001 ***
H	1, 4	176.6	<0.001 ***	1, 4	915.1	<0.001 ***
b) Fresh water / 50% Glycerol						
A	1, 4	1519.8	<0.001 ***	1, 4	96.31	0.001 **
B	1, 4	248.9	<0.001 ***	1, 4	387.2	<0.001 ***
C	1, 4	21.97	0.009 **	1, 4	16.49	0.015 *
D	1, 4	13.09	0.022 *	1, 4	4.920	0.091
E	1, 4	3.550	0.133	1, 4	2.910	0.163
F	1, 4	320.7	<0.001 ***	1, 4	93.65	0.001 **
G	1, 4	72.93	0.001 **	1, 4	219.2	<0.001 ***
H	1, 4	28.92	0.006 **	1, 4	10.14	0.033 *
Part II: Sediment type (A/B/C/D/E/F/G/H)						
Air	7, 16	71.53	<0.001 ***	7, 16	21.87	<0.001 ***
Water	7, 16	797.2	<0.001 ***	7, 16	36.92	<0.001 ***
50% Glycerol	7, 16	421.1	<0.001 ***	7, 16	156.3	<0.001 ***

For S1 sediments A, B, C, D, E, F, G and H see table 1.1 and figure 3.1.

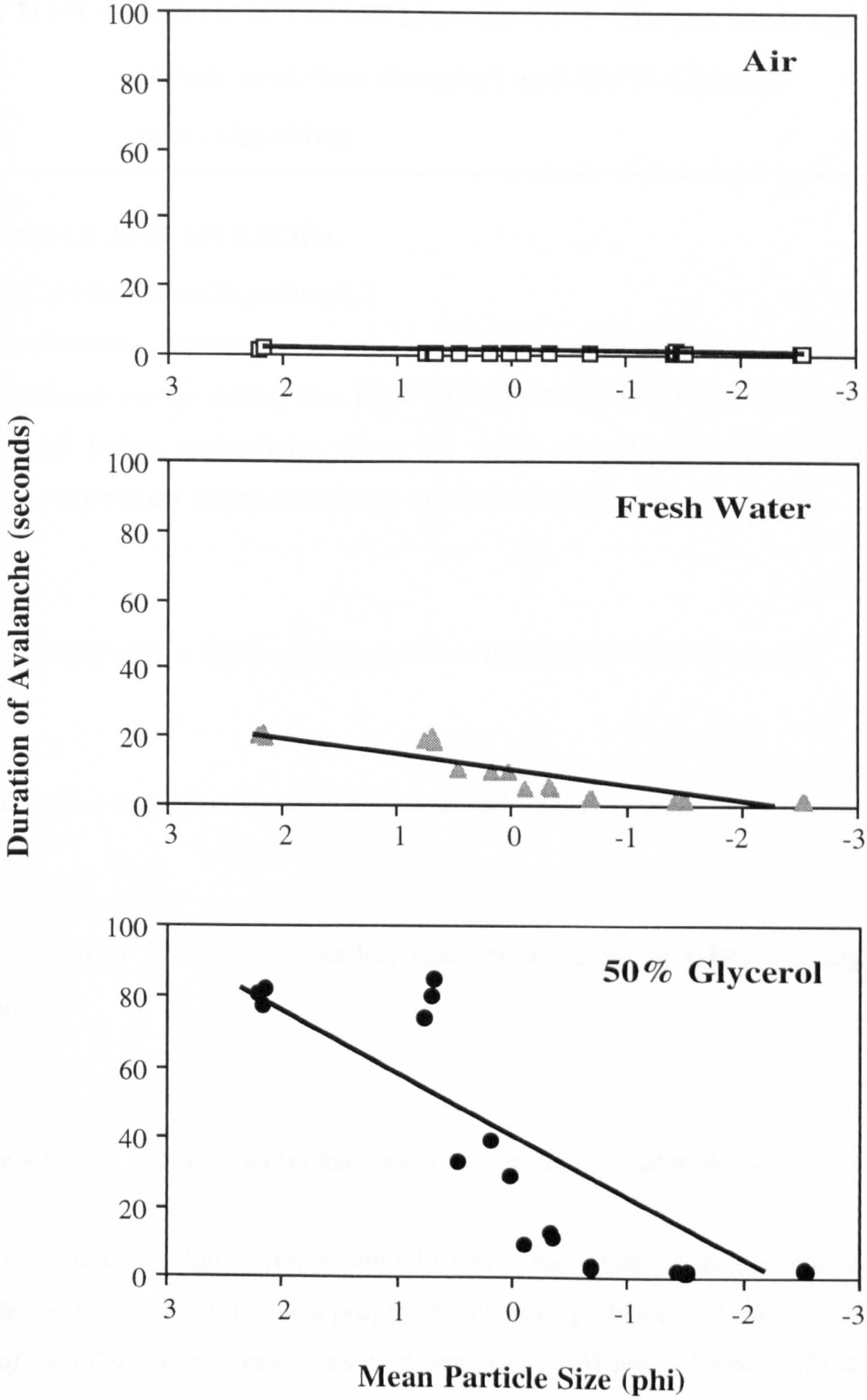


Figure 3.8 Avalanching experiment 2. Combined data of sediments A, B, C, D, E, F, G and H. Relationship between the duration of the first avalanche (seconds) and mean particle size in phi (ϕ) units. **Top:** sediments in air (y = 0.149 x + 0.895, $F_{1, 22} = 6.98$ P=0.015 *). **Middle:** sediments in fresh water (y = 4.89 x + 9.49, $F_{1, 22} = 93.34$ P<0.001 ***). **Bottom:** sediments in 50% glycerol (y = 20.5 x + 35.2, $F_{1, 22} = 69.23$ P<0.001 ***).

SECTION 4: Effects of Viscous Liquids: GF/F filtered fresh water, Alginic acid (low viscosity) and 100% Glycerol on Avalanching

4.1 MATERIALS AND METHODS

4.1.1 Design of Avalanching Experiment 3

Avalanching experiment 3 was designed to test whether the viscosity of supporting liquid and the settling time (time for which the sediment was left to stand in a viscous liquid before avalanching) affects the angles of avalanche and the angles of repose. The experiment design allowed me to answer the following hypotheses.

Hypothesis 1:
Does the viscosity of the liquid affect angles of avalanche and angles of repose?

Hypothesis 2:
Does the settling time affect angles of avalanche and angles of repose?

Hypothesis 3:
Does the viscosity of liquid and settling time affect factors of safety and angles of dilatation?

Hypothesis 4:
Does the viscosity of liquid and settling time affect the duration of avalanche?

Three different liquids (GF/F filtered fresh water, Alginic acid low viscosity and 100% Glycerol) were used. Physical properties of these liquids are presented in table 4.1. 400 ml of the following sediments was used: sediment A (63 μm to 1 mm), sediment E = (1:1:1; B:C:D) (coarse sediments), sediment F = (2:1; A:E) and sediment H = (1:2; A:E) (fine: coarse). The sediments in the container were left to stand for six different settling times. 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and for 15 hours before being avalanched. Two replicate readings were taken (Fig 4.1).

(Note: A, E, F and H are the fractions of the S1 sediment described in Section 1.1.2, see table 1.1)

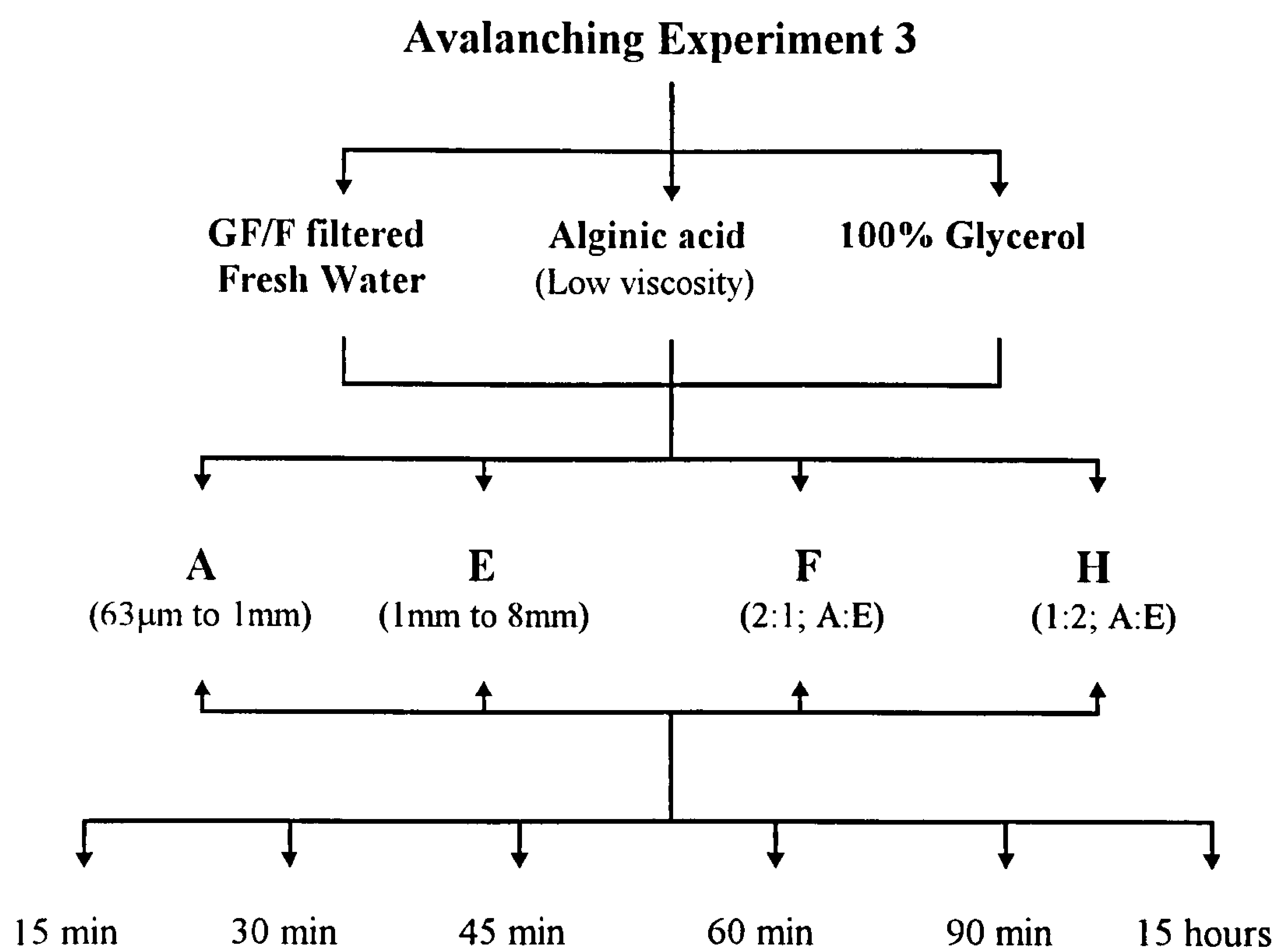


Figure 4.1 Avalanching experiment 3. Three liquids of different viscosity's: GF/F filtered fresh water, Alginic acid (low viscosity) and 100% Glycerol. Six settling times: 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and for 15 hours for which the sediments were left to stand before avalanching. Four S1 sediments A, E, F and H (see Table 1.1). Sediment A = Fine sand (63 µm to 1 mm). Sediment E = (1:1:1; B:C:D) means sediment E contain one part of sediment B (1 mm to 2 mm), one part of sediment C (2 mm to 4 mm) and one part of sediment D (4 mm to 8 mm). Sediments F and H were prepared by mixing sediment A and sediment E in a proportion of 1:2 and 2:1. Sediment F = (2:1; A:E) contain 2 parts of sediment A to 1 part of sediment E. Sediment H = (1:2; A:E) contain 1 part of sediment A to 2 parts of sediment E . Two replicate readings were taken.

4.1.2 Preparation of GF/F filtered fresh Water and Alginic acid

GF/F water and 2% alginic acid (low viscosity) solution were prepared as follows.

GF/F Water: GF/F filtered fresh water was prepared by filtering fresh water through a Glass Microfibre Filter (GF/F) of pore size = 0.7 μm.

Alginic acid (low viscosity): 1000 ml of alginic acid was prepared by mixing 20 grm of the alginic acid powder and GF/F filtered fresh water making the volume upto 1000 ml.

4.1.3 Conduct of Avalanching Experiment 3

Twenty four glass containers were set up. These were divided into three groups of each containing eight containers, two replicate containers for each of the four sediments A, E, F, and H (Fig. 4.1). The first group of eight containers contained sediments submerged in GF/F water, the second group of eight containers contained sediments submerged in alginic acid and the third group of eight containers contained sediments submerged in 100% Glycerol. Each of the containers were left to stand for six different settling times before avalanching, for 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and for 15 hours.

The inclinometer used to avalanche the container is explained in figure 2.3. The procedure of avalanching the container was similar to the avalanching in 2.1.4.

The detailed procedure was as follows. The container was first filled with 1000 ml of liquid. 400 ml of dry sediment was added to the liquid in the container. Sediment and the liquid were then mixed by a metal rod to remove the air bubbles. The container was then covered by an aluminium foil cover, and the sediment in the container allowed to soak in liquid overnight. Next day the sediment and liquid were mixed again, and left to stand for 15 minutes. The container was transferred to the inclinometer. The sediment in the container was avalanched and the first angle of avalanche (A_1) and the first angle of repose (R_1) were then recorded. The duration of the first avalanche (T_1) in seconds were also recorded. The sediment in the container was then avalanched a second time, and the second angle of avalanche (A_2), second angle of repose (R_2) were measured and the duration of the second avalanche (T_2) in seconds were recorded. The container was then taken off the inclinometer, and the sediment mixed and levelled, and left to stand for then taken off the inclinometer, and the sediment mixed and levelled, and left to stand for 30 minutes. The container was then put back on the inclinometer and readings were taken for 30 minutes settling time. After completing readings for 30 minutes settling time the container was set up for 45 minutes settling time which was then followed by 60 minutes, 90 minutes and 15 hours settling time. Two replicate containers were set up together by staggering the settling times.

Table 4.1 Physical properties of the liquids used in avalanching experiment 3.

Solution	Density (ρ_l) g/ml	Viscosity (η) ✱ Poise
Air	0.0013	0.0002
Fresh Water (GF/F filtered)	1.006±0.007	0.010
Alginic acid (Low viscosity)	0.9855±0.001	2.500
100% Glycerol	1.2305±0.022	17.60
The following are included for comparison because although not used in this experiment they were used in avalanching experiment 2 in section 3.		
Fresh Water (Unfiltered)	1.043±0.076	0.010
50 % Glycerol	1.1365±0.004	0.083

✱ The viscosity and density values for air were obtained from Weast and Astle, 1979. The viscosity values for fresh water, 100 % glycerol and for 50 % glycerol were obtained from Weast and Astle, 1979. The viscosity value for alginic acid (low viscosity) was obtained from the label on the bottle of alginic acid (Sigma Chemical Co) supplied.

4.2 RESULTS

The results and the statistical analyses of avalanching experiment 3 are shown in table 4.2 to table 4.15.

The mean±SD data of the two replicate readings for the first angles of avalanche (A_1) and first angles of repose (R_1) are presented in table 4.2 and 4.3. The statistical analyses on the first angles of avalanche and repose are shown in table 4.4 to table 4.5. The mean±SD data of two replicate readings for the second angles of avalanche (A_2') and second angles of repose (R_2) are presented in table 4.6 and 4.7.

The mean±SD data of the two replicate readings for the factors of safety in the first avalanche (F_1) and the angles of dilatation in the first avalanche are shown in table 4.8 and 4.9 The statistical analyses on the factors of safety and the angles of dilatation are presented in table 4.10 and 4.11.

The mean±SD data of the two replicate readings of the duration in the first avalanche (T_1) and in second avalanche (T_2) are presented in table 4.12 and 4.13. The data for the duration of avalanche were statistically analysed in table 4.14 to table 4.15.

4.2.1 Hypothesis 1: Does the viscosity of the liquid affect angles of avalanche and angles of repose?

First angles of avalanche (A_1) and first angles of repose (R_1)

The data were statistically analysed by forty eight 1×3 one-way analyses of variance comparing the three liquids (GF/F water, Alginic acid and 100% Glycerol) as follows (Table 4.4). Twenty four of these were on the first angles of avalanche, and twenty four were on the first angles of repose. Out of the twenty four analyses, six were done on each of the four sediments A, E, F and H. Out of the six analyses, one analysis was done on each of the settling times 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours.

Thirty six out of the total forty eight one-way analyses of variance were significant (Table 4.4 column 4 and 7). Of these, twenty one out of the twenty four comparisons for the angles of avalanche were significant and fifteen out of the twenty four comparisons for the angles of repose were significant, as follows.

Angle of avalanche (twenty one significant comparisons): In fourteen of these (sediments A, F and H), the first angles of avalanche in GF/F water were significantly higher than in alginic acid and in 100% glycerol. In one of these (sediment A at 15 hours), the first angle of avalanche in 100% glycerol (47.75°) was significantly higher than in GF/F water and in alginic acid (43.15°, 34.00°). In the remaining six (sediment E), the first angles of avalanche in 100% glycerol were significantly higher than in alginic acid and in GF/F water (Table 4.2 Table 4.4).

Angle of repose (fifteen significant comparisons): In all the comparisons, the first angles of repose in GF/F water were significantly higher than in alginic acid and in 100% glycerol.

Second angle of avalanche (A_2') and Second angle of repose (R_2)

The mean±SD data of two replicate readings for the second angles of avalanche (A_2') and second angles of repose (R_2) are presented in table 4.6 and 4.7. The effects of viscosity of liquid on the second angles of avalanche and repose show similar but much less obvious trend than the first angles of avalanche and repose. The detailed statistical analyses conducted on the data exactly the same as the first angles of avalanche and repose. Very few of these statistical tests were significant.

4.2.2 Hypothesis 2: Does the settling time affect angles of avalanche and angles of repose?

First angles of avalanche (A_1) and first angles of repose (R_1)

The differences between the settling times (15 minutes, 30 minutes, 45 minutes, 60 minutes and 90 minutes) in the first angles of avalanche and in the first angles of repose were statistically analysed by twenty four 1×6 one-way analyses of variance as follows (Table 4.5). Twelve 1×6 one-way analyses of variance were done on angles of avalanche, and twelve analyses were done on angles of repose. Of these twelve, one for each of the four sediments A, E, F and H were done on each of the three liquids (GF/F water, Alginic acid and 100% Glycerol). Out of the total of twenty four F ratios, nine were significant (Table 4.5 column 4 and 7). Five out of the twelve comparisons for

Angle of avalanche (five significant comparisons): The five significant comparisons of the effect of settling time on the first angles of avalanche are shown in table 4.5 column 2, 3 and 4 rows 5, 8, 9, 11 and 12). An inspection of the data in table 4.2 for these comparisons (rows 2, 3, 9, 11 and 12) shows a consistent trend. The first angles of avalanche increased with settling time from 15 minutes to 15 hours.

Angle of repose (four significant comparisons): The four statistically significant comparisons on the effects of settling time on the first angles of repose are shown in table 4.5 column 5, 6, and 7; rows 5, 9, 11 and 12. An inspection of data for these comparisons (Table 4.3 rows 2, 3, 9 and 12) shows a consistent but slightly less obvious trend. The first angles of repose increased with time from 15 minutes to 15 hours.

Second angle of avalanche (A_2') and Second angle of repose (R_2)

The mean±SD data of two replicate readings for the second angles of avalanche (A_2') and second angles of repose (R_2) are presented in table 4.6 and 4.7. The effects of settling time on the second angles of avalanche and repose show similar but much less obvious trend than the first angles of avalanche and repose. The detailed statistical analyses conducted on the data exactly the same as the first angles of avalanche and repose. Very few of these statistical tests were significant.

Table 4.2 Avalanching experiment 3. Effects of viscosity. 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours times before the container being avalanched. First angles of avalanche (A_1). Mean ± SD of two replicate readings.

Sediment	Medium	First Angle of Avalanche (A_1) (degrees)					
		15 min	30 min	45 min	60 min	90 min	15 hours
A	GF/F Water	39.50±2 828	39.75±3.889	43.15±0.919	40.50±0.707	42.75±1.768	43.15±0.495
	Alginic acid	16.75±0.354	18.00±0.000	23 50±2.121	28.25±2.475	29.75±1.061	34.00±1.414
	100% Glycerol	15.00±1.414	16.50±0.707	21.25±1.768	28.50±0.707	32 50±1.414	47.75±2.475
E	GF/F Water	39.20±1.131	38.70±0.707	39.85±0.071	39.70±1.131	40.50±0.990	39.65±0.212
	Alginic acid	44.30±0.424	45.00±0.707	45.65±0.212	44.85±0.495	45.30±0.707	45.65±0.495
	100% Glycerol	45.40±0.283	46.35±0.212	46.25±0.354	46.15±0.495	45.65±0.919	47.00±0.283
F	GF/F Water	41.80±4.243	43.50±2.121	44.10±1.273	44.25±1.768	44.50±0.707	46.00±1.414
	Alginic acid	22.00±2.828	31.00±5.657	33.00±8.485	36.00±8.485	33.00±1.414	24.85±2.333
	100% Glycerol	10.90±1.273	14.80±2.828	18.90±1.556	28.05±1.485	37.35±3.041	41.75±1.768
H	GF/F Water	44.00±1.414	43.50±2.121	45.00±0.000	46.10±1.556	44.75±0.354	43.75±1.768
	Alginic acid	20.00±2.546	27.50±5.657	36.90±4.384	39.50±3.536	29.75±5.303	39.25±6.718
	100% Glycerol	19.25±1.061	25.10±1.556	31.25±1.061	36.25±2.475	43.75±0.354	43.75±1.768

Sediments A, E, F and H are as follows (see table 1.1 in section 1). Sediment A = Fine sand (63 μm to 1 mm), sediment E = (1:1:1; B:C:D) means that sediment E consist of one part of sediment B = Coarse sand (1 mm to 2 mm), one part of sediment C = Granules (2 mm to 4 mm), and one part of sediment D = Pebbles (4 mm to 8 mm). Sediments F and H were prepared by mixing sediment A and sediment E in a proportion of 2:1 and 1:2. Sediment F = (2:1; A:E) means 2 parts of sediment A to 1 part of sediment E and Sediment H = (1:2; A:E) means 1 parts of sediment A to 2 part of sediment E.

Table 4.3 Avalanching experiment 3 Effects of viscosity. 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours times before the container being avalanched. First angles of repose (R_1). Mean ± SD of two replicate readings.

Sediment	Medium	First Angle of Repose (R_1) (degrees)					
		15 min	30 min	45 min	60 min	90 min	15 hours
	GF/F Water	28.25±2.475	30.65±0.212	30.90±0.141	30.50±0.707	31.15±1.626	29.95±1.485
A	Alginic acid	15.00±1.414	16.00±0.000	17.25±0.354	22.25±2.475	27.50±1.838	27.40±4.808
	100% Glycerol	8.000±1.414	12.60±0.566	17.00±2.121	22.25±3.889	26.15±4.738	36.10±2.687
	GF/F Water	33.90±1.273	35.00±0.707	35.00±0.000	35.50±0.000	35.00±0.707	35.05±0.636
E	Alginic acid	33.90±0.141	35.55±0.071	34.85±0.495	35.50±0.000	34.90±0.141	34.75±0.636
	100% Glycerol	35.10±0.849	35.30±0.141	33.80±0.000	34.75±0.354	34.90±0.424	34.40±0.566
	GF/F Water	32.30±0.707	30.90±2.687	29.50±3.536	29.85±3.748	29.75±2.475	32.00±0.707
F	Alginic acid	14.90±2.687	22.75±1.768	22.50±3.536	18.75±0.354	19.00±2.121	17.00±2.121
	100% Glycerol	7.000±2.828	9.400±0.849	13.60±3.394	19.75±3.182	30.00±0.707	26.60±0.849
	GF/F Water	36.30±0.707	37.50±0.990	38.00±0.000	39.25±1.061	37.40±0.849	36.50±2.121
H	Alginic acid	13.00±2.828	19.00±3.536	16.75±1.061	17.25±1.061	19.30±3.536	20.85±3.323
	100% Glycerol	13.10±1.273	16.00±0.000	16.50±0.707	18.50±2.828	20.10±0.141	19.25±0.354

For S1 Sediments A, E, F and H see table 1.1 and figure 4.1.

Table 4.4 Avalanching experiment 3. Statistical analyses for the effects of viscosity of fluid (GF/F filtered fresh water, Alginic acid (low viscosity) and 100% Glycerol) on the first angles of avalanche (A_1) and on first angles of repose (R_1).

Factors	A_1			R_1		
	DF	F ratio	Probability	DF	F ratio	Probability
Comparison: GF/F Water/Alginic acid/100% Glycerol						
a) Sediment A						
15 min	2, 3	110.7	0.002 **	2, 3	62.68	0.004 **
30 min	2, 3	65.02	0.003 **	2, 3	1512.3	<0.001 ***
45 min	2, 3	102.8	0.002 **	2, 3	81.72	0.002 **
60 min	2, 3	41.28	0.007 **	2, 3	6.260	0.085
90 min	2, 3	45.06	0.006 **	2, 3	1.410	0.370
15 hours	2, 3	35.12	0.008 **	2, 3	3.690	0.155
b) Sediment E						
15 min	2, 3	21.50	0.017 *	2, 3	1.220	0.409
30 min	2, 3	95.73	0.002 **	2, 3	1.130	0.430
45 min	2, 3	428.3	<0.001 ***	2, 3	10.47	0.044 *
60 min	2, 3	39.44	0.007 **	2, 3	9.000	0.054
90 min	2, 3	21.37	0.017 *	2, 3	0.030	0.972
15 hours	2, 3	248.2	<0.001 ***	2, 3	0.560	0.620
c) Sediment F						
15 min	2, 3	53.22	0.005 **	2, 3	63.95	0.003 **
30 min	2, 3	27.92	0.012 *	2, 3	63.89	0.003 **
45 min	2, 3	12.59	0.035 *	2, 3	10.43	0.045 *
60 min	2, 3	5.090	0.109	2, 3	9.310	0.052
90 min	2, 3	17.22	0.023 *	2, 3	21.27	0.017 *
15 hours	2, 3	71.05	0.003 **	2, 3	60.55	0.004 **
d) Sediment H						
15 min	2, 3	123.8	0.001 **	2, 3	106.8	0.002 **
30 min	2, 3	15.42	0.026 *	2, 3	60.35	0.004 **
45 min	2, 3	14.09	0.030 *	2, 3	562.4	<0.001 ***
60 min	2, 3	7.180	0.072	2, 3	89.38	0.002 **
90 min	2, 3	14.87	0.028 *	2, 3	47.40	0.005 **
15 hours	2, 3	0.790	0.531	2, 3	34.78	0.008 **

Table gives F ratios and probability values obtained from forty eight 1×3 one-way analyses comparing liquids (GF/F water, Alginic acid and 100% Glycerol). Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***. For S1 Sediments A, E, F and H see table 1 1 and figure 4.1.

Table 4.5 Avalanching experiment 3. Statistical analyses for the effects of settling time (15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours) for which containers were left to stand before avalanching on the first angles of avalanche (A_1) and on first angles of repose (R_1).

Factors	A_1			R_1		
	DF	F ratio	Probability	DF	F ratio	Probability
Comparison: 15 min/30 min/45 min/60 min/90 min/15 hours						
a) GF/F Water						
Sediment A	5, 6	1.300	0.375	5, 6	1.150	0.426
Sediment E	5, 6	1.090	0.452	5, 6	1.120	0.439
Sediment F	5, 6	0.760	0.610	5, 6	0.430	0.813
Sediment H	5, 6	0.920	0.525	5, 6	1.770	0.254
b) Alginic acid						
Sediment A	5, 6	40.38	<0.001 ***	5, 6	11.03	0.006 **
Sediment E	5, 6	0.410	0.825	5, 6	1.350	0.359
Sediment F	5, 6	1.820	0.242	5, 6	3.530	0.078
Sediment H	5, 6	5.050	0.037 *	5, 6	1.940	0.222
c) 100% Glycerol						
Sediment A	5, 6	126.4	<0.001 ***	5, 6	23.68	0.001 **
Sediment E	5, 6	2.680	0.131	5, 6	2.570	0.141
Sediment F	5, 6	70.71	<0.001 ***	5, 6	33.05	<0.001 ***
Sediment H	5, 6	84.74	<0.001 ***	5, 6	7.720	0.014 *

Table gives F ratios and probability values obtained from twenty four 1×6 one-way analyses comparing settling time (15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours) for which containers were left to stand before avalanching. Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***. For S1 Sediments A, E, F and H see table 1.1 and figure 4.1.

Table 4.6 Avalanching experiment 3. Effects of viscosity. 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours times before the container being avalanched. Second angles of avalanche (A_2'). Mean ± SD of two replicate readings.

Sediment	Medium	Second Angle of Avalanche (A_2') (degrees)					
		15 min	30 min	45 min	60 min	90 min	15 hours
A	GF/F Water	37.10±1.980	36.00±1.131	36.30±2.687	36.00±0.000	35.85±1.909	35.50±0.707
	Alginic acid	45.40±0.141	47.70±0.424	39.25±6.010	45.65±3.041	46.00±2.546	43.55±3.889
	100% Glycerol	24.00±1.414	36.85±0.919	36.25±2.475	39.75±4.596	37.40±7.212	45.75±6.718
E	GF/F Water	38.70±1.697	39.15±2.616	38.75±0.354	40.95±0.636	40.20±0.990	41.30±0.566
	Alginic acid	42.70±1.556	42.85±0.071	42.25±0 071	43.65±1.202	42.10±1.273	42.25±0.636
	100% Glycerol	44.70±0.283	43.35±0.919	43.15±0.212	42.85±0.212	43.70±0.141	44.50±0.707
F	GF/F Water	37.75±0.354	38.15±1.909	35.80±3.111	35.70±4.243	37.25±1.768	37.75±0.354
	Alginic acid	37.90±2.970	40.00±2.828	42.75±1.061	34.50±1.414	37.45±1.485	37.40±1.556
	100% Glycerol	17.55±5.162	16.10±1.273	30.70±1.131	34.30±0.849	38.90±4.101	37.10±0.141
H	GF/F Water	41.95±2.333	43.80±0.849	43.35±2.051	44.55±0.778	44.55±2.192	42 25±0.778
	Alginic acid	39.50±0.990	39.70±1.697	33.00±1.414	32.50±1.131	39.05±2.192	31.60±2.687
	100% Glycerol	30.70±2.121	33.40±0.141	30.25±3.182	32.10±1.556	35.00±4.950	36.65±0.495

For S1 Sediments A, E, F and H see table 1.1 and figure 4.1.

Table 4.7 Avalanching experiment 3 Effects of viscosity. 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours times before the container being avalanched. Second angles of repose (R_2). Mean ± SD of two replicate readings.

Sediment	Medium	Second Angle of Repose (R_2) (degrees)					
		15 min	30 min	45 min	60 min	90 min	15 hours
A	GF/F Water	32.75±1.061	32.65±0.212	32.80±1.414	32.25±0.354	32.25±0.354	32.75±0.636
	Alginic acid	25.60±1.980	26.25±1.061	27.00±2.121	26.50±1.414	26.50±1.414	26.15±3.323
	100% Glycerol	19.90±0.141	32.00±1.414	34.50±2.121	33.75±0.354	30.60±6.223	31.00±0.707
E	GF/F Water	35.50±2.121	35.90±0.141	34.75±1.768	35.50±0.707	35.25±0.354	35.40±0.849
	Alginic acid	35.50±0.000	35.30±0.707	35.00±0.000	35.25±0.354	35.25±0.354	35.55±0.354
	100% Glycerol	35.40±0.141	35.25±0.354	34.60±0.283	35.10±0.141	35.00±0.707	33.75±0.354
F	GF/F Water	34.25±3.182	34.00±2.546	33.05±1.768	32.75±2.475	33.25±0.354	33.75±0.354
	Alginic acid	24.25±1.768	22.60±0.849	23.50±4.243	23.75±0.354	24.75±1.768	21.75±2.475
	100% Glycerol	7.500±3.536	11.00±0.283	21.10±1.273	25.75±2.475	31.25±2.475	27.50±3.536
H	GF/F Water	38.00±2.828	37.00±2.121	38.10±0.566	38.50±2.121	38.00±1.414	38.75±0.354
	Alginic acid	19.50±0.000	20.00±1.414	22.75±3.182	25.90±1.273	22.75±1.768	24.50±1.414
	100% Glycerol	21.05±2.616	16.75±0.354	17.70±1.697	20.50±1.414	25.00±1.414	23.65±2.616

For S1 Sediments A, E, F and H see table 1.1 and figure 4.1.

4.2.3 Hypothesis 3: Does the viscosity of liquid and settling time affect factors of safety and angles of dilatation?

The factors of safety and the angles of dilatation calculated from the first angles of avalanche and repose are shown in table 4.8 and 4.9. The results were statistically analysed in table 4.10 and 4.11. The statistical analyses were divided into two parts. In part one, the differences between the three liquids: GF/F water, alginic acid and 100% glycerol were analysed (Table 4.10). In part two, the differences in the six settling times: 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours were analysed (Table 4.11).

I. *Part one*: Eight out of the twenty four comparisons for the factors of safety of the first avalanche were significant (Table 4.10 column 2, 3 and 4). In these statistically significant comparisons, the factors of safety in 100% glycerol were significantly higher than in alginic acid and GF/F water (Table 4.8).

Twelve out of the twenty four comparisons for the angles of dilatation of first avalanche were significant (Table 4.10 column 5, 6 and 7). In eight comparisons, the angles of dilatation in 100% glycerol were significantly higher than in alginic acid and GF/F water. In three comparisons, the angles of dilatation in GF/F water were significantly higher than in alginic acid and 100% glycerol. In one comparison, the angles of dilatation in alginic acid were significantly higher than in 100% glycerol and GF/F water (Table 4 9).

II. *Part two*: Two out of the twelve comparisons for the factors of safety of first avalanche for the six settling times were significant (Table 4.11 column 2, 3 and 4). These were for sediment H in alginic acid and 100% glycerol. In both cases an inspection of the data in table 4.8 rows 11 and 12 shows that the 15 minutes and 30 minutes factors of safety were lower than the factors of safety for longer time periods

Three out of the twelve comparisons for the angles of dilatation of first avalanche between the six settling times were significant (Table 4.11 column 5, 6 and 7). An inspection of the data in table 4.9 rows 9, 11 and 12 shows that in all three cases, the 15 minutes angles of dilatation were lower than the angles of dilatation for longer time periods

Regression Analyses on Factor of safety against First Angles of Avalanche and Repose

The relationship between the factor of safety and the first angle of avalanche and repose was investigated by six regression analyses. Two out of the three regression analyses for the relationship between the factor of safety and the angle of avalanche (GF/F filered fresh water and alginic acid) were significant (Fig. 4.2). The highest slope was shown by the sediment in GF/F filtered fresh water. Only one out of the three regression analyses for the relationship between the factor of safety and angle of repose (GF/F water) was significant (Fig. 4.3).

Table 4.8 Avalanching experiment 3. Effects of viscosity. 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours times before the container being avalanched. Factors of safety in the first avalanche (Tan A_1 / Tan R_1). Mean ± SD of two replicate readings.

Sediment	Medium	Factor of Safety in First Avalanche (Tan A_1 / Tan R_1)					
		15 min	30 min	45 min	60 min	90 min	15 hours
A	GF/F Water	1.536±0.005	1.410±0.206	1.567±0.059	1.451±0.078	1.530±0.003	1.628±0.069
	Alginic acid	1.130±0.136	1.133±0.000	1.403±0.173	1.316±0.026	1.099±0.040	1.317±0.201
	100% Glycerol	1.955±0.538	1.325±0.001	1.275±0.052	1.345±0.221	1.314±0.204	1.524±0.281
E	GF/F Water	1.216±0.107	1.145±0.059	1.192±0.003	1.164±0.047	1 221±0.075	1.182±0.019
	Alginic acid	1.453±0.029	1.400±0.038	1.470±0.037	1.395±0.024	1.449±0.028	1.476±0.060
	100% Glycerol	1.443±0.031	1.481±0.019	1.561±0.019	1.501±0.006	1.468±0.070	1.567±0.018
F	GF/F Water	1.419±0.173	1.601±0.288	1.722±0.172	1.722±0.365	1.724±0.130	1.658±0.036
	Alginic acid	1.526±0.072	1.434±0.197	1.569±0.238	2.184±0.717	1.905±0.331	1.518±0.039
	100% Glycerol	1.667±0.492	1.619±0.468	1.445±0.249	1.497±0.168	1.323±0.107	1.787±0.177
H	GF/F Water	1.317±0.099	1.238±0.047	1.280±0.000	1.275±0.117	1.297±0.024	1.295±0.021
	Alginic acid	1.592±0.140	1.512±0.062	2.498±0.231	2.658±0.161	1.635±0.028	2.154±0.141
	100% Glycerol	1.504±0.062	1.635±0.115	2.049±0.007	2.238±0.566	2.616±0.052	2.743±0.115

For S1 Sediments A, E, F and H see table 1.1 and figure 4.1.

Table 4.9 Avalanching experiment 3. Effects of viscosity. 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours times before the container being avalanched Angles of dilatation in the first avalanche (A_1 - R_1). Mean ± SD of two replicate readings.

Sediment	Medium	Angles of Dilatation in First Avalanche (A_1 - R_1)					
		15 min	30 min	45 min	60 min	90 min	15 hours
A	GF/F Water	11.25±0.354	9.100±4.101	12.25±1.061	10.00±1.414	11.60±0.141	13.20±0.990
	Alginic acid	1.750±1.768	2.000±0.000	6.250±2.475	6.000±0.000	2.250±0.778	6.600±3.394
	100% Glycerol	7.000±2.828	3.900±0.141	4.250±0.354	6.250±3.182	6.350±3.323	11.65±5.162
E	GF/F Water	5.300±2.404	3.700±1.414	4.850±0.071	4.200±1.131	5.500±1.697	4.600±0.424
	Alginic acid	10.40±0.566	9.450±0.778	10.80±0.707	9.350±0.495	10.40±0.566	10.90±1.131
	100% Glycerol	10.30±0.566	11.05±0.354	12.45±0.354	11.40±0.141	10.75±1.344	12.60±0.283
F	GF/F Water	9.500±3.536	12.60±4.808	14.60±2.263	14.40±5.515	14.75±1.768	14.00±0.707
	Alginic acid	7.100±0.141	8.250±3.889	10.50±4.950	17.25±8.839	14.00±3.536	7.850±0.212
	100% Glycerol	3.900±1.556	5.400±3.677	5.300±1.838	8.300±1.697	7.350±2.333	15.15±2.616
H	GF/F Water	7.700±2.121	6.000±1.131	7.000±0.000	6.850±2.616	7.350±0.495	7.250±0.354
	Alginic acid	7.000±0.283	8.500±2.121	20.15±3.323	22.25±2.475	10.45±1.768	18.40±3.394
	100% Glycerol	6.150±0.212	9.100±1.556	14.75±0.354	17.75±5.303	23.65±0.495	24.50±1.414

For S1 Sediments A, E, F and H see table 1.1 and figure 4.1.

Table 4.10 Avalanching experiment 3. Statistical analyses for the effects of viscosity of liquid (GF/F filtered fresh water, Alginic acid and 100% Glycerol) on the factors of safety in first avalanche (Tan A_1 / Tan R_1) and angles of dilatation in first avalanche (A_1 - R_1).

Factors	Tan A_1 / Tan R_1			A_1 - R_1		
	DF	F ratio	Probability	DF	F ratio	Probability
Comparison: GF/F Water/Alginic acid / 100% Glycerol						
a) Sediment A						
15 min	2, 3	3.310	0.174	2, 3	12.08	0.037 *
30 min	2, 3	2.830	0.204	2, 3	4.810	0.116
45 min	2, 3	3.570	0.161	2, 3	14.10	0.030 *
60 min	2, 3	0.550	0.626	2, 3	2.480	0.231
90 min	2, 3	6.470	0.082	2, 3	11.29	0.040 *
15 hours	2, 3	1.210	0.412	2, 3	1.830	0.303
b) Sediment E						
15 min	2, 3	8.050	0.062	2, 3	6.960	0.075
30 min	2, 3	34.40	0.009 **	2, 3	1.540	0.347
45 min	2, 3	124.4	0.001 **	2, 3	152.2	0.001 **
60 min	2, 3	63.55	0.004 **	2, 3	53.44	0.005 **
90 min	2, 3	9.990	0.047 *	2, 3	10.33	0.045 *
15 hours	2, 3	56.64	0.004 **	2, 3	69.21	0.003 **
c) Sediment F						
15 min	2, 3	0.330	0.739	2, 3	3.170	0.182
30 min	2, 3	0.180	0.841	2, 3	1.520	0.349
45 min	2, 3	0.780	0.535	2, 3	12.66	0.034 *
60 min	2, 3	1.090	0.441	2, 3	1.130	0.432
90 min	2, 3	3.860	0.148	2, 3	4.720	0.118
15 hours	2, 3	3.200	0.180	2, 3	12.51	0.035 *
d) Sediment H						
15 min	2, 3	3.560	0.162	2, 3	0.780	0.533
30 min	2, 3	12.78	0.034 *	2, 3	1.980	0.283
45 min	2, 3	5.050	0.109	2, 3	18.76	0.020 *
60 min	2, 3	8.380	0.059	2, 3	9.150	0.053
90 min	2, 3	684.3	<0.001 ***	2, 3	124.4	0.001 **
15 hours	2, 3	94.95	0.002 **	2, 3	33.65	0.009 **

Table gives F ratios and probability values obtained from forty eight 1×3 one-way analyses comparing liquids (GF/F water, Alginic acid and 100% Glycerol). Probability: $0.05>P>0.01$ *; $0.01>P>0.001$ **; $P<0.001$ ***. For S1 Sediments A, E, F and H see table 1.1 and figure 4.1.

Table 4.11 Avalanching experiment 3. Statistical analyses for the effects of time (15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours) for which containers were left to stand before avalanching on the factors of safety in first avalanche (Tan A_1 / Tan R_1) and angles of dilatation in first avalanche (A_1 - R_1).

Factors	Tan A_1 / Tan R_1			A_1 - R_1		
	DF	F ratio	Probability	DF	F ratio	Probability
Comparison: 15 min/30 min/45 min/60 min/90 min/15 hours						
a) GF/F Water						
Sediment A	5, 6	1.310	0.372	5, 6	1.270	0.386
Sediment E	5, 6	0.450	0.802	5, 6	0.450	0.800
Sediment F	5, 6	0.580	0.716	5, 6	0.660	0.670
Sediment H	5, 6	0.320	0.881	5, 6	0.310	0.888
b) Alginic acid						
Sediment A	5, 6	2.150	0.190	5, 6	3.120	0.099
Sediment E	5, 6	1.650	0.278	5, 6	1.180	0.417
Sediment F	5, 6	1.410	0.340	5, 6	1.490	0.319
Sediment H	5, 6	4.910	0.039 *	5, 6	14.23	0.003 **
c) 100% Glycerol						
Sediment A	5, 6	1.740	0.258	5, 6	1.660	0.277
Sediment E	5, 6	4.390	0.050	5, 6	4.160	0.056
Sediment F	5, 6	0.560	0.727	5, 6	5.660	0.028 *
Sediment H	5, 6	8.610	0.010 *	5, 6	20.39	0.001 **

Table gives F ratios and probability values obtained from twenty four 1×6 one-way analyses comparing time (15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours) for which containers were left to stand before avalanching. Probability: $0.05>P>0.01$ *; $0.01>P>0.001$ **; $P<0.001$ ***. For S1 Sediments A, E, F and H see table 1.1 and figure 4.1.

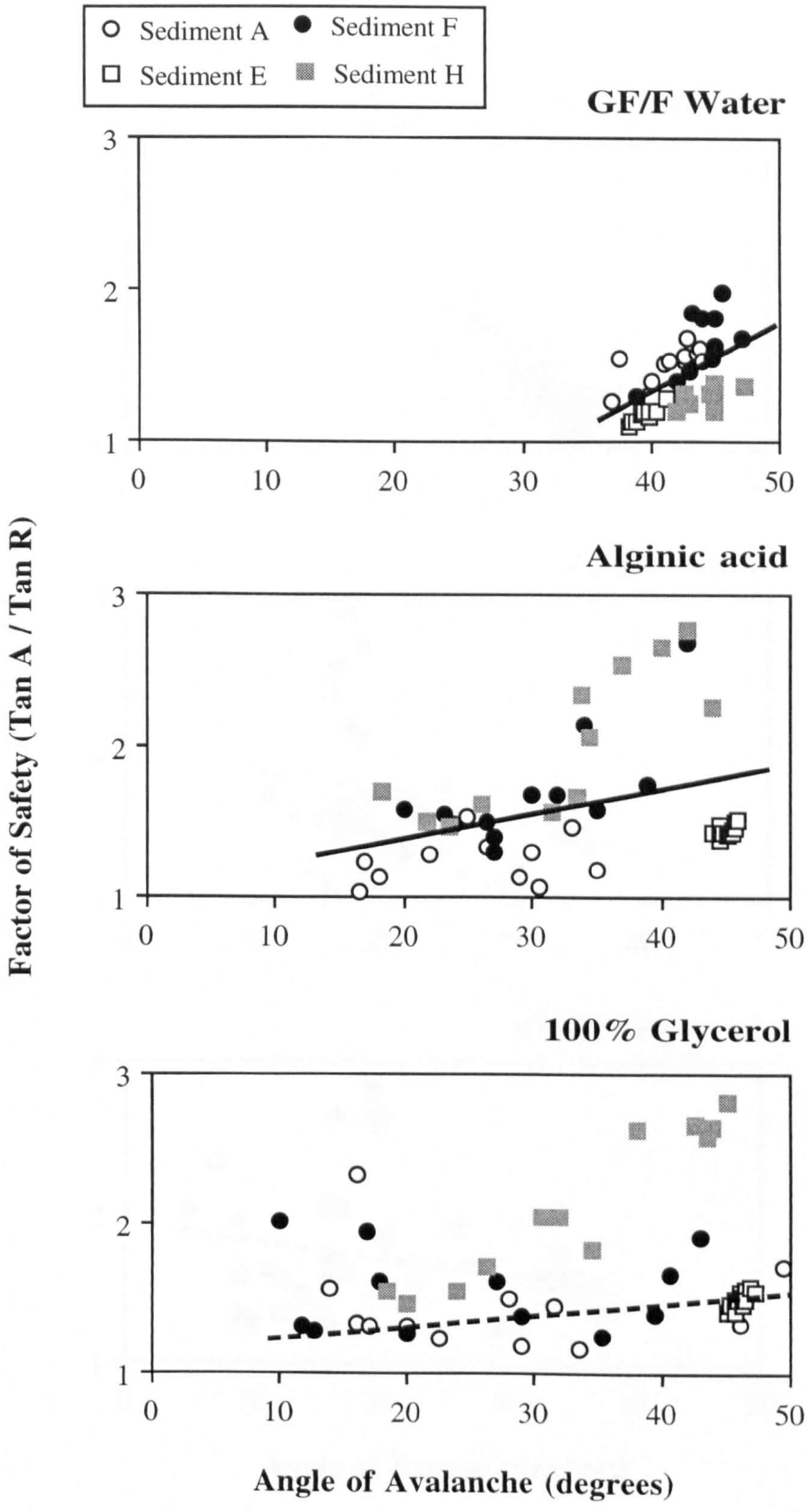


Figure 4.2 Avalanching experiment 3. S1 Sediments A, E, F & H. Relationship between the factor of safety and first angle of avalanche. **Top:** sediments in GF/F filtered fresh water ($y = 0.040x - 0.305$, $F_{1,46} = 14.69$ $P<0.001$ ***). **Middle:** sediments in Alginic acid ($y = 0.016x + 1.090$, $F_{1,46} = 4.900$ $P=0.032$ *). **Bottom:** sediments in 100% Glycerol ($y = 0.006x + 1.450$, $F_{1,46} = 1.660$ $P=0.204$ ns).

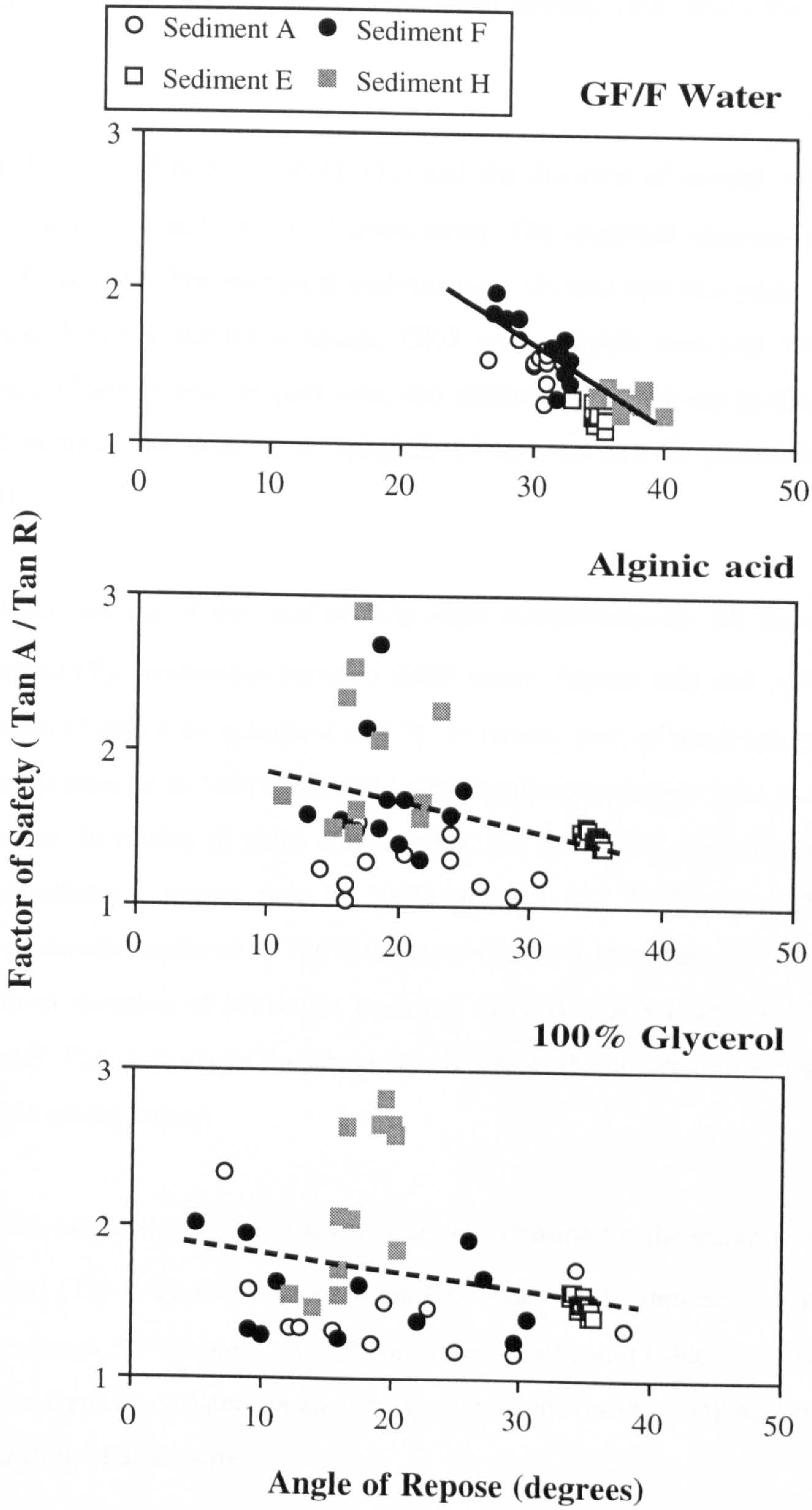


Figure 4.3 Avalanching experiment 3. S1 Sediments A, E, F & H. Relationship between the factor of safety and first angle of repose. **Top:** sediments in GF/F filtered fresh water ($y = -0.050x + 3.080$, $F_{1,46} = 74.80$ $P<0.001$ ***). **Middle:** sediments in alginic acid ($y = -0.016x + 1.990$, $F_{1,46} = 3.610$ $P=0.064$ ns). **Bottom:** sediments in 100% glycerol ($y = -0.011x + 1.920$, $F_{1,46} = 3.420$ $P=0.071$ ns).

4.2.4 Hypothesis 4: Does the viscosity of liquid and settling time affect the duration of avalanche?

The duration of first avalanche (T_1) and the duration of second avalanche (T_2) are shown in table 4.12 and table 4.13 respectively. The statistical analyses are presented in tables 4.14 and 4.15. The statistical analyses were divided into two parts. In part one, the differences between the three liquids: GF/F water, alginic acid and 100% glycerol were analysed (Table 4.14). In part two, the differences in the six settling times: 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours were analysed (Table 4.15).

I. *Part one*: Thirty six out of the total of forty eight comparisons for the duration of first (T_1) and second (T_2) avalanches between GF/F water, Alginic acid and 100% Glycerol were significant (Table 4.14 column 4 and 7). In twenty four of these comparisons, the duration's of avalanche in 100% glycerol were significantly longer than in alginic acid and GF/F water. In twelve of these comparisons, the duration's of avalanche in alginic acid were significantly longer than in 100% glycerol and GF/F water. The longest duration of avalanche occurred in 100% Glycerol (Table 4.12 column 6, 584.8 seconds) and the shortest duration of avalanche occurred in GF/F water (Table 4.12 column 1, 1.230 seconds). The viscosity of the liquid clearly affects the duration of avalanche, more viscous liquids taking longer.

II. *Part two*: Five out of the total of twenty four comparisons for the duration of first (T_1) and the second (T_2) avalanches between settling times of 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours were significant (Table 4.15 column 4 and 7). The results were inconsistent in all the five significant results. Settling time does not affect the duration of avalanche.

Table 4.12 Avalanching experiment 3. Effects of viscosity 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours times before the container being avalanched. Duration of the first avalanche (T_1). Mean ± SD of two replicate readings.

Sediment	Medium	Duration of First Avalanche (T_1) (seconds)					
		15 min	30 min	45 min	60 min	90 min	15 hours
A	GF/F Water	28.15±6.790	22.03±2.160	24.00±0.000	18.70±4.310	25.95±11.03	25.43±6.470
	Alginic acid	95.45±50.91	180.4±112.0	95.45±36.49	108.3±24.47	150.9±41.86	276.2±7.570
	100% Glycerol	141.8±25.60	129.0±9.160	206.7±6.750	307.4±16.26	284.6±69.44	442.8±63.50
E	GF/F Water	1.230±0.035	1.500±0.424	1.500±0.071	1.680±0.035	1.700±0.141	1.530±0.389
	Alginic acid	48.75±4.808	46.45±4.667	44.85±1.414	43.75±0.707	49.05±3.960	65.20±2.616
	100% Glycerol	186.5±8.627	205.3±60.25	245.6±24.18	257.3±28.07	281.0±17.40	184.8±1.945
F	GF/F Water	21.63±1.945	16.38±6.824	15.55±1.838	19.05±1.131	18.98±8.167	27.18±6.116
	Alginic acid	134.4±32.32	147.3±26.73	263.0±97.09	183.9±92.77	166.38±36.59	183.6±0.212
	100% Glycerol	126.5±35.11	135.1±9.553	263.0±3.995	329.5±63.89	347.7±10.15	584.8±24.18
H	GF/F Water	8.175±0.247	11.50±2.333	10.08±0.106	10.48±0.742	12.53±0.601	19.53±15.52
	Alginic acid	116.8±22.06	144.7±51.55	294.5±5.162	224.5±69.97	173.3±21.28	214.5±4.985
	100% Glycerol	196.2±3.076	211.4±107.3	208.8±125.0	139.9±4.207	332.0±93.13	393.5±186.3

For S1 Sediments A, E, F and H see table 1.1 and figure 4.1.

Table 4.13 Avalanching experiment 3. Effects of viscosity. 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours times before the container being avalanched. Duration of the second Avalanche (T_2) Mean ± SD of two replicate readings.

Sediment	Medium	Duration of Second Avalanche (T_2) (seconds)					
		15 min	30 min	45 min	60 min	90 min	15 hours
A	GF/F Water	21.40±1.630	18.43±0.600	19.83±3.780	17.25±4.380	16.85±5.800	22.65±4.380
	Alginic acid	773.5±348.7	1015±45.96	639.2±628.3	851.5±347.9	1181.5±138.6	1012.1±180.8
	100% Glycerol	235.7±140.7	240.3±2.900	340.8±23.19	294.0±116.7	277.0±79.41	920.0±105.4
E	GF/F Water	1.400±0.283	1.380±0.318	1.200±0.000	1.350±0.212	1.680±0.177	1.750±0.141
	Alginic acid	47.95±11.60	35.10±3.889	42.25±4.808	39.40±0.212	41.65±4.667	39.48±5.197
	100% Glycerol	169.3±28.85	171.3±73.68	225.8±11.67	162.2±16.69	153.2±25.31	205.1±39.46
F	GF/F Water	14.73±1.167	12.10±1.061	12.88±0.530	13.53±1.025	17.58±3.924	13.35±2.828
	Alginic acid	462.1±136.2	502.7±17.43	338.9±290.3	276.7±218.4	282.3±45.47	514.7±193.0
	100% Glycerol	148.7±40.09	123.5±3.288	351.0±185.0	303.9±47.98	294.8±60.74	479.8±98.54
H	GF/F Water	8.850±0.566	5.975±3.571	9.425±2.934	6.350±2.970	15.05±9.617	10.93±2.722
	Alginic acid	228.1±60.46	181.2±9.687	232.9±49.57	118.0±22.52	201.9±62.58	134.4±27.58
	100% Glycerol	200.9±32.53	347.9±21.32	522.4±286.3	199.4±2.051	159.8±33.38	318.0±87.68

For S1 Sediments A, E, F and H see table 1.1 and figure 4.1.

Table 4.14 Avalanching experiment 3. Statistical analyses for the effects of viscosity of liquid (GF/F filtered fresh water, Alginic acid and 100% Glycerol) on the duration of first avalanche (T_1) and on the duration of second avalanche (T_2).

Factors	T_1			T_2		
	DF	F ratio	Probability	DF	F ratio	Probability
Comparison: GF/F Water/Alginic acid/100% Glycerol						
a) Sediment A						
15 min	2, 3	5.940	0.090	2, 3	6.370	0.830
30 min	2, 3	3.100	0.186	2, 3	774.3	<0.001 ***
45 min	2, 3	37.09	0.008 **	2, 3	1.460	0.361
60 min	2, 3	148.6	0.001 **	2, 3	8.050	0.062
90 min	2, 3	14.99	0.027 *	2, 3	87.77	0.002 **
15 hours	2, 3	64.10	0.003 **	2, 3	40.90	0.007 **
b) Sediment E						
15 min	2, 3	569.3	<0.001 ***	2, 3	46.60	0.006 **
30 min	2, 3	18.83	0.020 *	2, 3	8.910	0.055
45 min	2, 3	173.3	0.001 **	2, 3	538.9	<0.001 ***
60 min	2, 3	142.9	0.001 **	2, 3	152.1	0.001 **
90 min	2, 3	421.0	<0.001 ***	2, 3	55.80	0.004 **
15 hours	2, 3	2821.5	<0.001 ***	2, 3	44.30	0.006 **
c) Sediment F						
15 min	2, 3	10.42	0.045 *	2, 3	15.70	0.026 *
30 min	2, 3	36.81	0.008 **	2, 3	1256.8	<0.001 ***
45 min	2, 3	12.96	0.033 *	2, 3	1.860	0.298
60 min	2, 3	11.41	0.040 *	2, 3	3.090	0.187
90 min	2, 3	107.8	0.002 *	2, 3	25.48	0.013 *
15 hours	2, 3	797.5	<0.001 ***	2, 3	10.01	0.047 *
d) Sediment H						
15 min	2, 3	107.7	0.002 **	2, 3	18.18	0.021 *
30 min	2, 3	4.380	0.129	2, 3	312.7	<0.001 ***
45 min	2, 3	8.160	0.061	2, 3	4.700	0.119
60 min	2, 3	14.19	0.030 *	2, 3	108.3	0.002 **
90 min	2, 3	16.78	0.024 *	2, 3	11.25	0.040 *
15 hours	2, 3	6.000	0.089	2, 3	16.94	0.023 *

Table gives F ratios and probability values obtained from forty eight 1×3 one-way analyses comparing liquids (GF/F water, Alginic acid (Lv) and 100% Glycerol). Twenty four for the duration of first avalanche and twenty four for the duration of second avalanche. Probability: 0.05>P>0.01 *; 0.01>P>0.001 **; P<0.001 ***. For S1 Sediments A, E, F and H see table 1.1 and figure 4.1.

Table 4.15 Avalanching experiment 3. Statistical analyses for the effects of time (15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours) for which containers were left to stand before avalanching on duration of the first avalanche (T_1) and on duration of the second avalanche (T_2).

Factors	T_1			T_2		
	DF	F ratio	Probability	DF	F ratio	Probability
Comparison: 15 min/30 min/45 min/60 min/90 min/15 hours						
a) GF/F Water						
Sediment A	5, 6	0.570	0.725	5, 6	0.720	0.632
Sediment E	5, 6	0.970	0.505	5, 6	1.910	0.227
Sediment F	5, 6	1.340	0.362	5, 6	1.660	0.276
Sediment H	5, 6	0.750	0.612	5, 6	1.020	0.479
b) Alginic acid						
Sediment A	5, 6	3.120	0.099	5, 6	0.660	0.667
Sediment E	5, 6	10.68	0.006 **	5, 6	0.970	0.501
Sediment F	5, 6	1.160	0.422	5, 6	0.760	0.609
Sediment H	5, 6	5.700	0.028 *	5, 6	2.420	0.156
c) 100% Glycerol						
Sediment A	5, 6	16.93	0.002 **	5, 6	16.42	0.002 **
Sediment E	5, 6	3.600	0.075	5, 6	1.070	0.460
Sediment F	5, 6	56.13	<0.001 ***	5, 6	4.070	0.059
Sediment H	5, 6	1.550	0.303	5, 6	2.370	0.161

Table gives F ratios and probability values obtained from twenty four 1×6 one-way analyses comparing time (15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes and 15 hours) for which containers were left to stand before avalanching. Twelve for the duration of first avalanche and twelve for the duration of second avalanche. Probability: $0.05>P>0.01$ *; $0.01>P>0.001$ **; $P<0.001$ ***. For S1 Sediments A, E, F and H see table 1.1 and figure 4.1.

Section 5: Biological Stabilisation: Effects of *Nereis diversicolor*, *Corophium volutator*, and microorganisms plus meiofauna on Avalanching

5.1 MATERIALS AND METHODS

5.1.1 Experimental Design

Biological experiments 1 and 2 were designed to test the effects of burrowing organisms *Nereis diversicolor* and *Corophium volutator* on avalanching (Fig. 5.1). The stabilisation of sediment by these two organisms and the slope failure mechanisms were also studied. Biological experiment 3 was designed to test the effects of microorganisms plus meiofauna on avalanching (Fig. 5.2). The design of biological experiments 1, 2 and 3 allowed me to answer the following four hypotheses. Sketches of *Nereis diversicolor* and *Corophium volutator* are shown in figure 5.3, micr915organisms and microbial colonies on a sand grain (Fig 5.4) and some examples of microorganism and meiofauna living in sediment are given in figure 5.5.

Hypothesis 1:

Do *Nereis diversicolor*, *Corophium volutator* and microorganisms plus meiofauna affect angles of avalanche and repose and do these effects increased with time?

Hypothesis 2:

Do *Nereis diversicolor*, *Corophium volutator* and microorganisms plus meiofauna affect factors of safety and angle of dilatation and do these effects increased with time?

Hypothesis 3:

Do *Nereis diversicolor*, *Corophium volutator* and microorganisms plus meiofauna affect duration of avalanche and do these effects increased with time?

Hypothesis 4:

Do *Nereis diversicolor*, *Corophium volutator* and microorganisms plus meiofauna affect the change in volume of sediment after an avalanche and do these effects increased with time?

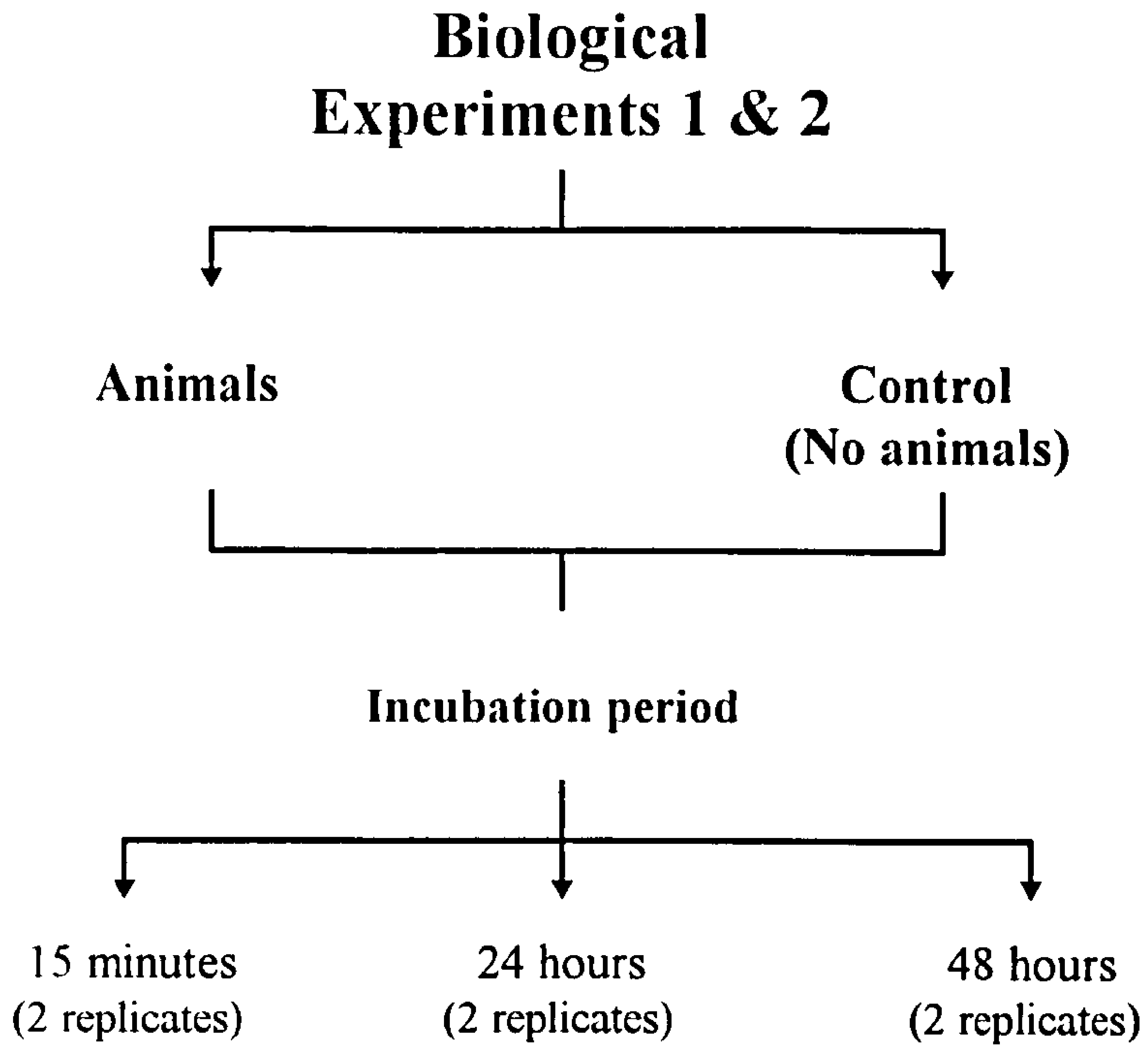


Figure 5.1 Design of biological experiments 1 and 2. Animals: sediment containing *Nereis diversicolor* (Nd) in biological experiment 1 and *Corophium volutator* (Cv) in biological experiment 2. Control: sediment containing no *Nereis diversicolor* (CNd) in biological experiment 1 and sediment containing no *Corophium volutator* (CCv) in biological experiment 2. Two replicate containers left to stand before avalanche for each time; 15 minutes, 24 hours and 48 hours.

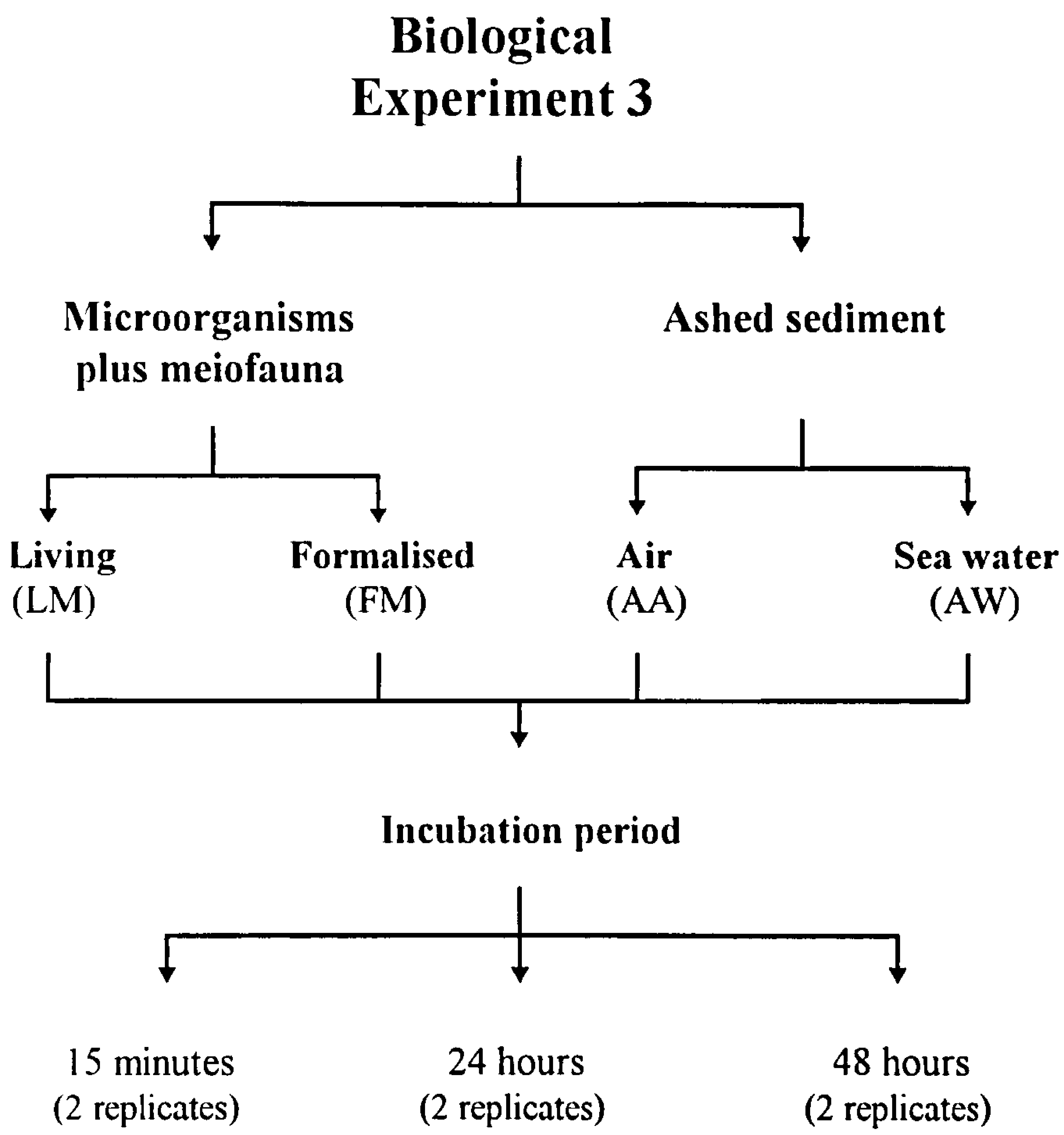


Figure 5.2 Design of biological experiment 3. Natural sediment from the field containing living microorganisms plus meiofauna in sea water (LM) and the same treated with formalin (FM). Ashed sediment: sediment from the field ashed at 480 °C. Ashed sediment in air (AA) and in GF/F filtered sea water (AW). Two replicate containers left to stand before avalanche for each time; 15 minutes, 24 hours and 48 hours.

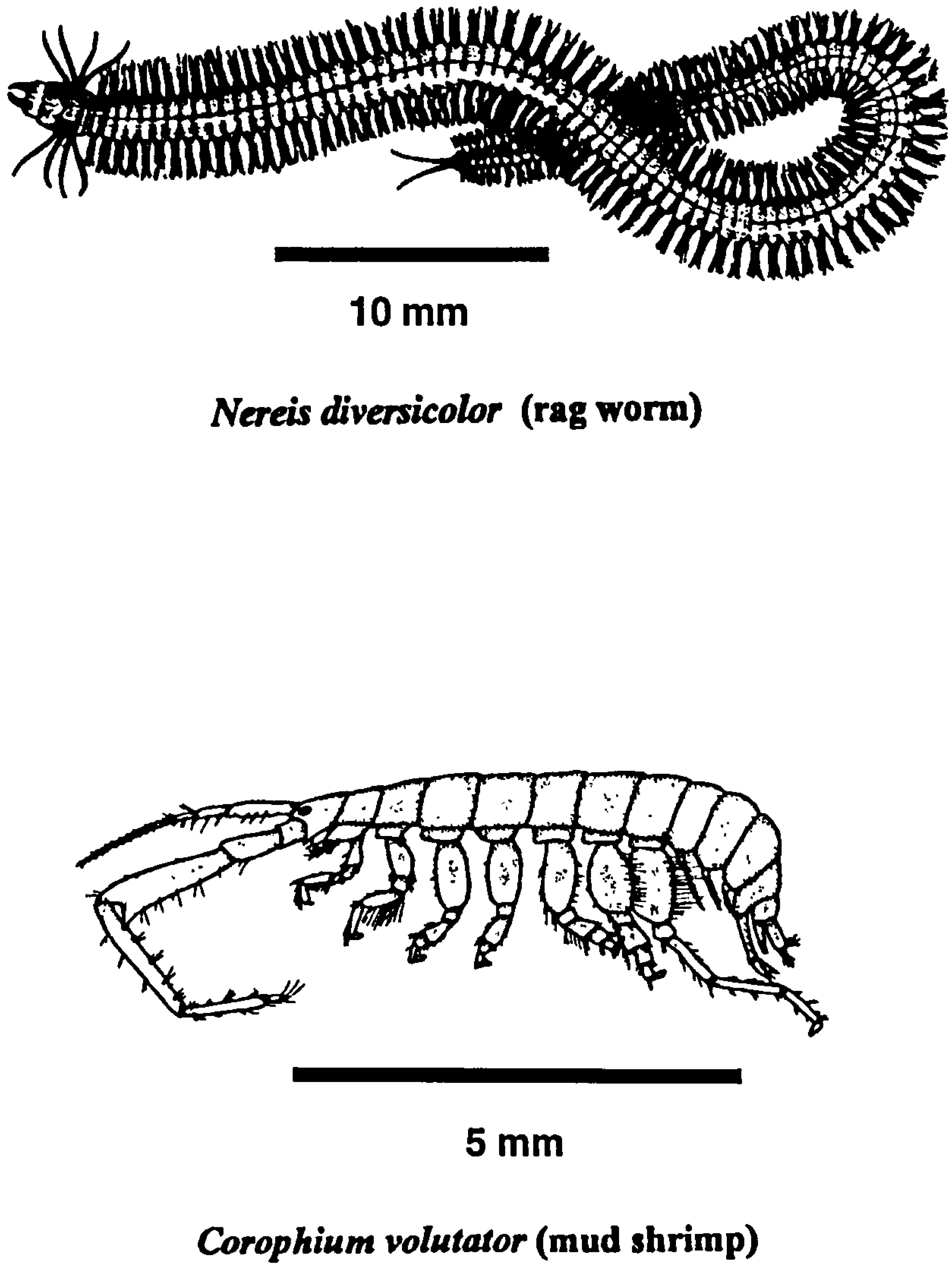


Figure 5.3 Examples of animal used in experiments. Top: *Nereis diversicolor* (Haas & Knorr 1966). Bottom: *Corophium volutator* (Fish & Fish 1989).

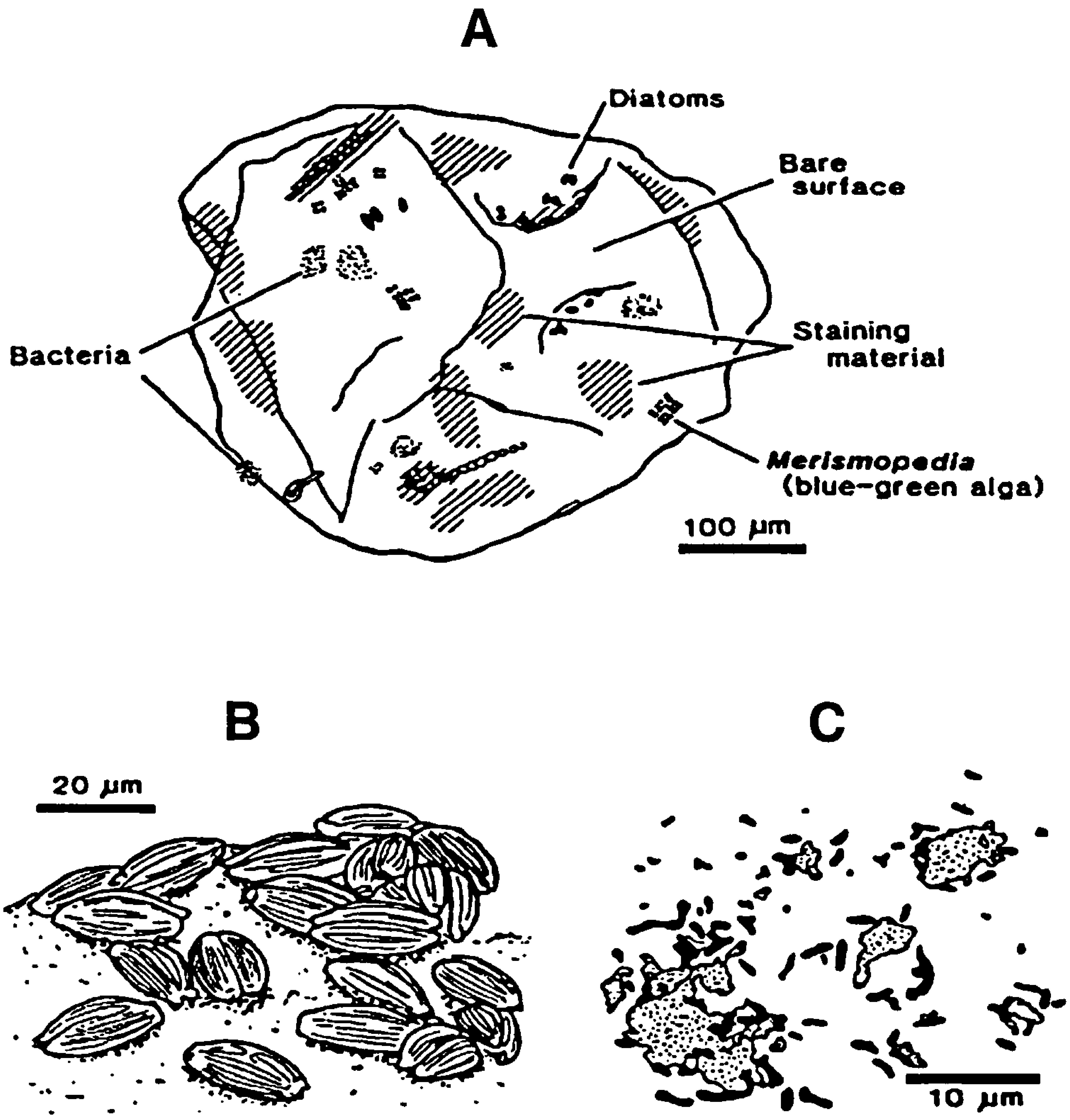


Figure 5.4 Microorganisms on sediment. a) Example of microbial colonies on a sand grain (Meadows & Anderson 1966, 1968; Meadows & Campbell 1988). b) Colony of an *Amphora* sp. (diatom) (Tufail 1985). c) Bacteria around detrital matter (Tufail 1985).

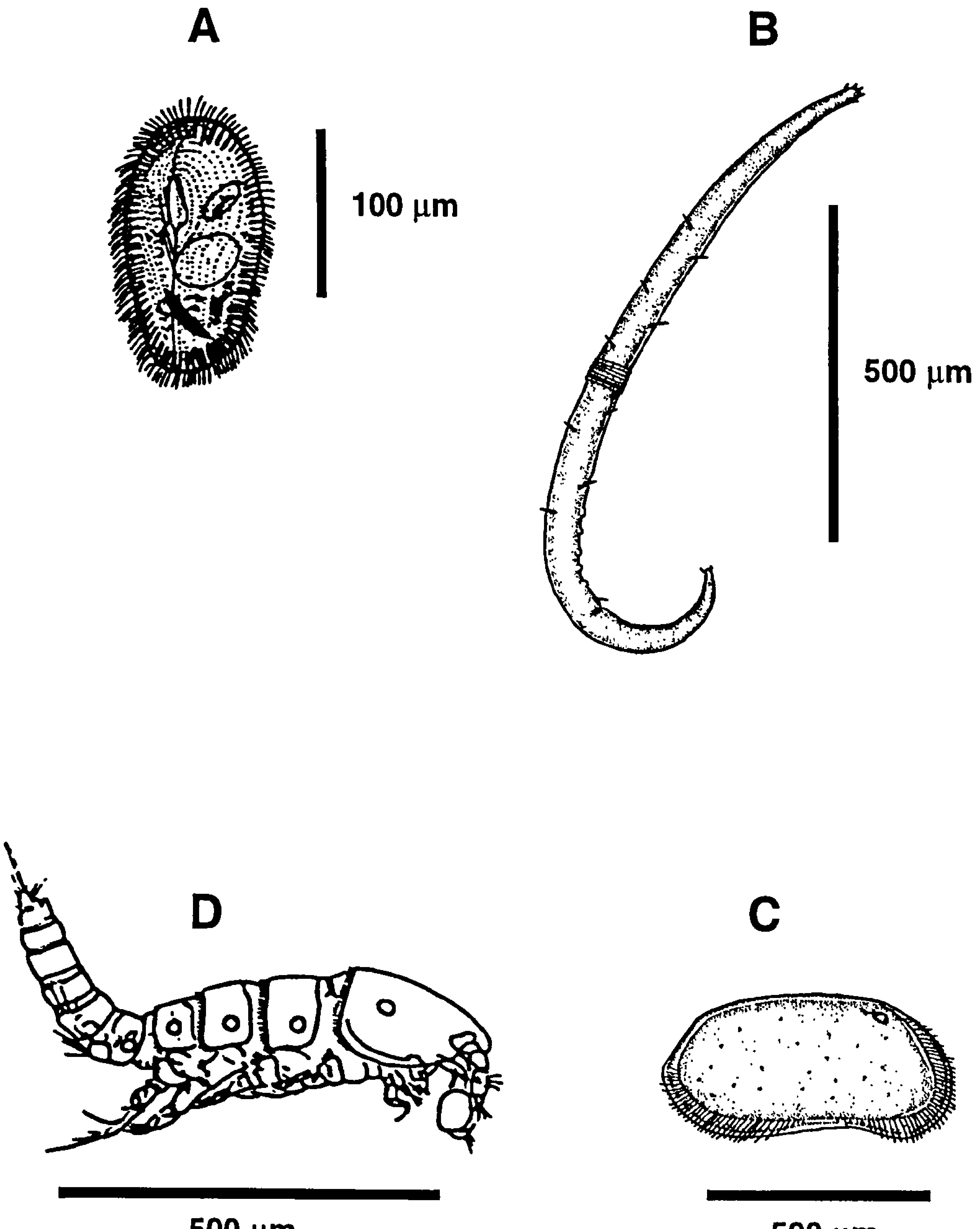


Figure 5.5 Examples of meiofauna living in sediments. a) large ciliates, b) nematodes, c) ostracods, d) harpacticoids. (Swedmark 1964; Cullen 1973; Fenchel 1978; Chandler & Fleeger 1984; Platt & Warwick 1988; Hayward & Ryland 1995).

5.1.2 Collection and Treatment of Sediment and Animals

Sediment was collected from the mid-tide level at Ardmore Bay. *Corophium volutator* (Cv) was collected from the high-tide area of Ardmore bay and *Nereis diversicolor* (Nd) was collected from the mid-tide area at Langbank (since *Nereis diversicolor* is more abundant at Langbank than at Ardmore). Throughout my research I have used sediment from Ardmore Bay. Sediment and organisms were used for experiments within 6 hours of collection.

In the laboratory, the S2 sediment (Table 1.1) was prepared by wet sieving through a 710 μm sieve to remove infauna and large particles thus leaving only microorganisms and meiofauna in the sediment. The wet sieving was done twice. Microscopic examination of the twice-sieved sediment showed that it contained large numbers of microorganisms on the surfaces of the sediment particles (bacteria, diatoms, blue green algae) and some meiofauna between the sediment particles (large ciliates, nematodes, ostracods, harpacticoids). The sediment was then maintained in sea water until used for the experiments. *Corophium volutator* (Cv) and *Nereis diversicolor* (Nd) were removed from the sediment by sieving through a 710 μm sieve, which was then backwashed gently by sea water. The animals were maintained in sea water until used in the experiment.

5.1.3 Conduct of Experiments

Biological Experiments 1 and 2:

Twenty four glass containers were set up, twelve for biological experiment 1 (*Nereis diversicolor*) and twelve for biological experiment 2 (*Corophium volutator*) (Fig. 5.1). In each biological experiment six containers had animals (Nd, Cv) and six (control) containers had no animals (CNd, CCv). Two replicate containers of the six were left to stand for 15 minutes before avalanching, two for 24 hours before avalanching, and two for 48 hours before avalanching. The container was set up as follows. Approximately 400 ml of sediment was added to the 1000 ml of sea water in the container. The animals were added to the sediment in the container by using a brush. The container was then aerated. The numbers of animals used in the experiments were as follows. In biological experiment 1, each of the *Nereis diversicolor* containers contained 33 animals. This is equivalent to 2933 animals m^{-2}. In biological experiment 2, each of the *Corophium volutator* containers contained 100 animals. This is equivalent to 8888 animals m^{-2}. The animal densities were chosen to be equivalent to average densities on the intertidal zone in the Clyde Estuary (Meadows & Tait 1989). Animals were counted at the beginning and end of each experiment. There was no mortality of animals during the experiments and animals displayed normal burrowing behaviour.

Biological Experiment 3:

Twenty four glass containers were set up. These were divided into four groups each containing six containers (Fig. 5.2). The first group contained natural 710 μm sieved sediment in sea water. The second, third and fourth group contained control sediment. The second group contained 710 μm sieved natural sediment which was previously formalised, the third group contained (480°C) ashed sediment in GF/F (0.7 μ m) filtered sea water (AW), and the fourth group contained ashed sediment in air (AA). The containers for ashed sediment were sterilised by 70 % alcohol before use. Replicate containers were set up for all treatments as in biological experiments 1 and 2.

The sediment in the first group therefore contained living microorganisms plus meiofauna (LM), the control sediment in the second group contained microorganisms plus meiofauna killed by formalin (FM), and the control sediment in third and fourth groups contained no microorganisms, no meiofauna and no organic matter. Sediment was ashed at 480 °C for four hours for the third and fourth group. In each of the four groups two replicate containers were left to stand for 15 minutes before avalanching, two were left to stand for 24 hours before avalanching, and two were left to stand for 48 hours before avalanching. Great care was taken to ensure that the ashed sediment in the containers in group 4 were kept completely dry before the experiment and during the experiment. This was done by covering the container with a porous bag containing silica gel.

The clinometer used to avalanche the container is explained in figure 2.3. The procedure of avalanching the container was similar to the avalanching in 2.1.4. In each of the above experiments, two replicate sets of readings were taken as in 2.1.3 and 2.1.4.

5.2 RESULTS

The results are divided into the following sections. I firstly describe the effects of biological and microbiological activity on the first angle of avalanche (A_1) and the first angle of repose (R_1), and on the second angle of avalanche (A_2') and second angle of repose (R_2) (section 5.2.1). This is followed by a section on the factor of safety and the angle of dilatation (section 5.2.2). I then describe the effects of biological and microbiological activity on the duration of avalanching (section 5.2.3) and resultant increase in volume of the sediment during the avalanching process (section 5.2.4).

5.2.1 Hypothesis 1: Do *Nereis diversicolor*, *Corophium volutator* and microorganisms plus meiofauna affect angles of avalanche and repose?

First angle of Avalanche and Repose

The results of biological experiment 1 (effects of *Nereis diversicolor*), biological experiment 2 (effects of *Corophium volutator*), and biological experiment 3 (effects of microorganisms plus meiofauna) are presented in table 5.1. The data is plotted in figure 5.6, figure 5.7 and in figure 5.8 respectively. Statistical analyses of these results are presented in tables 5.2 to 5.5.

Biological Experiments 1 and 2: Both *Nereis diversicolor* (biological experiment 1; Table 5.1 and Table 5.2) and *Corophium volutator* (biological experiment 2; Table 5.1 and Table 5.3) increased the angles of avalanche when compared with control sediments. This effect increased as the experiment progressed, and was more obvious at 48 hours. *Nereis diversicolor* had a greater effect than *Corophium volutator*.

In detail, there were significant differences between the animal and control sediments at 15 minutes, 24 hours and 48 hours for *Nereis diversicolor* (biological experiment 1), but this difference was only significant at 48 hours for *Corophium volutator* (biological experiment 2). The effects of the two species on angles of repose were much less marked and only significant at 15 minutes and 48 hours for *Nereis diversicolor* (biological experiment 1).

Table 5.1 Data from experiment 1, 2 and 3. First angle of avalanche (A_1) and first angle of repose (R_1). Mean ± SD of two replicate readings.

Treatment	A_1 (degrees)			R_1 (degrees)		
	15 minutes	24 hours	48 hours	15 minutes	24 hours	48 hours
Experiment 1.	***Nereis diversicolor***					
Nd	42.90±0.707	60.75±1.061	63.80±0.849	34.55±0.354	37.45±3.606	41.75±1.061
CNd	40.25±0.354	45.60±0.566	50.35±1.909	32.25±0.354	35.25±0.354	36.40±0.283
Experiment 2.	***Corophium volutator***					
Cv	44.80±2.263	51.55±0.919	56.85±0.919	31.70±0.707	32.95±0.778	32.45±0.495
CCv	40.65±0.778	47.55±1.909	49.45±0.778	31.95±0.212	32.90±2.687	34.05±1.626
Experiment 3.	**Microorganisms plus meiofauna**					
LM	39.55±1.344	44.20±1.414	48.85±1.344	32.00±1.697	34.00±0.707	34.75±1.344
FM	38.95±0.212	38.15±0.495	37.70±0.283	32.95±0.071	31.65±0.495	30.10±0.424
AA	35.70±1.838	37.00±0.283	36.20±1.273	33.15±0.495	33.95±0.212	33.10±0.566
AW	41.95±0.212	43.90±1.273	44.60±0.849	32.00±1.131	29.15±0.919	30.85±2.330

Nd = sediment containing *Nereis diversicolor*, CNd = control sediment containing no *Nereis diversicolor*, Cv = sediment containing *Corophium volutator*, CCv = control sediment containing no *Corophium volutator*, LM = sediment containing living microorganisms plus meiofauna, FM = sediment containing dead (formalised) microorganisms plus meiofauna, AA = ashed sediment in air, and AW = ashed sediment in GF/F filtered sea water.

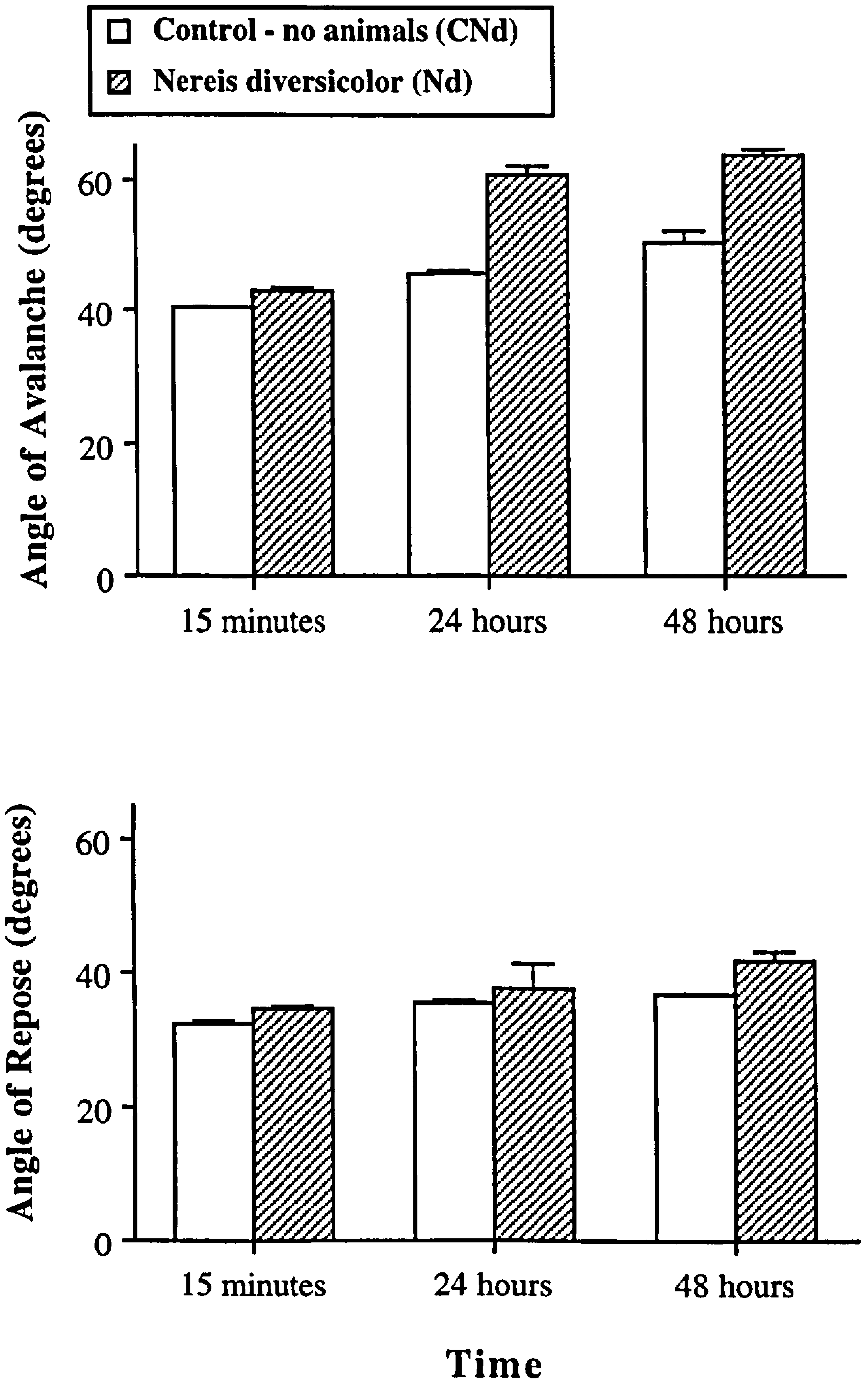


Figure 5.6 Biological experiment 1 (*Nereis diversicolor*). Mean±SD of two replicate readings. **Top**: angle of avalanche in 15 minutes, 24 hours and 48 hours. **Bottom**: angle of repose in 15 minutes, 24 hours and 48 hours. Nd = sediment containing *Nereis diversicolor* CNd = Control: sediment containing no *Nereis diversicolor*.

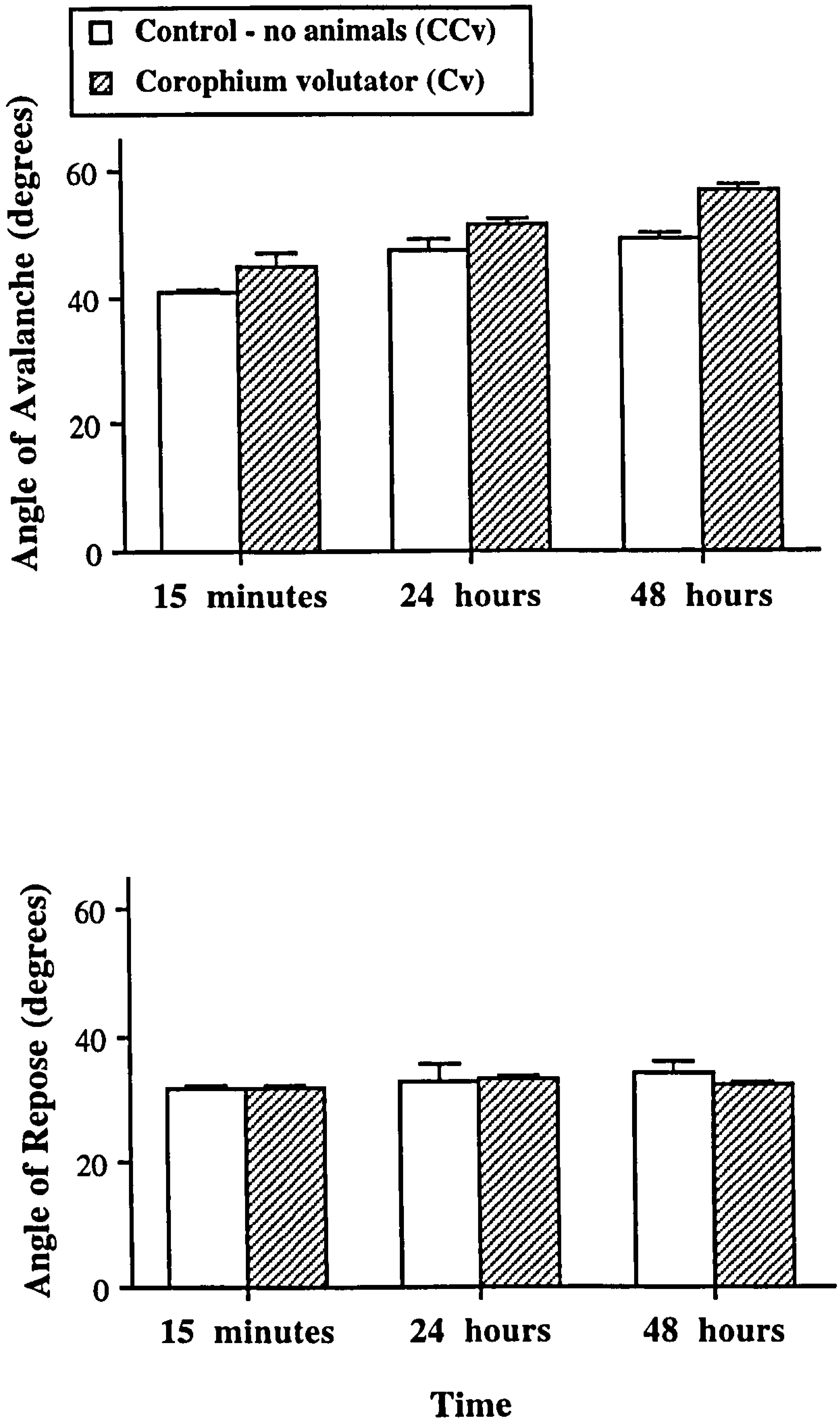


Figure 5.7 Biological experiment 2 (*Corophium volutator*). Mean±SD of two replicate readings. **Top**: angle of avalanche in 15 minutes, 24 hours and 48 hours. **Bottom**: angle of repose in 15 minutes, 24 hours and 48 hours. Cv = *Corophium volutator*. Ccv = Control. sediment containing no *Corophium volutator*.

Table 5.2 Biological experiment 1. Statistical analyses of the effects of animal activity (*Nereis diversicolor*) on the first angle of avalanche (A_1) and the first angle of repose (R_1).

Factors		DF	A_1		R_1	
			F ratio	Probability	F ratio	Probability
a) Nd/CNd						
	15 minutes	1, 2	22.47	0.042 *	42.32	0.023*
	24 hours	1, 2	317.7	0.003**	0.740	0.481 ns
	48 hours	1, 2	82.89	0.012*	47.51	0.020*
b) 15m/24h/48h						
	Nd	2, 3	326.1	P<0.0001***	5.520	0.099 ns
	CNd	2, 3	37.46	0.008**	83.47	0.002**

The table gives the F ratios and probability values obtained from one-way analyses of variance. a) three 1×2 analyses comparing sediment containing *Nereis diversicolor* (Nd) and the control sediment containing no *Nereis diversicolor* (CNd). b) two 1×3 analyses comparing 15 minutes, 24 hours and 48 hours. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Table 5.3 Biological experiment 2. Statistical analyses of the effects of animal activity (*Corophium volutator*) on the first angle of avalanche (A_1) and the first angle of repose (R_1).

Factors		DF	A_1		R_1	
			F ratio	Probability	F ratio	Probability
a) Cv/CCv						
	15 minutes	1, 2	6.020	0.134 ns	0.320	0.679 ns
	24 hours	1, 2	7.130	0.116 ns	0.000	0.982 ns
	48 hours	1, 2	75.53	0.013*	1.770	0.315 ns
b) 15m/24h/48h						
	Cv	2, 3	32.14	0.009**	1.760	0.312 ns
	CCv	2, 3	26.50	0.012*	0.670	0.575 ns

The table gives the F ratios and probability values obtained from one-way analyses of variance. a) three 1×2 analyses comparing sediment containing *Corophium volutator* (Cv) and the control sediment containing no *Corophium volutator* (CCv). b) two 1×3 analyses comparing 15 minutes, 24 hours and 48 hours. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Biological Experiment 3: Sediment containing living microorganisms plus meiofauna (LM) had a greater angle of avalanche than control sediment containing dead (formalised) microorganisms plus meiofauna (FM) (Table 5.4). Ashed sediment in sea water (AW) had a higher angle of avalanche than both ashed sediment in air (AA) and sediment containing dead (formalised) microorganisms plus meiofauna (FM). There were statistically significant differences in the angles of avalanche between the treatments at 15 minutes, 24 hours and 48 hours. The angle of avalanche in the sediment containing living microorganisms plus meiofauna (LM) increased as the experiment progressed, being most marked at 48 hours. This increase with time in angle of avalanche did not occur in the sediments containing the dead (formalised) microorganisms plus meiofauna (FM), or in the ashed sediment whether in sea water (AW) or in air (AA). The effects of treatments on angles of repose were mostly not significant.

Comparison of 48 hours Data: The 48 hours data from biological experiments 1, 2 and 3 were compared in detail by a series of one-way analyses of variance on the angle of avalanche and the angle of repose. The F ratios from these comparisons are shown in table 5.5 in which the top right hand triangle represents the F ratios for the angle of avalanche comparisons and the bottom left hand triangle represents the F ratios for the angle of repose comparisons. Twenty four out of the twenty eight angle of avalanche comparisons were significant, while only thirteen out of the twenty eight angle of repose comparisons were significant.

A detailed inspection of the statistical comparisons in table 5.5 together with the 48 hours data of biological experiments 1, 2 and 3 in table 5.1 reveal a number of important points. The highest angles of avalanche were obtained with *Nereis diversicolor* (biological experiment 1: 63.80°) followed by *Corophium volutator* (biological experiment 2 56.85°). The angles of avalanche of the control sediments containing no *Nereis diversicolor* (biological experiment 1: 50.35°), the control sediment containing no *Corophium volutator* (biological experiment 2: 49.45°) and the sediment containing living microorganisms plus meiofauna (biological experiment 3: 48.85°) were all lower than both those of the sediment containing *Nereis diversicolor* (biological experiment 1 Nd) and *Corophium volutator* (biological experiment 2 Cv) but were not significantly different from each other. In fact, these three treatments are experimentally equivalent because they all contained living microorganisms plus meiofauna. The ashed sediment in water (AW) had an angle of avalanche significantly lower than the above three sediments (44.60°) as did the formalised sediment containing dead (formalised) microorganisms plus meiofauna (37.70°). The lowest angle of avalanche was shown by the ashed sediment in air (36.20°).

There were fewer significant differences between the angles of repose. However, I wish to draw attention to a significantly higher angle of repose of the sediment containing *Nereis diversicolor* (biological experiment 1: 41.75°) compared with all the other angles of repose in biological experiments 1, 2 and 3. The lowest angle of repose was shown by the formalised sediment (30.10°) which was significantly lower than five out of the seven angles of repose (Table 5.5). The angle of repose of the formalised sediment (FM) was not significantly different from the angle of repose of the CCv and the ashed sediment in water (AW). However, it was significantly lower than the angle of repose of ashed sediment in air (AA).

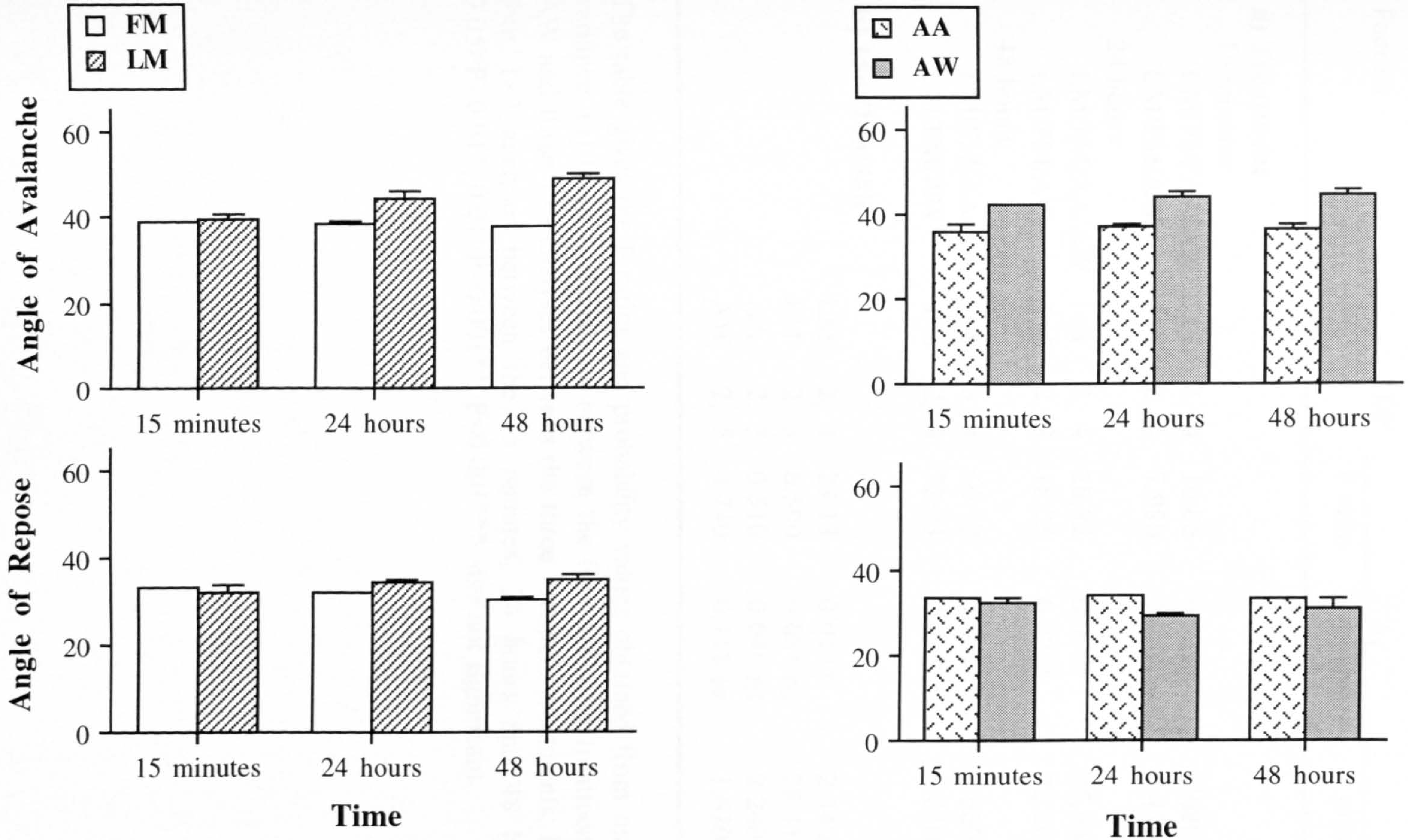


Figure 5.8 Biological experiment 3 (Microorganisms plus meiofauna). Mean±SD of two replicate readings. **Left**: living microorganisms plus meiofauna and formalised microorganisms plus meiofauna. top; angle of avalanche. botttom; angle of repose. **Right**: ashed sediment in air and ashed sediment in GF/F filtered sea water. top; angle of avalanche. botttom; angle of repose. LM = sediment containing living microorganisms plus meiofauna in sea water. FM = sediment treated with formalin. AA = Ashed sediment in air. AW = ashed sediment in GF/F filtered sea water

Table 5.4 Biological experiment 3. Statistical analyses of the effects of living microorganisms plus meiofauna (LM) and formalised microorganisms plus meiofauna (FM), and of ashed sediment dry (AA) and wet (AW) on the first angle of avalanche (A_1) and the first angle of repose (R_1).

Factors		DF	A_1		R_1	
			F ratio	Probability	F ratio	Probability
a) Treatment						
15 minutes						
LM/FM/AA/AW	1×4	3, 4	10.06	0.025*	0.680	0.609 ns
LM/FM/AW	1×3	2, 3	7.980	0.063 ns	0.430	0.683 ns
24 hours						
LM/FM/AA/AW	1×4	3, 4	28.82	0.004**	25.94	0.004**
LM/FM/AW	1×3	2, 3	18.05	0.021*	22.20	0.016*
48 hours						
LM/FM/AA/AW	1×4	3, 4	66.72	0.001**	4.660	0.086 ns
LM/FM/AW	1×3	2, 3	72.93	0.003**	5.030	0.110 ns
b) 15m/24h/48h						
	LM	2, 3	23.13	0.015*	2.340	0.244 ns
	FM	2, 3	6.500	0.081 ns	28.41	0.011*
	AA	2, 3	0.510	0.646 ns	2.240	0.254 ns
	AW	2, 5	4.740	0.118 ns	1.630	0.332 ns

The table gives the F ratios and probability values obtained from one-way analyses of variance (a) three 1×4 analyses between the four sediment treatments: LM, FM, AA, AW and three 1×3 analyses between the three sediment treatments: FM, LM, AW. (b) four 1×3 analyses between the 15 minutes, 24 hours and 48 hours. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Table 5.5 Biological experiments 1, 2 and 3 (48 hours). Pairs of treatments were compared in turn by 1×2 one way analyses of variance (DF = 1, 2 and n = 2). The table gives F ratios from these analyses. Upper right triangle: first angle of avalanche (A_1). Lower left triangle: first angle of repose (R_1). Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Treatment	Nd	CNd	Cv	CCv	LM	FM	AA	AW
Nd		82.89 *	61.73 *	310.8 **	177.0 **	1703.0 **	651.08 **	512.0 **
CNd	47.51 *		18.83 *	0.380 ns	0.830 ns	85.92 *	76.06 *	15.15 *
Cv	126.3 **	96.02 *		75.53 *	48.30 *	792.9 **	345.98 **	191.8 **
CCv	31.45 *	4.050 ns	1.770 ns		0.300 ns	403.1 **	157.81 **	35.51 *
LM	33.45 *	2.890 ns	5.160 ns	0.220 ns		131.9 **	93.44 *	14.31 *
FM	208.0 **	305.3 **	25.99 *	11.05 ns	21.70 *		2.65 ns	119.0 **
AA	103.6 *	54.45 *	1.500 ns	0.610 ns	2.560 ns	36.00 *		60.31 *
AW	36.17 *	11.15 ns	0.900 ns	2.530 ns	4.200 ns	0.200 ns	1.76 ns	

For Nd, CNd, Cv, CCv, LM, FM, AA and AW see table 5.1.

Second Angle of Avalanche and Repose

The results of biological experiments 1, 2 and 3 are shown in table 5.6 and their statistical analyses are shown in tables 5.7 to 5.10.

Second Angle of Avalanche (A_2'): The 48 hours data for the second angle (A_2') of avalanche in table 5.6 column 4 were compared by a series of 1×2 one way analyses of variance between the treatments in the three experiments. Fourteen out of the twenty eight comparisons were significant (Table 5.7 top right hand triangle). In comparison there were twenty four out of twenty eight significant comparisons for the first angle of avalanche (A_1) (see table 5 5).

Biological Experiment 1 & 2: There are two important differences in biological experiments 1 and 2 between the first angle of avalanche (A_1) and the second angle of avalanche (A_2') at 48 hours. Firstly, in biological experiment 1 there was no difference between the second angle of avalanche (A_2') of the sediment containing animals and the control sediment containing no animals (Table 5.6, Table 5.7 Nd/CNd: 45.60°/45.20°, F ratio = 0.19 not significant). This difference was significant for the first angle of avalanche (A_1). Secondly, in biological experiment 2 the second angle of avalanche (A_2') of the sediment containing animals was significantly lower than the control sediment containing no animals (Table 5.6, Table 5.7 Cv/CCv: 37.75°/40.20°, F ratio = 36.94 *). The first angle of avalanche (A_1) of the sediment containing animals was significantly higher than the control sediment containing no animals (Table. 5.1, Table 5.5 Cv/CCv: 56.85°/49 45°, F ratio = 75.53 *).

The second angle of avalanche (A_2') of the sediment containing living microorganisms plus meiofauna in biological experiment 3 (LM) was not significantly different from the second angle of avalanche in the control sediment of biological experiment 1 (CNd) or the control sediment of biological experiment 2 (CCv) (Table 5.7 F ratios = 7.92 and 0.80). However there was a statistically significant difference between the two control sediments of biological experiment 1 and biological experiment 2 (Table 5.7 CNd/CCv: F ratio = 29.41 *). As already noted the three sediments CNd, CCv, and LM are experimentally equivalent, containing only living microorganisms plus meiofauna.

Biological Experiment 3: The second angle of avalanche (A_2') for the formalised sediment (FM) in biological experiment 3 was significantly lower than the second angle of avalanche of all the sediments in biological experiments 1 and 2 except for the Cv sediment. It was also significantly lower than the second angle of avalanche of the LM sediment containing living microorganisms plus meiofauna in biological experiment 3. These results are broadly similar to the FM comparisons for the first angle of avalanche.

Second Angle of Repose (R_2): The 48 hours data for the second angle of repose (R_2) in table 5.6 column 7 were compared by a series of 1×2 one way analyses of variance between the treatments in the three experiments (Table 5.7 bottom left hand triangle). Five out of the twenty eight comparisons of the second angle of repose were significant. The number of significant comparisons for the first angle of repose (R_1) was much higher, thirteen out of twenty eight (see table 5.5).

As in the first angle of repose (R_1), the sediment containing formalised dead microorganisms plus meiofauna (FM) in biological experiment 3 had a lower second angle of repose (R_2) than all the other sediments. However the second angle of repose (R_2) of the sediment containing *Nereis diversicolor* in biological experiment 1 (Nd) was not significantly different from any of the other second angles of repose (Table 5.7 column 2) This is in marked contrast to the results of the first angles of repose (R_1), in which the first angle of repose of *Nereis diversicolor* was significantly greater than all the other first angles of repose (Table 5.5 column 2).

Table 5.6 Data from biological experiments 1, 2 and 3. True second corrected angle of avalanche ($A_2' = (A_2 - A_1) + R_1$) and second angle of repose (R_2) Mean ± SD of two replicate readings.

Experiment	A_2' (degrees)			R_2 (degrees)		
	15 minutes	24 hours	48 hours	15 minutes	24 hours	48 hours
Biological Experiment 1. ***Nereis diversicolor***						
Nd	42.65±0.778	42.25±4.313	45.60±0.283	34.65±2.051	40.75±2.192	40.90±4.384
CNd	40.25±0.354	42.80±0.283	45.20±1.273	34.50±0.707	34.90±0.141	36.30±0.707
Biological Experiment 2. ***Corophium volutator***						
Cv	38.65±0.212	40.35±1.485	37.75±0.495	31.80±0.000	35.15±0.495	34.85±0.495
CCv	39.25±0.212	38.35±2.475	40.20±0.283	34.75±2.192	34.85±0.919	34.60±0.849
Biological Experiment 3. Microorganisms plus meiofauna						
LM	40.15±1.485	40.70±0.849	41.20±1.556	34.60±0.566	35.25±0.354	36.00±0.849
FM	40.20±0.283	37.10±0.283	35.70±0.849	33.10±0.141	29.85±1.344	30.20±0.283
AA	37.25±2.051	37.15±0.071	37.35±0.778	33.35±0.212	33.20±1.273	33.50±0.990
AW	35.40±1.556	32.35±1.626	35.00±2.404	32.80±0.707	31.55±0.778	32.15±1.344

For Nd, CNd, Cv, CCv, LM, FM, AA and AW see table 5.1.

Table 5.7 Biological experiments 1, 2 and 3 (48 hours). Pairs of treatments compared in turns by 1× 2 one way analyses of variance (DF = 1, 2 and n = 2). The table gives F ratios from these analyses. Upper right triangle: true second corrected angle of avalanche (A_2') Lower left triangle: second angle of repose (R_2). Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0 001***. ns= not significant.

Treatment	Nd	CNd	Cv	CCv	LM	FM	AA	AW
Nd		0.190 ns	379.2 **	364.5 **	15.49 ns	245.0 **	198.72 **	38.35 *
CNd	2.150 ns		59.52 *	29.41 *	7.920 ns	77.14 *	55.39 *	28.12 *
Cv	3.760 ns	5.640 ns		36.94 *	8.930 ns	8.710 ns	0.38 ns	2.510 ns
CCv	3.980 ns	4.740 ns	0.130 ns		0.800 ns	50.62 *	23.72 *	9.230 ns
LM	2.410 ns	0.150 ns	2.740 ns	2.720 ns		19.27 *	9.80 ns	9.380 ns
FM	11.86 ns	128.3 **	133.1 **	48.40 *	84.10 *		4.11 ns	0.150 ns
AA	5.420 ns	10.59 ns	2.980 ns	1.420 ns	7.350 ns	20.55 *		1.730 ns
AW	7.280 ns	14.94 ns	7.110 ns	4.750 ns	11.74 ns	4.030 ns	1.31 ns	

For Nd, CNd, Cv, CCv, LM, FM, AA and AW see table 5.1.

Comparison of First and Second Angles of Avalanche and Repose: The second angle of avalanche (A_2') increased much more slowly than the first angle of avalanche (A_1) during the experiment, while the second angle of repose (R_2) was broadly the same as first angle of repose (R_1). For example, in biological experiment 1 at 48 hours, the first angle of avalanche (A_1) was 63.80° and the second angle of avalanche (A_2') was 45.60° for Nd, and the same angles for CNd were 50.35° and 45.2°. In contrast the angles of repose for these treatments were 41.75° and 40.90°, and 36.40° and 36.30° respectively (Table 5.1 & Table 5.6).

The differences between the first and second angles of avalanche and the first and second angles of repose at 48 hours were quantified by expressing them as $((A_2'/A_1)\times 100\%)$ and as $((R_2/R_1)\times 100\%)$. The statistical significance between these first and second angles comparing replicates 1 and 2 were assessed by Student's paired t-test. The differences and their statistical significance are shown in tables 5.8 and 5.9.

First and Second Angles of Avalanche: The percentages comparing the first and second angles of avalanche $((A_2'/A_1)\times 100\%)$ shown in table 5.8 column 4 are all less than 100%, except for one replicate treatment in the ashed sediment in air (AA) of biological experiment 3 (107.4%). The paired t-tests shown in table 5.8 column 5 show that the second angle of avalanche (A_2') in three out of the four treatments in biological experiments 1 and 2 (Nd, Cv, CCv) were significantly different from the first angle of avalanche (A_1). However only one of the treatments in biological experiment 3, the sediment containing living microorganisms plus meiofauna (LM), had a significantly lower second angle of avalanche (A_2') than the first angle of avalanche (A_1).

The 48 hour ratios (A_2'/A_1) for the first angles of avalanche (A_1) and second angles of avalanche (A_2') between treatments in the three experiments were compared by a series of 1×2 one way analyses of variance. The F ratios from these 28 analyses are shown in the top right hand triangle of table 5.10. Fourteen out of the twenty eight comparisons are significant. In biological experiments 1 and 2 the sediment containing animals had significantly lower ratios (A_2'/A_1) than the control sediment containing no animals. (Biological experiment 1: 0.70, 0.72 / 0.94, 0.85 ; F ratio = 18.16 *, Biological experiment 2: 0.69, 0.65 / 0.81, 0.82 ; F ratio = 100.5*) (see tables 5.6, 5.8 and 5.10). In contrast there were no significant differences between the sediment containing animals (Nd/Cv) in biological experiments 1 and 2, and between the control sediments

(CNd/CCv) in biological experiments 1 and 2 (Table 5.10 top right hand triangle: F ratio; 8.79, 4.13 not significant). The differences between the sediment containing living microorganisms plus meiofauna (LM) in biological experiment 3 and control sediments (CNd and CCv) in biological experiments 1 and 2 were also not significant (Table 5.10 top right hand triangle: F ratio; 1.74, 14.75 not significant). These latter three sediments (CNd, CCv, LM) are exactly equivalent because they all contain living microorganisms plus meiofauna. The ratios (A_2'/A_1) for the formalised sediment (FM) containing dead microorganisms plus meiofauna in biological experiment 3 (Table 5.8 0.96, 0.94) were significantly higher than the ratios (A_2'/A_1) of three out of the four treatments in biological experiments 1 and 2 (Nd, Cv, CCv) (Table 5.10 top right hand triangle: F ratio; 243.6 **, 252.7 **, 123.0 **).

First and Second Angles of Repose: The percentages comparing the first and second angles of repose ((R_2/R_1)×100%) for 48 hours shown in table 5.9 column 4 are all close to 100%. The paired t-tests shown in table 5.9 in column 5 are all non significant showing that there is no difference between percentage ratios of the first and second angles of repose.

The 48 hour ratios (R_2/R_1) for the first and second angles of repose between treatments in the three experiments were compared by a series of 1×2 one way analyses of variance. The F ratios from these 28 analyses are shown in the bottom left hand triangle of table 5.10. None of these were significant.

Table 5.8 48 hours data from biological experiments 1, 2 and 3. Comparison of first angle of avalanche (A_1) and true corrected second angle of avalanche (A_2') by Student's paired t-test (DF = 1, Fisher and Yates 1963). Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Experiment	Treatment	Repl	A_2'/A_1	$(A_2'/A_1)\times100$	Student's t	Probability
1. Biological Experiment 1.	***Nereis diversicolor***					
	Nd	1	0.705	70.50	22.75	0.028 *
		2	0.725	72.50		
	CNd	1	0.941	94.10	2.290	0.260 ns
		2	0.857	85.70		
2. Biological Experiment 2.	***Corophium volutator***					
	Cv	1	0.678	67.80	19.10	0.033 *
		2	0.650	65.00		
	CCv	1	0.808	80.80	26.43	0.024 *
		2	0.818	81.80		
3. Biological Experiment 3.	**Microorganisms plus meiofauna**					
	LM	1	0.837	83.70	51.00	0.012 *
		2	0.849	84.90		
	FM	1	0.958	95.80	5.000	0.130 ns
		2	0.936	93.60		
	AA	1	1.074	107.4	-0.360	0.780 ns
		2	0.992	99.20		
	AW	1	0.737	73.70	-1.860	0.310 ns
		2	0.834	83.40		

For Nd, CNd, Cv, CCv, LM, FM, AA and AW see table 5.1.

Table 5.9 48 hours data from biological experiments 1, 2 and 3. Comparison of first angle of repose (R_1) and second angle of repose (R_2) by Student's paired t-test (DF = 1, Fisher and Yates 1963). Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Experiment	Treatment	Repl	R_2/R_1	$(R_2/R_1)\times 100$	Student's t	Probability
1. Biological Experiment 1.	***Nereis diversicolor***					
	Nd	1	0.9220	92.20	0.360	0.780 ns
		2	1.0350	103.5		
	CNd	1	0.9780	97.80	0.140	0.910 ns
		2	1.0170	101.7		
2. Biological Experiment 2.	***Corophium volutator***					
	Cv	1	1.0750	107.3	Values are identical	
		2	0.0000	107.5		
	CCv	1	1.0700	96.60	-0.310	0.810 ns
		2	0.0000	107.0		
3. Biological Experiment 3.	**Microorganisms plus meiofauna**					
	LM	1	1.0470	104.7	-3.570	0.170 ns
		2	1.0250	102.5		
	FM	1	0.9870	98.70	-0.200	0.870 ns
		2	1.0200	102.0		
	AA	1	1.0460	104.6	-0.360	0.780 ns
		2	0.9790	97.90		
	AW	1	1.0680	106.8	-1.860	0.310 ns
		2	1.0180	101.8		

For Nd, CNd, Cv, CCv, LM, FM, AA and AW see table 5.1.

Table 5.10 48 hours data from biological experiments 1, 2 and 3. Pairs of treatments compared in turns by 1×2 one way analyses of variance (DF = 1, 2 and n = 2). The table gives F ratios from these analyses. Upper right triangle: ratio of true second corrected angle of avalanche to the first angle of avalanche (A_2'/A_1). Lower left triangle: ratio of second angle of repose to the first angle of repose (R_2/R_1). Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Treatment	Nd	CNd	Cv	CCv	LM	FM	AA	AW
Nd		18.16 *	8.790 ns	76.83 *	120.5 **	243.6 **	56.78 *	2.030 ns
CNd	0.100 ns		28.18 *	4.130 ns	1.740 ns	1.220 ns	5.210 ns	3.130 ns
Cv	2.860 ns	0.140 ns		100.5 *	138.1 **	252.7 **	72.54 *	5.790 ns
CCv	2.860 ns	0.140 ns	1.160 ns		14.75 ns	123.0 **	28.37 *	0.320 ns
LM	1.000 ns	1.000 ns	11.84 ns	11.84 ns		68.89 *	21.03 *	1.380 ns
FM	0.060 ns	0.060 ns	0.070 ns	0.070 ns	2.690 ns		4.100 ns	10.55 ns
AA	0.270 ns	0.270 ns	3.370 ns	3.370 ns	0.440 ns	0.060 ns		15.19 ns
AW	2.060 ns	2.060 ns	0.190 ns	0.707 ns	0.070 ns	1.740 ns	0.530 ns	

For Nd, CNd, Cv, CCv, LM, FM, AA and AW see table 5.1.

5.2.2 Hypothesis 2: Do *Nereis diversicolor*, *Corophium volutator* and microorganisms plus meiofauna affect factors of safety and angle of dilatation?

The factor of safety and angles of dilatation calculated from the first angles of avalanche (A_1) and the first angles of repose (R_1) for biological experiments 1 and 2 with their statistical analyses are shown in tables 5.11 and 5.12 and for biological experiment 3 in tables 5.13 and 5.14.

Biological Experiments 1 and 2

Factors of safety and angles of dilatation increased with time in both experiments. These increases were all statistically significant (Table 5.12 rows 4, 5, 9, 10). Inspection of the data in table 5.11 shows that the effect had become stabilised by 24 hours for the Nd sediment, while the Cv sediment had its highest values at 48 hours. In biological experiment 1, the factors of safety was significantly higher for the sediments containing animals than for the control sediments at 24 hours and 48 hours (Table 5.12 rows 2, 3 column 6). However the angles of dilatation was only significant at 24 hours (Table 5.12 row 2 column 4). In biological experiment 2, the factors of safety and angles of dilatation were significantly higher for the sediments containing animals than for the control sediments only at 24 hours (Table 5.12 row 8).

Biological Experiment 3

In general, factors of safety and angles of dilatation increased with time, as they did in biological experiments 1 and 2, however the effect was only significant for the formalised sediment containing dead microorganisms plus meiofauna (FM) (Table 5.14 row 11). There were significant differences between the sediment treatments which were most obvious at 48 hours (Table 5.14 rows 7, 8). In particular, at 48 hours the factor of safety and angles of dilatation of the sediment containing living microorganisms plus meiofauna (LM) were higher than those of formalised sediment containing dead microorganisms plus meiofauna (FM) (Table 5.13 rows 1, 2: 1.65/1.33, 14.10/7.60). The factor of safety and angles of dilatation of the ashed sediment avalanched in water (AW) were also higher than those of ashed sediment avalanched in air (AA) (Table 5.13 rows 3, 4: 1.66/1.12, 13.75/3.10).

Table 5.11 Data from biological experiments 1 and 2. Angle of dilatation (A_1-R_1) and factor of safety (Tan (A_1)/Tan (R_1)). Mean ± SD of two replicate readings.

Treatment	Angle of Dilatation			Factor of Safety		
	15 minutes	24 hours	48 hours	15 minutes	24 hours	48 hours
Biological Experiment 1. *Nereis diversicolor*						
Nd	8.350±1.061	23.30±2.546	22.05±1.909	1.350±0.057	2.340±0.204	2.290±0.164
CNd	8.000±0.707	10.35±0.212	13.95±2.192	1.340±0.035	1.460±0.009	1.650±0.116
Biological Experiment 2. *Corophium volutator*						
Cv	13.10±2.970	18.60±1.697	24.40±1.414	1.610±0.172	1.950±0.122	2.410±0.130
CCv	8.700±0.990	14.65±0.778	15.40±0.849	1.380±0.049	1.690±0.061	1.730±0.059

Nd, CNd, Cv and CCv, as in table 5.1.

Table 5.12 Statistical analyses of the effects of animals *Nereis diversicolor* (Biological experiment 1) and *Corophium volutator* (Biological experiment 2) on angle of dilatation and factor of safety. The table gives the F ratios and probability values obtained from one-way analyses of variance. (a) three 1×2 analyses comparing sediment containing animals and the control sediment containing no animals. (b) two 1×3 analyses comparing 15 minutes, 24 hours and 48 hours. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Factors		DF	Angle of Dilatation		Factor of Safety	
			F ratio	Probability	F ratio	Probability
Biological Experiment 1. *Nereis diversicolor*						
a) Nd/CNd	15 minutes	1, 2	0.060	0.824 ns	0.010	0.948 ns
	24 hours	1, 2	51.40	0.019 *	38.45	0.025 *
	48 hours	1, 2	17.53	0.053 ns	20.11	0.046 *
b) 15m/24h/48h	Nd	2, 3	37.13	0.008 **	26.13	0.013 *
	CNd	2, 3	12.72	0.034 *	9.830	0.048 *
Biological Experiment 2. *Corophium volutator*						
a) Cv/CCv	15 minutes	1, 2	3.950	0.185 ns	3.470	0.204 ns
	24 hours	1, 2	8.950	0.096 ns	6.920	0.119 ns
	48 hours	1, 2	56.56	0.016 *	45.33	0.021 *
b) 15m/24h/48h	Cv	2, 3	13.98	0.030 *	15.72	0.026 *
	CCv	2, 3	35.08	0.008 **	23.53	0.015 *

Nd, CNd, Cv and CCv, as in table 5.1.

Table 5.13 Biological experiment 3. Angle of dilatation (A_1-R_1) and factor of safety (Tan (A_1)/Tan (R_1)). Mean ± SD of two replicate readings.

Treatment	Angle of Dilatation			Factor of Safety		
	15 minutes	24 hours	48 hours	15 minutes	24 hours	48 hours
LM	7.550±3.041	10.20±2.121	14.10±0.000	1.320±0.149	1.440±0.109	1.650±0.004
FM	6.000±0.283	6.500±0.000	7.600±0.141	1.250±0.013	1.270±0.002	1.330±0.008
AA	2.550±2.333	3.050±0.495	3.100±0.707	1.100±0.096	1.120±0.021	1.120±0.028
AW	9.950±0.919	14.75±2.192	13.75±3.182	1.440±0.052	1.730±0.142	1.660±0.202

LM, FM, AA and AW as in table 5.1.

Table 5.14 Statistical analyses of the effects of living microorganisms plus meiofauna and of ashed sediment on angle of dilatation and factor of safety in biological experiment 3. The table gives the F ratios and probability values obtained from one-way analyses of variance. (a) Nine one way analyses of variance. One 1×4 analyses comparing the four sediment treatments: LM, FM, AA, AW, one 1×2 analyses comparing the two sediment treatments: LM, FM and one 1×2 analyses comparing the two sediment treatments: AA, AW on each of the time 15minutes, 24 hours and 48 hours. (b) four 1×3 analyses comparing the 15 minutes, 24 hours and 48 hours, one on each of the four treatments: LM, FM, AA, AW. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Factors		DF	Angle of Dilatation		Factor of Safety	
			F ratio	Probability	F ratio	Probability
a) Treatment						
15 minutes						
LM/FM/AA/AW	1×4	3, 4	4.930	0.079 ns	4.730	0.084 ns
FM/LM	1×2	1, 2	0.520	0.547 ns	0.530	0.542 ns
AA/AW	1×2	1, 2	17.41	0.053 ns	19.22	0.048 *
24 hours						
AA/AW/FM/LM	1×4	3, 4	21.11	0.006 **	16.66	0.010 *
FM/LM	1×2	1, 2	6.080	0.132 ns	4.750	0.161 ns
AA/AW	1×2	1, 2	54.21	0.018 *	35.97	0.027 *
48 hours						
AA/AW/FM/LM	1×4	3, 4	20.97	0.007 **	13.02	0.016 *
FM/LM	1×2	1, 2	4225	<0.0001 ***	2233.1	<0.0001 ***
AA/AW	1×2	1, 2	21.35	0.044 *	13.78	0.066 ns
b)15m/24h/48h	LM	2, 3	4.740	0.118 ns	4.830	0.115 ns
	FM	2, 3	40.20	0.007 **	48.53	0.005 **
	AA	2, 3	0.090	0.917 ns	0.080	0.927 ns
	AW	2, 3	2.440	0.235 ns	2.150	0.264 ns

LM, FM, AA and AW as in table 5.1.

Relationship between Factor of Safety and Angles of avalanche and Repose for Biological Experiment 1, 2 and 3

Figure 5.9, which includes the data for all the three experiments, shows that there is a strong linear relationship between the factor of safety and the angle of avalanche but not between the factor of safety and angle of repose. The relationship between the factor of safety and the angle of avalanche was further analysed by considering the following sets of data separately: Biological experiment 1 (Nd+CNd), biological experiment 2 (Cv+CCv), biological experiment 3 (LM+FM) and biological experiment 3 (AA+AW). These separate sets of data are shown in figure 5.10 and were analysed by four regression analyses (see legend of Fig. 5.10). All four regressions were significant.

The slopes of the four separate regression lines were then statistically compared (Snedecor & Cochran 1980). The F ratios from these comparisons are presented in table 5.15. There were significant differences between the slopes of all the lines except for the A/C comparison. The ashed sediment in air and water (Fig. 5.10 D: AA+AW) had a highest slope (0.0697). The data from biological experiment 2 (Fig. 5.10 B: Cv+CCv) had a lower slope (0.0607). The lowest slopes were shown by the sediments containing the microorganisms plus meiofauna in biological experiment 3 and the sediments in biological experiment 1 (Fig. 5.10 C: LM+FM, Fig. 5.10 A: Nd+CNd) (0.0331, 0.0467).

Table 5.15 Comparisons of regression equations. Factor of safety (Y-axis) against angle of avalanche (X-axis). Regression equations given in Fig. 5.10 legend. Pairs of regression equations of categories A, B, C and D were compared in turn. Table gives F_{slope} and level of significance. A=(Nd+CNd); biological experiment 1. B=(Cv+CCv); biological experiment 2. C=(LM+FM); biological experiment 3. D=(AA+AW); Biological experiment 3. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Categories	A	B	C	D
A		14.99 **	4.566 ns	15.96 **
B			12.96 *	5.441 *
C				27.22 ***
D				

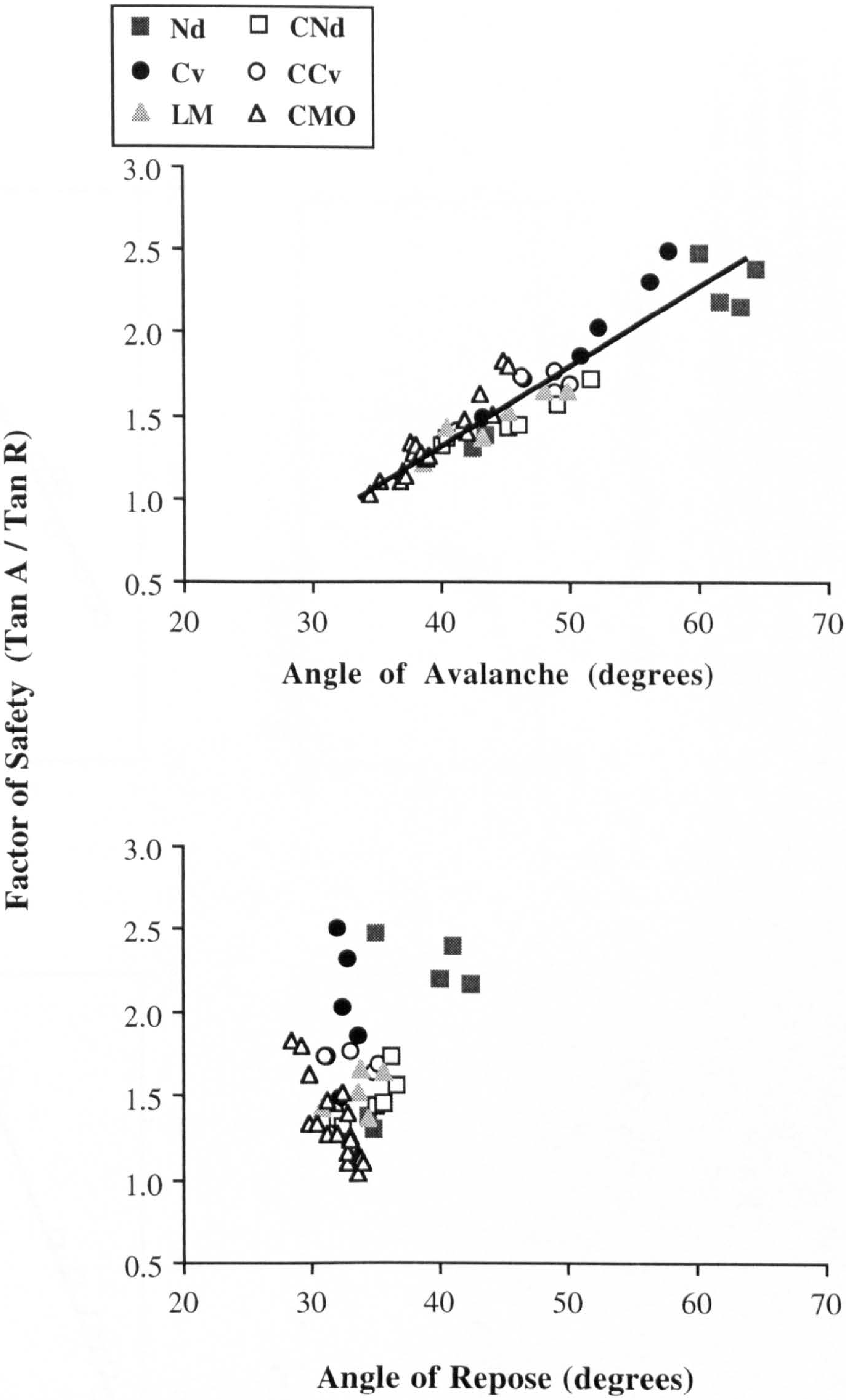


Figure 5.9 Data from biological experiment 1 (*Nereis diversicolor*), biological experiment 2 (*Corophium volutator*) & biological experiment 3 (Microorganisms plus meiofauna). **Top**: relation between angle of avalanche and factor of safety (y=0.0200x + 0.4460, $F_{1,45}$=112.7, P<0.001 ***). **Bottom**: relation between angle of repose and factor of safety (y=0.00738x + 1.100, $F_{1,45}$=0.5900, P=0.440 ns). Nd=*Nereis diversicolor*; CNd=control containing no *Nereis diversicolor*; Cv=*Corophium volutator*; CCv=control containing no *Corophium volutator*; LM=living microorganisms plus meiofauna; CMO=FM+AA+AW (sediments containing either killed or no microorganisms and no meiofauna).

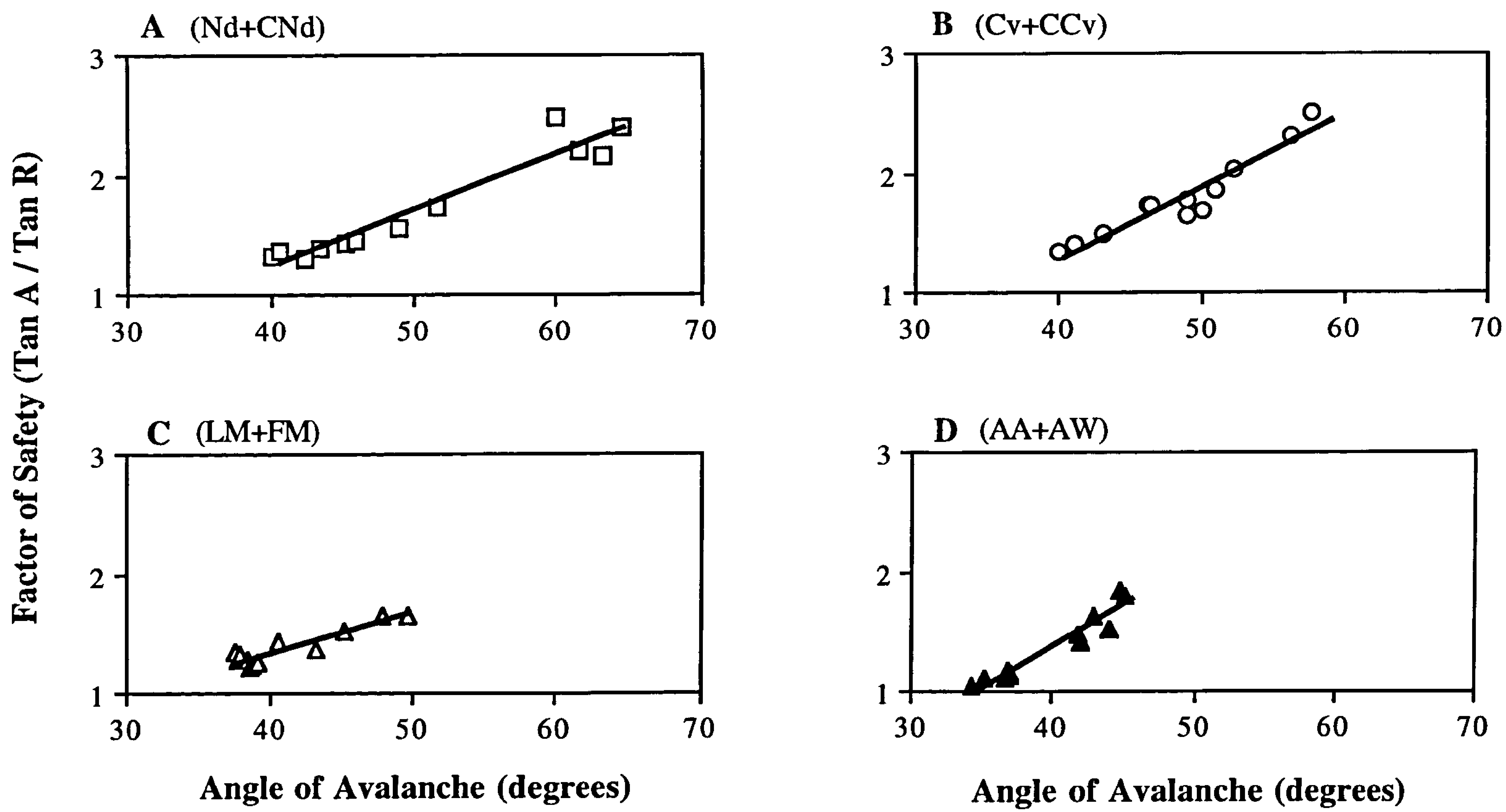


Figure 5.10 Regression of angle of avalanche against factor of safety. (A) Animal and control data from biological experiment 1 (*Nereis diversicolor*) (y=0.0467x - 0.6280, $F_{1,10}$=128.6, P<0.001***). (B) Animal and control data from biological experiment 2 (*Corophium volutator*) (y=0.0607x - 1.150, $F_{1,10}$=96.55, P<0.001***). (C) Living microorganisms plus meiofauna and formalised microorganisms plus meiofauna data from biological experiment 3 (Microorganisms plus meiofauna) (y=0.0331x + 0.012, $F_{1,10}$=59.08, P<0.001***). (D) Ashed sediment in air and ashed sediment in GF/F filtered sea water data from biological experiment 3 (y=0.0697x - 1.420, $F_{1,10}$=129.2, P<0.001***).

5.2.3 Hypothesis 3: Do *Nereis diversicolor*, *Corophium volutator* and microorganisms plus meiofauna affect duration of avalanche?

Table 5.16 shows the duration in seconds of the first and second avalanches at 15 minutes, 24 hours and 48 hours in biological experiment 1, 2 and 3. The data for the duration of the first avalanche (T_1) were analysed by one way analyses of variance in table 5.17. The avalanches with the longest duration occurred with sediments containing animals in biological experiment 1 (Nd/CNd: 130 seconds / 35 seconds). The AA treatment had an extremely short duration of between 1 and 2 seconds (Table 5.16 and Table 5.17). In general highest duration of avalanches were shown by animals treatment in experiment 1 and 2. Intermediate durations were shown by the controls in biological experiment 1 and 2 and the LM and FM treatments in biological experiment 3 (23 to 37 seconds). The lowest duration of avalanches were shown by the AA treatment (Table 5.16) When the data for the duration of the first avalanche (T_1) of all three experiments was plotted against the first angle of avalanche for the duration of the first avalanche (A_1) there was a highly significant positive relationship (Fig. 5.11).

In biological experiment 1 and 2 at 48 hours the duration of the second avalanche (T_2) was higher than the duration of the first avalanche (T_1) except for CCv. However in biological experiment 3, the duration of the second avalanche (T_2) was lower than the duration of the first avalanche (T_1).

5.2.4 Hypothesis 4: Do *Nereis diversicolor*, *Corophium volutator* and microorganisms plus meiofauna affect the change in volume of sediment after an avalanche?

All the sediments increased in volume during the first avalanche (Table 5.18) and this effect increased with time. The increase in volumes range from a maximum of about 31% (Biological experiment 1: Nd 48 hours) to a minimum of less than 1% (Biological experiment 3: AA 15 minutes). In both biological experiments 1 and 2 the sediment containing animals showed a greater increase in volume than the control sediment not containing animals (48 hours: Nd/CNd; 30.74% / 7.21%, Cv/CCv; 12.95% / 7.2%). In biological experiment 3 the increase in volume shown by the LM, FM and AW sediments at 48 hours were 5% to 8% and the AA sediment was about 3%. It is interesting that the CNd, CCv and LM sediments, all of which are exactly equivalent containing living microorganisms plus meiofauna, had very similar increases in sediment volume of 7.21%, 7.26% and 7.39%. When the percentage (arcsine) increases in volume for all the experiments were plotted against angle of avalanche, the data showed a highly significant positive relationship (Fig. 5.12).

Table 5.16 Data from biological experiments 1, 2 & 3 Duration of first avalanche (T_1) and duration of second avalanche (T_2). Mean ± SD of two replicate readings

Treatment	T_1 (seconds)			T_2 (seconds)		
	15 minutes	24 hours	48 hours	15 minutes	24 hours	48 hours
Biological Experiment 1. ***Nereis diversicolor***						
Nd	69.38±10.08	134.55±13.58	130.0±22.13	27.50±4.950	138.2±31.40	153.0±41.22
CNd	22.33±4.914	27.25±4.384	35.60±24.96	17.63±2.652	36.45±15.84	44.85±0.283
Biological Experiment 2. ***Corophium volutator***						
Cv	23.60±3.606	40.95±11.80	42.60±10.82	26.78±14.74	141.4±69.79	76.50±73.33
CCv	21.80±2.758	23.30±11.24	23.13±7.036	21.23±1.237	56.63±23.23	23.10±3.889
Biological Experiment 3. Microorganisms plus meiofauna						
LM	34.35±15.98	83.50±55.65	37.05±5.940	31.25±6.930	49.55±13.86	28.25±0.141
FM	74.70±66.82	76.43±68.84	35.20±5.586	20.30±11.53	25.18±1.662	24.10±2.051
AA	1.000±0.707	1.330±0.177	1.550±0.778	1.330±0.318	1.850±0.424	1.230±0.035
AW	25.50±0.919	31.70±3.748	69.35±5.515	17.53±4.490	31.15±3.960	27.35±10.11

For Nd, CNd, Cv, CCv, LM, FM, AA and AW see table 5.1.

Table 5.17 Statistical analyses of the effects of animals *Nereis diversicolor* (biological experiment 1), *Corophium volutator* (biological experiment 2) and microorganisms plus meioorganisms (biological experiment 3) on duration of first avalanche (T_1). The table gives the F ratios and probability values obtained from one-way analyses of variance. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Factors			Duration of First Avalanche (T_1)		
			DF	F ratio	Probability
Experiment 1. ***Nereis diversicolor***					
a) Nd/CNd	15 minutes		1 2	35.23	0.027 *
	24 hours		1 2	113.13	0.009 **
	48 hours		1 2	16.01	0.057 *
b) 15m/24h/48h	Nd		2 3	10.24	0.046 *
	CNd		2 3	0.41	0.698 ns
Experiment 2. ***Corophium volutator***					
a) Cv/CCv	15 minutes		1 2	0.31	0.631 ns
	24 hours		1 2	1.41	0.357 ns
	48 hours		1 2	4.55	0.166 ns
b) 15m/24h/48h	Cv		2 3	1.28	0.397 ns
	CCv		2 3	0.02	0.978 ns
Experiment 3. Microorganisms plus meiofauna					
a) Treatment					
15 minutes					
	LM/FM/AA/AW	1×4	3 4	1.59	0.324 ns
	FM/LM	1×2	1 2	0.69	0.494 ns
	AA/AW	1×2	1 2	892.57	0.001 **
24 hours					
	AA/AW/FM/LM	1×4	3 4	1.53	0.336 ns
	FM/LM	1×2	1 2	0.01	0.920 ns
	AA/AW	1×2	1 2	131.09	0.008 **
48 hours					
	AA/AW/FM/LM	1×4	3 4	4.40	0.093 *
	FM/LM	1×2	1 2	0.10	0.779 ns
	AA/AW	1×2	1 2	296.33	0.003 **
b)15m/24h/48h		LM	2 3	1.35	0.381 ns
		FM	2 3	0.35	0.728 ns
		AA	2 3	1.59	0.338 ns
		AW	2 3	0.40	0.669 ns

Nd, CNd, Cv, CCv, LM, FM, AA and AW as in table 5.1.

Table 5.18 Data from biological experiments 1, 2 & 3. Percentage increase in volume of sediment after the first avalanche. Mean ± SD of two replicate readings.

Treatment	Percentage Increase in Volume		
	15 minutes	24 hours	48 hours
Biological Experiment 1. *Nereis diversicolor*			
Nd	5.980±0.269	14.64±10.387	30.74±5.586
CNd	5.320±1.676	4.030±2.256	7.210±1.492
Biological Experiment 2 *Corophium volutator*			
Cv	12.19±0.078	10.91±2.404	12.95±0.870
CCv	5.370±0.693	8.070±0.721	7.260±3.083
Biological Experiment 3. Microorganisms plus meiofauna			
LM	4.640±5.381	3.990±2.256	7.390±5.530
FM	0.780±1.103	3.970±1.711	5.170±1.082
AA	0.230±2.312	1.870±0.636	3.170±1.068
AW	2.910±0.573	6.110±4.547	7.840±0.898

For Nd, CNd, Cv, CCv, LM, FM, AA and AW see table 5.1.

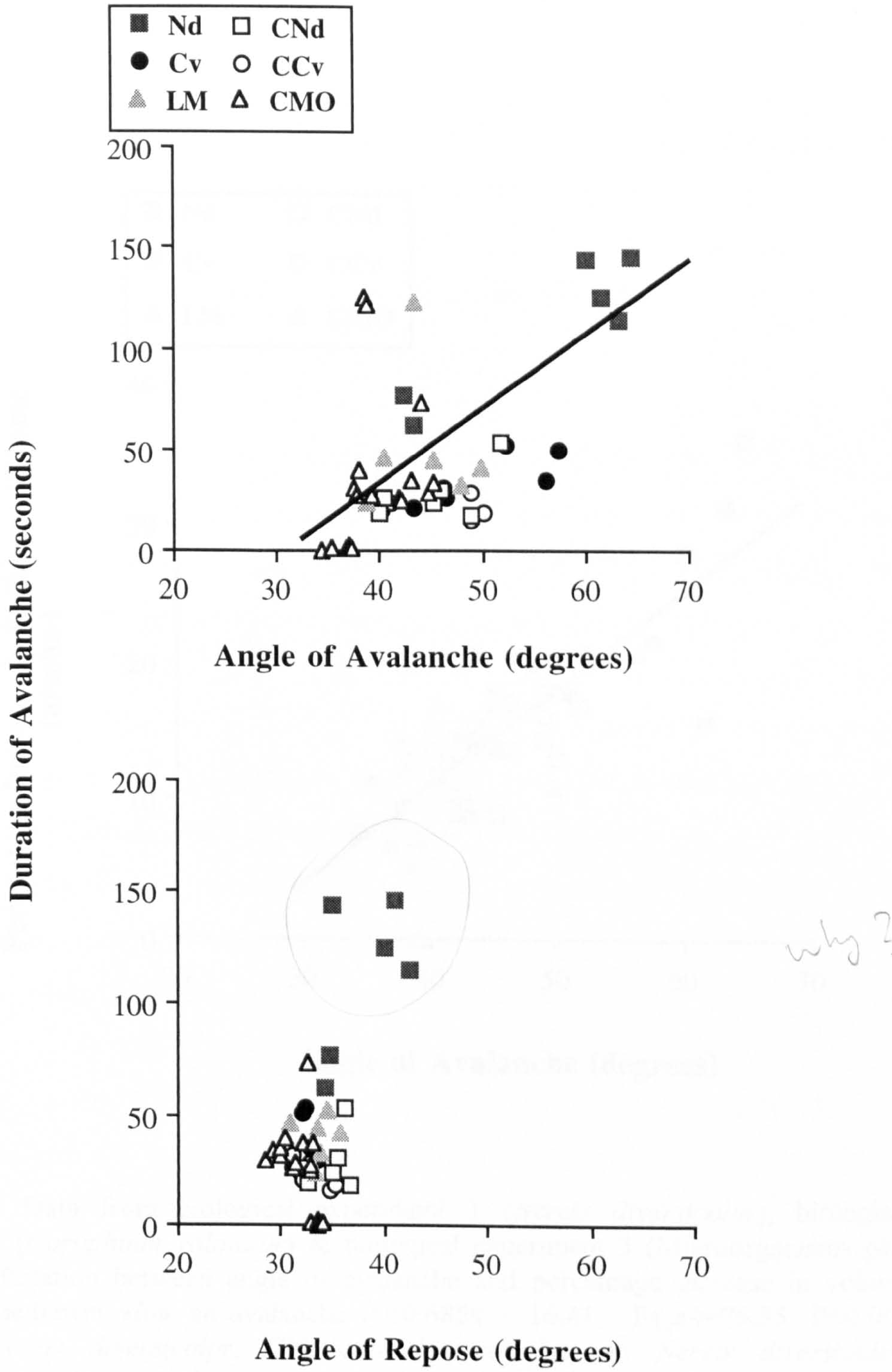


Figure 5.11 Data from biological experiment 1 (*Nereis diversicolor*), biological experiment 2 (*Corophium volutator*) & biological experiment 3 (Microorganisms plus meiofauna). Relation between angle of avalanche and duration of avalanche (y=3.600x – 112.0, $F_{1,45}$=11.49, P=0.001 **). Nd=*Nereis diversicolor*; CNd=control containing no *Nereis diversicolor*; Cv=*Corophium volutator*; CCv=control containing no *Corophium volutator*; LM=living microorganisms plus meiofauna; CMO=FM+AA+AW (sediments containing either killed or no microorganisms and no meiofauna).

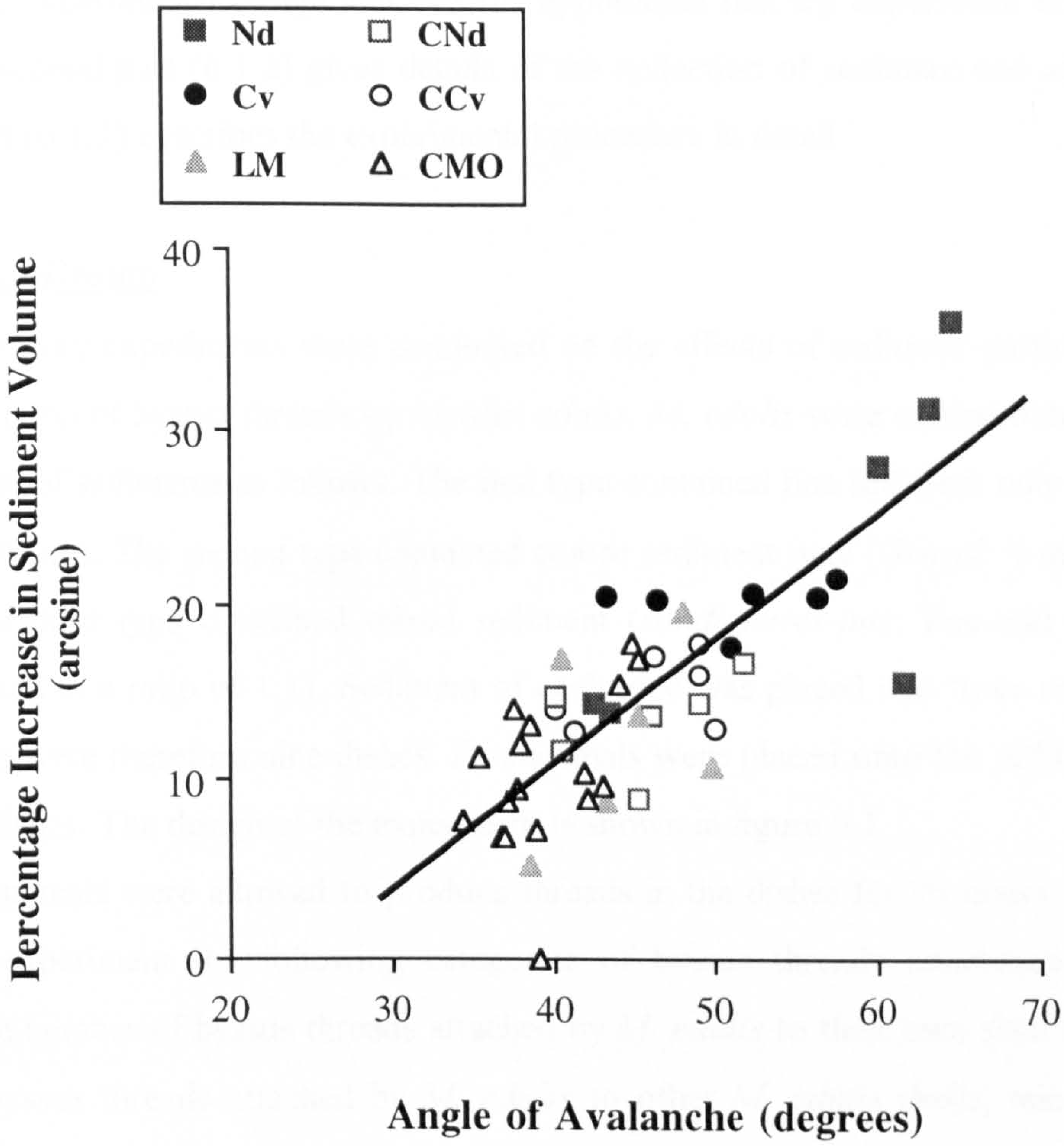


Figure 5.12 Data from biological experiment 1 (*Nereis diversicolor*), biological experiment 2 (*Corophium volutator*) & biological experiment 3 (Microorganisms plus meiofauna). Relation between angle of avalanche and percentage increase in volume (arcsine) of sediment after an avalanche ($y=0.685x - 16.41$, $F_{1,45}=76.55$, $P<0.001$ ***). Nd=*Nereis diversicolor*; CNd=control containing no *Nereis diversicolor*; Cv=*Corophium volutator*; CCv=control containing no *Corophium volutator*; LM=living microorganisms plus meiofauna; CMO=FM+AA+AW (sediments containing either killed or no microorganisms and no meiofauna).

Section 6: *Mytilus edulis* Byssus Thread Attachment to Sediment

6.1 MATERIALS AND METHODS

This section is divided into three parts. The first part (6.1.1) gives an overall picture of the experimental design and lists the hypotheses that the experiment intended to test. The second part (6.1.2) gives details of the collection of sediment and animals. The third part (6.1.3) describes the experimental procedure in detail.

6.1.1 Experimental Design

Laboratory experiments were conducted on the effects of sediment particle size on the production of byssus threads by *Mytilus edulis*. *M. edulis* were seeded onto three different types of sediments as follows. The first type contained fine sediment only (*sand*: 63 µm to 500 µm). The second type contained coarse sediment only (*Gravel*: 4 mm to 8 mm) and the third type contained mixed sediment (*sand/gravel mix*: fine and coarse sediment mixed in a ratio of 1:1). Sediment of each type was placed into three replicate dishes. There were therefore nine dishes. Five animals were placed onto the sediment in each of the dishes. The design of the experiment is shown in figure 6.1.

The animals were allowed to produce threads in the dishes for 96 hours. At the end of the experiment the following categories of byssus threads attachment were recorded: the number of byssus threads attached by *M. edulis* to their own shell (itself), number of byssus threads attached by *M. edulis* to other *M. edulis* shells, number of byssus threads attached to sediments, and number of threads attached to glass wall of the dish. A distinction was made between those threads that were still part of a byssus complex that was attached to the animal (attached byssus complexes) and those that were part of a byssus complex that had been released by the animal (released byssus complexes) (Fig 6.2). This experiment was conducted jointly with Mr Fraser West. The results of this joint experiment are being analysed and written up separately, and then included in our separate Ph.D.'s.

The experiment was designed to test whether groups of animals produced threads under laboratory conditions and if so to what objects the threads were attached in sediments of different particle sizes (*sand*, *sand/gravel mix* and *gravel*). With these overall objectives, the design of the experiment allowed the following specific questions to be answered.

Hypothesis 1:

Are there differences between the replicate dishes?

Hypothesis 2:

Are there differences in the number of threads in the different attachment categories?

Hypothesis 3:

Are there differences in the number of threads in each of the categories between the three different sediment types?

Hypothesis 4:

Are there differences between the number of grains attached to threads of each category?

Hypothesis 5:

Are there differences between the attached byssus complexes and released byssus complexes?

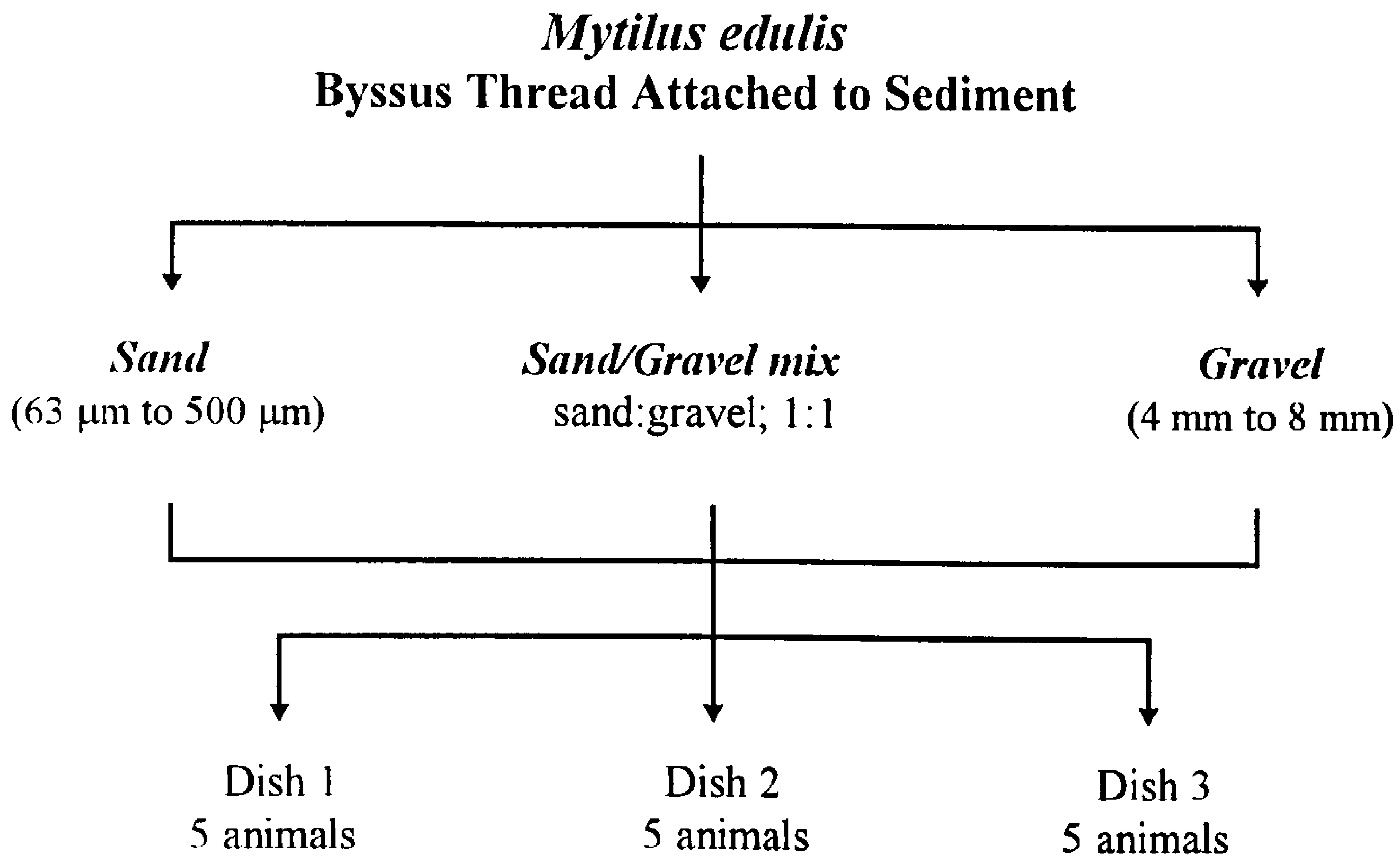


Figure 6.1 *Mytilus edulis* byssus thread attached to sediment. Experimental design. The experiment was run for 96 hours. Three replicate dishes each containing 5 mussels were set up for each type of sediment.

6.1.2 Collection of Sediment and *Mytilus edulis*

Fine sediment (sand) was collected from mid-tide level at Ardmore Bay and coarse grained sediment (gravel) was collected from high-tide level on a nearby exposed shore at Ardmore Bay. *Mytilus edulis* was collected from mid-tide level on the north shore of Ardmore Bay. The sediment and the mussels were both used within 24 hours of being collected.

Sediments: In the laboratory S2 sediment was prepared as follows. The fine sediment (sand) was wet sieved through a 500 µm BS sieve to remove invertebrate infauna and large particles, and then maintained in aerated sea water. The fine sediment was then washed three times with sea water and allowed to stand for 30 to 45 second before decanting off fine detrital material. The coarse sediment (gravel) was first wet sieved through an 8 mm BS sieve and then through a 4 mm BS sieve to provide a 4 to 8 mm size range of particles (see table 1.1).

Mytilus edulis: 3 to 3.5 cm long *M. edulis* were carefully selected and prepared just before seeding into the sediments. Barnacles attached to the mussel shells were removed by scraping the mussels with a pan scourer. The byssus threads and pads were then snipped at the animal's shell edge using sharp scissors. The cleaned mussels were maintained in sea water and used within half an hour.

6.1.3 Experimental procedure

Setting up the Experiment:

Nine pyrex glass dishes (internal diameter 20 cm, depth 9 cm) were set up. Three contained fine sediment, three contained fine and coarse sediment and three contained coarse sediment. The detailed procedure was as follows. Each dish was filled with sea water. Wet sediment was then added until the sediment depth was 5 cm (Fig. 3a). The volume of wet sediment used in each dish was therefore $5 \times 10^2 \times \pi \cong 1570$ ml. During this process the overlying sea water became very cloudy. Once the sediments had been added, the cloudy sea water was carefully syringed off and replaced by clean sea water. Five individuals of *M. edulis* were then placed in each dish. Four were placed at equal distances in a circle, approximately 5 cm diameter. The fifth was placed in the centre of the circle, as shown in figure 6.3b. The experiment was run for 96 hours.

Terminating the Experiment:

At the end of the 96 hours, the animals were narcotised and preserved *in situ*. The animals were narcotised by adding 1 to 2 ml of propylene phenoxitol into each dish. After four hours of narcotisation, animals were preserved by replacing 150 ml of sea water with 10 % Steedman's solution in each dish using a syringe. The positions of mussels, visible byssus threads and released complexes were then carefully traced in each dish (see figure 6.7, 6.8 and 6.9). Dishes were then emptied one by one, by decanting sea water and Steedman's solution and labelling each mussel individually. The mussels were labelled by blotting the mussel shells and then writing numbers on the shells using Pentel micro correction fluid. The mussels were labelled as a replicate/type of sediment/mussel number (i.e. mussel label 1/S/I represents replicate 1/sand (S)/mussel 1).

After labelling all the mussels in a dish, the dish was transferred into a large container (36 cm wide, 60 cm long and 18 cm deep) full with sea water. The dish was completely submerged in sea water in the large container as shown in figure 6.4.

The contents in each dish were dissected as follows. Loose sediment around the mussels and byssus complexes was carefully removed by siphoning off sea water plus loose sediment, using a paint brush to separate the loose sediment from the sediment bound by the animals and their byssus threads. The sea water in the large container was continuously replenished during this process by a constant sea water input. The mussels and the byssus complexes attached to sediments were then carefully removed from the dish in the large container into a separate white enamel tray (30 cm wide, 35 cm long and 4 cm deep) containing sea water. This was done by carefully infiltrating two pairs of hands under the mussel byssus complexes and sediment in the crystalline dish, and transferring the whole mass into the tray. The loose sediment transferred in this process was then separated from the clumps (animals, byssus threads and attached sediment). This was done using paint brushes. All the nine dishes were dissected by the procedure mentioned above.

Inspection of the byssus complex from each dish showed that there were two categories of byssus complex. Firstly, each of the five animals in the dish had a byssus complex. This is termed an "attached byssus complex". Secondly, in all dishes there were also some byssus complexes not attached to animals. These are termed "released byssus complexes" as shown in figure 6.2. Observations were carefully recorded on the attached complexes, classifying the threads into the following categories:

1. Number of threads broken at distal end (near pads) or whose pads were not attached to any object.
2. Number of byssus threads attached to the animal's own shell.
3. Number of byssus threads attached to other animal's shell.
4. Number of byssus threads attached to grains (sediments).
5. Number of grains (sediment) attached to the pad of a thread.

Exactly the same observations were recorded on the released complexes except that the observations in 2 and 3 above were combined and recorded as a number of threads attached to animals.

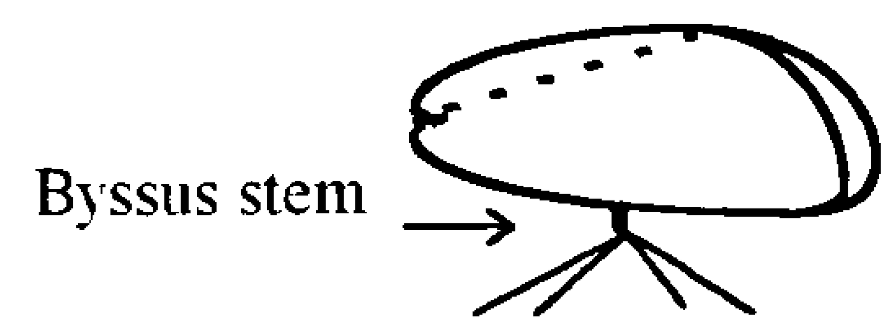
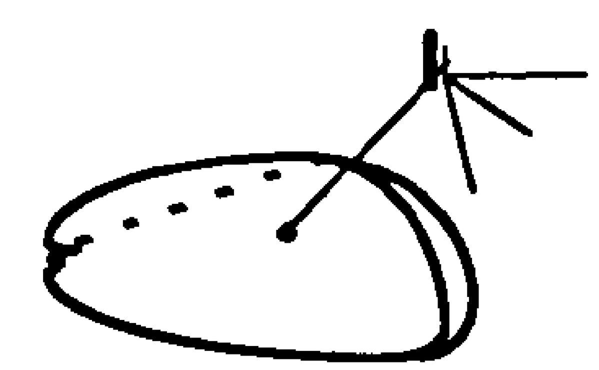
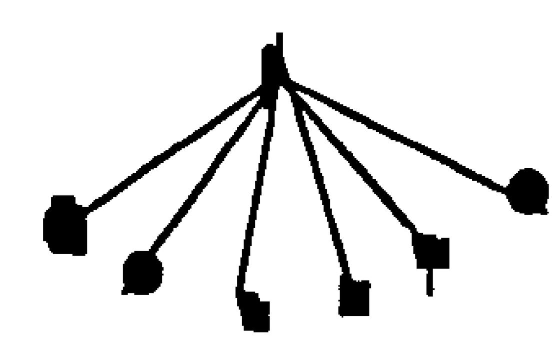
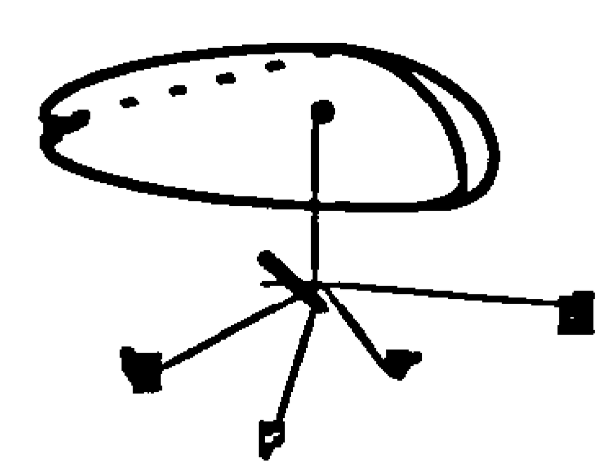
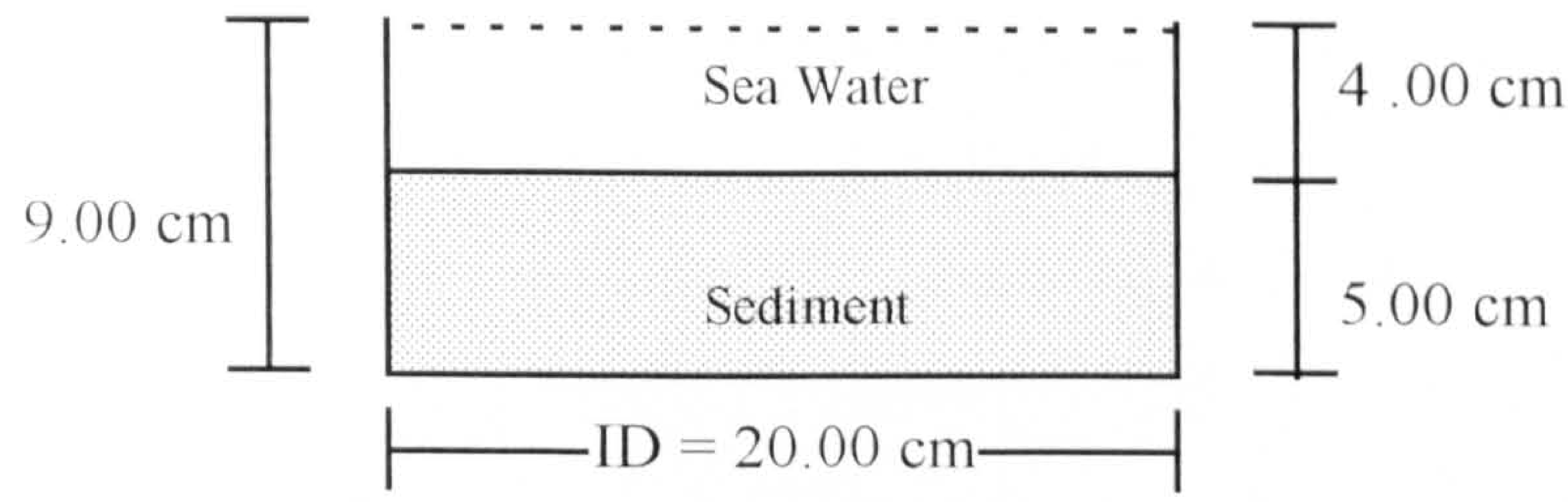
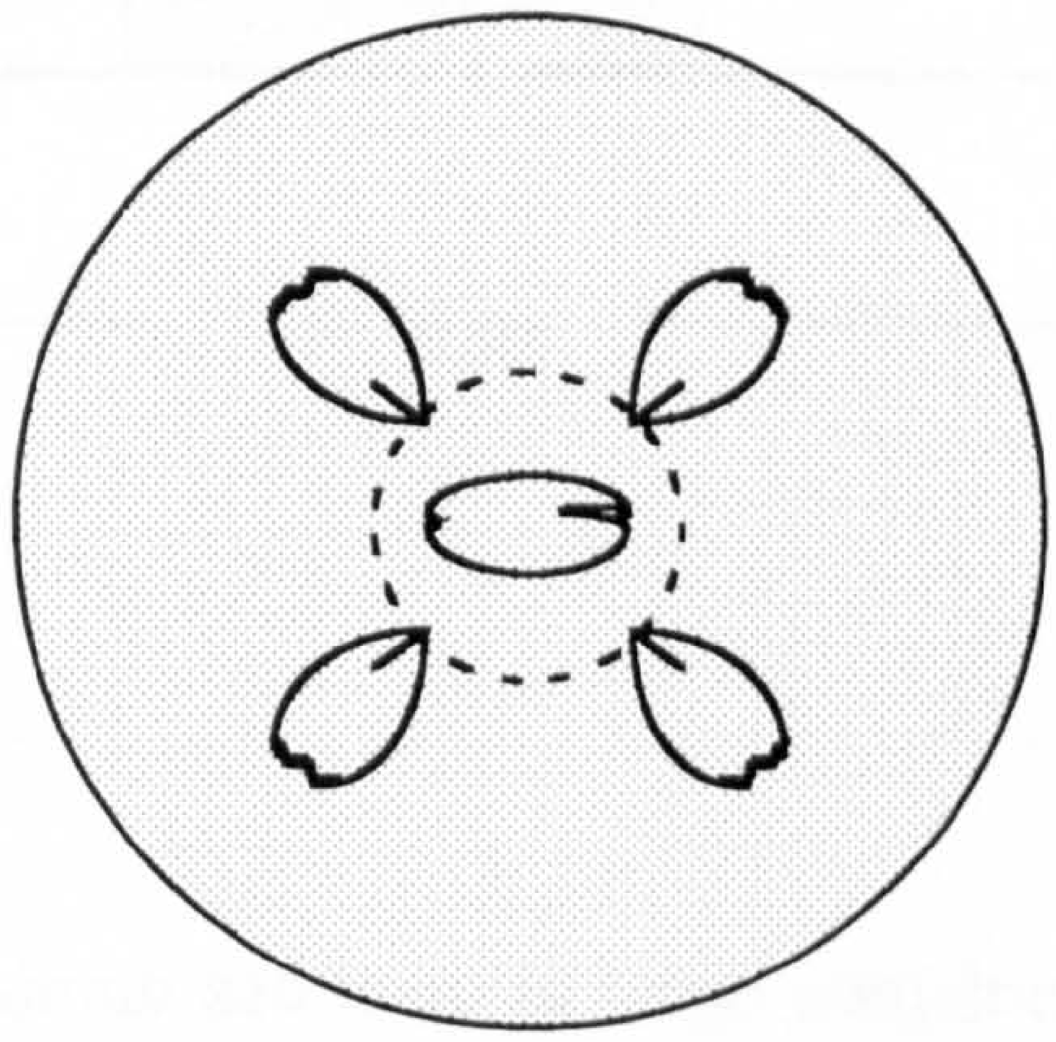
Term used for byssus complex	Figure	Explanation
1) Attached complex		Byssus stem attached to its origin (i.e. byssus glands) inside the parent animal shell or body.
2) Released complex		
a) Released complex anchored to animal shells.		Byssus stem released by the parent animal and pads of the threads anchored either on to its own shell or to the shell of another animal.
b) Released complex anchored to grains.		Byssus stem released by the parent animal and pads of the threads anchored on to the grain.
c) Released complex anchored to animal shell and grains.		Byssus stem released by the parent animal and pads of some threads anchored on grain and some on animal shell.

Figure 6.2 Explanation and illustration of categories of byssus complex technical terms used in text.



(a) Side elevation of glass dish.



(b) Plan of glass dish.

Figure 6.3 Figure illustrates the depth of sediment, depth of water and the position of mussels in glass dish at start. **Top**: side elevation of glass dish. **Bottom**: Plan of glass dish.

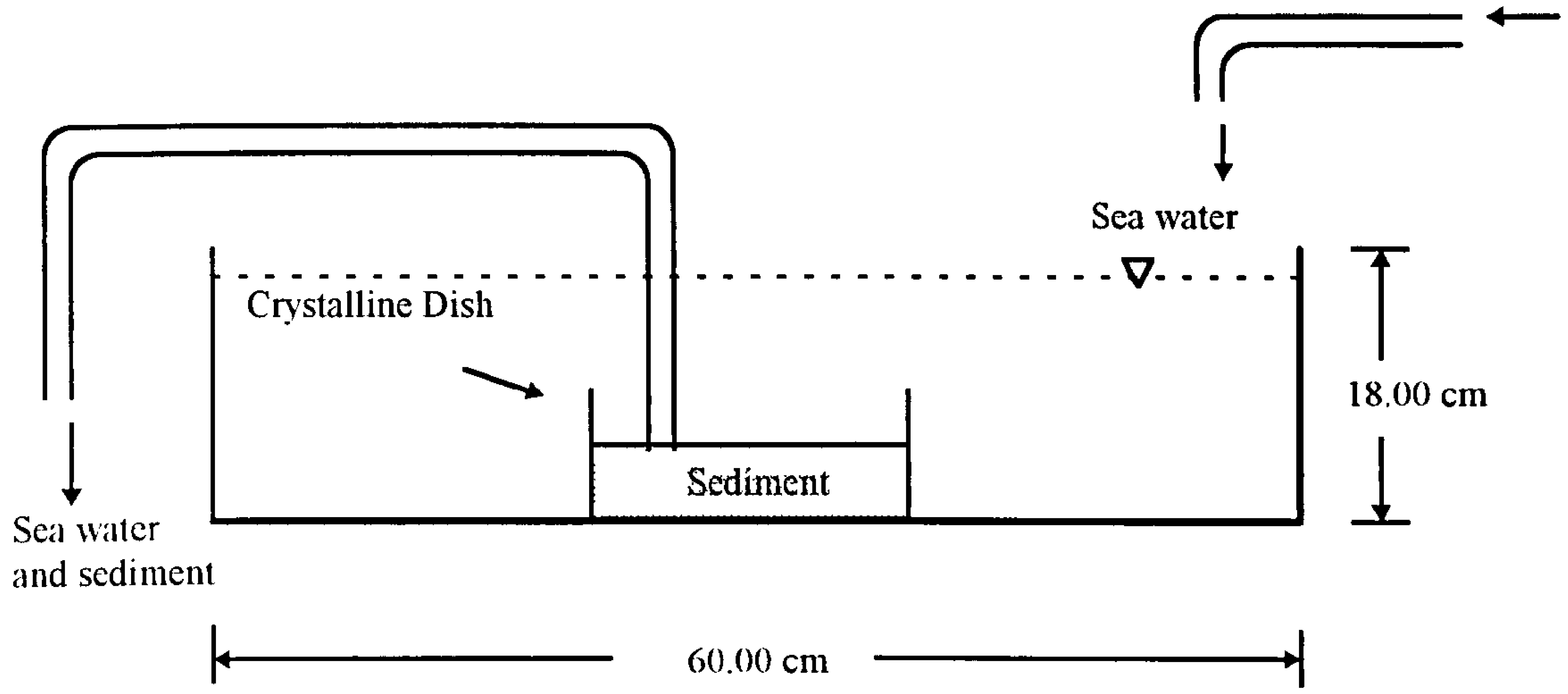


Figure 6.4 Glass dish containing sediment in large container (36 cm wide, 60 cm long and 18 cm deep) filled with sea water. Sea water in the large container was continuously replenished during the dissection of dishes.

6.2 RESULTS

The results of the experiment are given in table 6.1. The detailed results for each of the three replicate dishes containing *sand*, *sand/gravel mix*, and *gravel* are shown in appendix III: table 1.1 to appendix III: table 1.9. The statistical analyses of the experiment are shown in table 6.2 to table 6.6. The statistical analyses on replicate dishes are shown in table 6.2. The statistical analyses on attachment categories are shown in table 6 3. The statistical analyses on sediment types are shown in table 6.4. The statistical analyses on the number of grains attached to byssus threads are shown in table 6.5 and the statistical analyses comparing attached byssus complexes and released byssus complexes are shown in table 6.6.

With this background the results described below are divided into five parts. The first part (6 2.1) deals with hypothesis one, the second part (6.2.2) deals with hypothesis two, the third part (6.2.3) deals with hypothesis three, the fourth part (6.2.4) deals with hypothesis four, and the fifth part (6.2.5) deals with hypothesis five.

6.2.1 Hypothesis 1: Are there differences between the replicate dishes?

The differences between replicate dishes were tested by eleven 1×3 one-way analyses of variance in which the three levels were the three replicate dishes. Ten out of the eleven analyses were not significant (Table 6.2 and Appendix III: Table 2.1). This means that overall, there are no differences between the replicate dishes. Hence in the one-way analyses of variance conducted in part two and part three, the data for the 3 replicate dishes were placed in one cell, giving 3 × 5 = 15 observations per cell for subsequent analyses of variance.

Table 6.1 *M. edulis* byssus thread attachment in *sand, sand gravel mix and* in *gravel*. Summary tables from appendix III, table 1.1 to 1 9 R1, R2 & R3 = replicate dish 1, replicate dish 2 & replicate dish 3. Data is summed for five animals in each replicate dish.

Observations	**Attached Byssus Complexes**									**Released Byssus Complexes**								
	Sand			*Sand/gravel*			*Gravel*			*Sand*			*Sand/gravel*			*Gravel*		
	R 1	R 2	R 3	R 1	R 2	R 3	R 1	R 2	R 3	R 1	R 2	R 3	R 1	R 2	R 3	R 1	R 2	R 3
Number of Byssus Threads																		
a) attached to its own shell	11	8	2	6	0	0	4	0	0	10	19	19	4	7	15	0	0	18
b) attached to other animals	51	22	23	10	40	48	10	3	2									
c) total threads attached to shells	62	30	25	16	40	48	14	3	2	10	19	19	4	7	15	0	0	18
d) attached to grains	0	0	0	25	32	10	51	47	57	0	0	0	38	15	28	49	84	66
e) attached to glass	0	0	0	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0
f) unattached or broken	20	11	10	8	11	4	22	13	25	18	35	21	17	0	9	14	39	16
Σ=Total number of byssus threads	82	41	35	72	83	62	87	63	84	28	54	40	59	22	52	63	123	100
Number of Grains attached	0	0	0	21	20	9	43	42	57	0	0	0	38	15	28	49	70	55
Number of Grains shared	0	0	0	0	1	0	1	4	1	0	0	0	0	0	0	0	4	0
Number of Byssus complexes	5	5	5	5	5	5	4	5	5	3	2	3	4	2	4	3	6	5

Clumps of animals in each dish	*Sand*			*Sand/gravel*			*Gravel*		
	R1	R2	R3	R1	R2	R3	R1	R2	R3
Number of animals clumped together	5 √√	5 √√	5 √√	3 √	5 √√	5 √√	5 √	3 √	5 √
Animal attached to each other within clump	5	5	5	2	5	5	4	2	2

√ Animals clump loosely. √√ Animals clump tightly.

Table 6.2 Summary table from appendix III; table 2.1 (a), 2.1 (b) & 2.1 (c). The table gives the F ratios, probability values and level of significance obtained from eleven 1×3 one-way analyses of variance on replicate dishes. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Factors	DF	F ratios	Probability
a) Replicate dishes in *sand*			
Number of byssus threads			
I attached to animals own shell.	2, 12	0.797	0.473 ns
II. attached to other animals shells.	2, 12	5.444	0.021 *
III. attached to sediments (grains).	Note: None of the threads attached to grains.		
IV. unattached.	2, 12	1.124	0.357 ns
b) Replicate dishes in *sand/gravel mix*			
Number of byssus threads			
I. attached to animals own shell.	2, 12	2.243	0.148 ns
II attached to other animals shells.	2, 12	2.147	0.160 ns
III attached to sediments (grains).	2, 12	2.998	0.088 ns
IV. unattached.	2, 12	0.905	0.431 ns
c) Replicate dishes in *gravel*			
Number of byssus threads			
I. attached to animals own shell.	2, 12	1.000	0.397 ns
II. attached to other animals shells.	2, 12	1.727	0.219 ns
III attached to sediments (grains).	2, 12	0.038	0.963 ns
IV. unattached.	2, 12	0.696	0.517 ns

6.2.2 Hypothesis 2: Are there differences in the number of threads in the different attachment categories?

The differences between the attachment categories were analysed by three 1×4 one-way analyses of variance, each with fifteen observations per cell (five from each of the replicate dishes). All the three F ratios are highly significant (Table 6.3 and Appendix III: Table 2.2). The statements made below are based on the significant F ratios obtained from these one-way analyses of variance and the data in table 6.1.

(a) *Sand*: In sand, the highest number of threads were attached to other animal's shells. An intermediate number of threads were unattached or broken, and a few threads were attached to the animals own shell. No threads were attached to grains.

(b) *Sand/gravel mix*: In the sand/gravel mix, the highest number of threads were attached to other animal's shells. An intermediate number of threads were attached to grains (sediments). Small number of threads were unattached or broken, and only six threads were attached to the animals own shell.

(c) *Gravel*: In gravel, the highest number of threads were attached to grains (sediments). An intermediate number of threads were unattached or broken. Small number of threads attached to other animal's shells and only four threads were attached to the animals own shell.

Generally more threads were attached to animal's shells in *sand* as compared to *sand/gravel mix*. In *gravel* the number of threads attached to animal's shells were lowest as shown in figure 6.5.

In ANOVA, how do you tell which group is significantly different

Table 6.3 Summary table from appendix III; table 2.2 (a), 2.2 (b) & 2.2 (c). The table gives the F ratios, probability values and level of significance obtained from three 1×4 one-way analyses of variance for the attachment categories (byssus threads attached to animals own shells / byssus threads attached to other animals shell / byssus threads attached to sediment / byssus threads unattached) in the three sediment types. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***.

Factors	DF	F ratios	Probability
a) *Sand*			
attachment categories	3, 56	12.67	P < 0.001 ***
b) *Sand/gravel mix*			
attachment categories	3, 56	7.986	P < 0.001 ***
c) *Gravel*			
attachment categories	3, 56	9.752	P < 0.001 ***

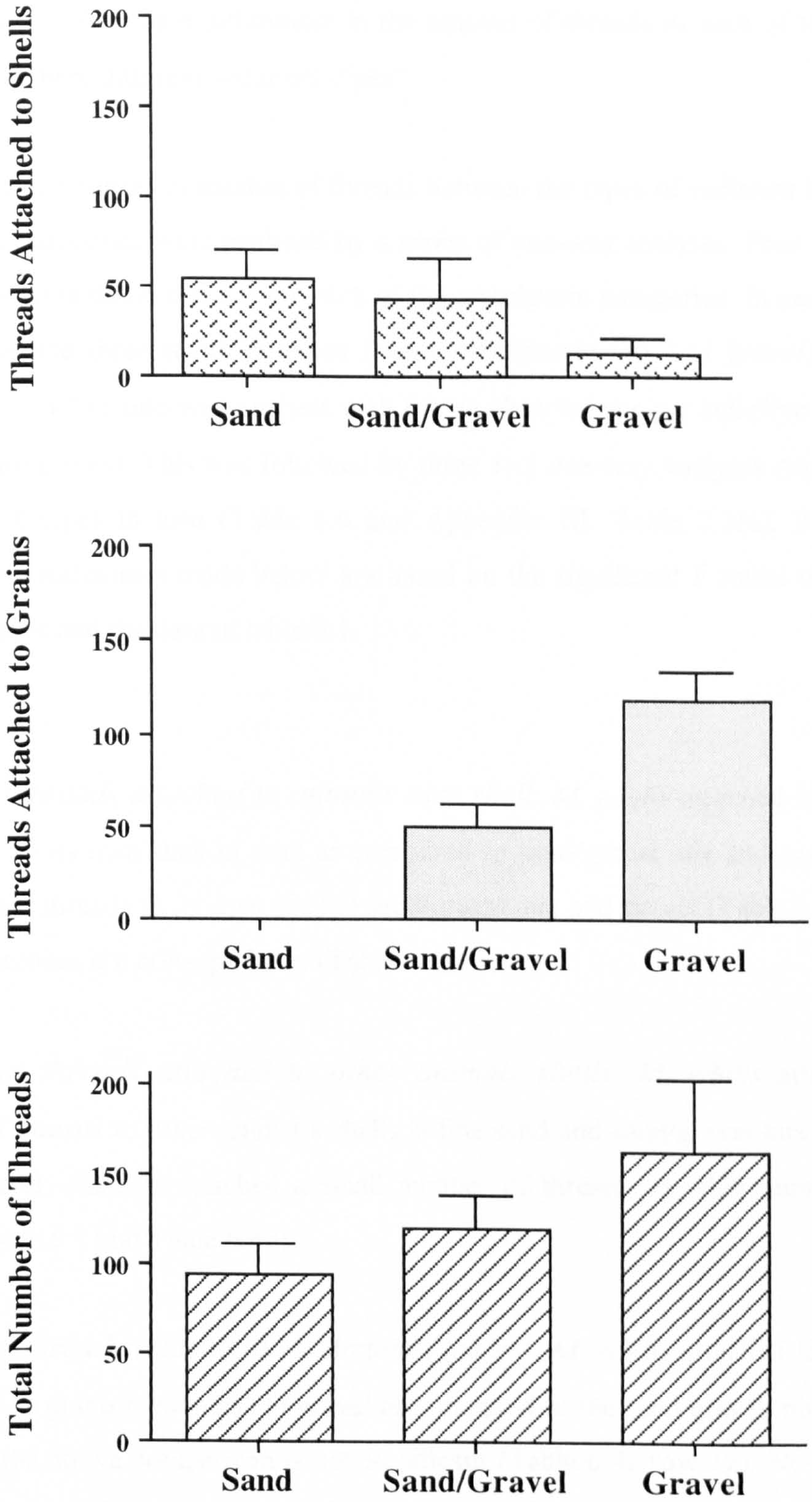


Figure 6.5 *Mytilus edulis* byssus thread attachment to sediment. Combined data from released and attached byssus complexes. Mean±SD of three replicates. **Top:** Number of threads attached to animal's shells. **Middle:** Number of threads attached to grains. **Bottom:** Total number of threads produced by the *M. edulis*.

6.2.3 Hypothesis 3: Are there differences in the number of threads in each of the categories between the three different sediment types?

The differences in number of threads between the types of sediment in each of the attachment categories were analysed by a series of one-way analyses. Four different sets of analyses were done, one set for each of the attachment categories. In each of the sets of analyses, the three sediment types (*sand*, *sand/gravel mix* and *gravel*) were firstly compared by a 1×3 one-way analysis with fifteen observations per cell (five from each of the replicate dishes). This was followed by three 1×2 one-way analyses comparing pairs of sediment types in turn (Table 6.4 and Appendix III: Table 2.3(a), 2.3(b), 2.3(c), 2.3(d)). The statements made below are based on the significant F ratios obtained from these analyses and the data in table 6.1.

(a) *Number of threads attached to animals own shell*: *M. edulis* attached higher number of threads to its own shell in sand as compared to sand/gravel mix and gravel. Animals attached few threads to its own shell in sand/gravel mix and gravel (Table 6.1). However these differences are not significant (Table 6.4a).

(b) *Number of threads attached to other animals shells*: *M. edulis* attached higher number of threads to other animal's shells in fine sand and sand/gravel mix as compared to the gravel. Animals attached a small number of threads to other animal's shells in gravel (Table 6.1 and Table 6 4b).

(c) *Number of threads attached to sediment (grains)*: *M. edulis* attached higher number of threads to grains (sediment) in gravel as compared to the sand/gravel mix (Table 6.1). However the above comparison is not significant (Table 6.4c row 12). No threads were attached to sand. In the gravel and sand/gravel mix, the threads were only attached to the gravel particles.

(d) *Unattached byssus threads*: More threads were unattached (or detached during handling the experiment) in sand and gravel as compared to the sand/gravel mix.

Table 6.4 Summary table from appendix III; table 2.3(a), 2.3(b), 2.3(c) & 2.3(d). The table gives the F ratios, probability values and level of significance obtained from four 1×3 one way analyses of variance and twelve 1×2 one-way for comparison of three different types of sediment in different attachment categories. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***.ns= not significant.

Factors	DF	F ratios	Probability
a) Byssus threads attached to animals own shell			
I. 1×3 *sand, sand/gravel & gravel*	2, 42	2.322	0.111 ns
II. 1×2 *sand & sand/gravel*	1, 28	2.351	0.136 ns
III. 1×2 *sand & gravel*	1, 28	3.117	0.088 ns
IV. 1×2 *sand/gravel & gravel*	1, 28	0.112	0.737 ns
b) Byssus threads attached to other animals shells			
I. 1×3 *sand, sand/gravel & gravel*	2, 42	6.297	0.004 ***
II. 1×2 *sand & sand/gravel*	1, 28	0.065	0.798 ns
III. 1×2 *sand & gravel*	1, 28	16.30	P < 0.001 ***
IV. 1×2 *sand/gravel & gravel*	1, 28	9.983	0.004 ***
c) Byssus threads attached to sediment (grains)			
I 1×3 *sand, sand/gravel & gravel*	2, 42	9.593	P < 0.001 ***
II. 1×2 *sand & sand/gravel*	1, 28	27.61	P < 0.001 ***
III. 1×2 *sand & gravel*	1, 28	13.92	0.001 **
IV 1×2 *sand/gravel & gravel*	1, 28	4.097	0.053 ns
d) Byssus threads unattached			
I. 1×3 *sand, sand/gravel & gravel*	2, 42	3.622	0.035 *
II. 1×2 *sand & sand/gravel*	1, 28	2.634	0.116 ns
III. 1×2 *sand & gravel*	1, 28	1.485	0.233 ns
IV 1×2 *sand/gravel & gravel*	1, 28	6.810	0.014 *

6.2.4 Hypothesis 4: Are there differences between the number of grains attached to threads of each category?

The differences between number of grains attached in the sediment types were tested by a 1×3 one-way analysis of variance and three 1×2 one-way analyses of variance (Table 6.5 and Appendix III: Table 3(I), 3 (II), 3(III), 3(IV)). All the four F ratios were significant. The statements made below are based on the significant F ratios obtained from these analyses and the data in table 6.1. A higher number of grains were attached to threads in gravel as compared to the sand/gravel mix (Fig. 6.5). *M. edulis* did not attach threads to sand grains.

6.2.5 Hypothesis 5: Are there differences between the attached byssus complexes and released byssus complexes?

A series of statistical analyses were conducted on the data. The difference between the attached complexes and released complexes were tested by thirty six 2×1 one-way analyses. Only four out of the thirty analyses are significant (Table 6.6 and Appendix III: Table 4.1, 4.2 & 4.3). In general, therefore, the difference between the attached byssus complexes and released byssus complexes are not significant.

Table 6.5 Summary table from appendix III; table 3(I), 3(II), 3(III) & 3(IV). The table gives the F ratios, probability values and level of significance from one 1×3 one-way analysis and three 1×2 one-way analyses for number of grains attached in different types of sediment. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***.

Factors	DF	F ratios	Probability
Number of grains attached			
I 1×3 *sand, sand/gravel & gravel*	2, 42	10.96	P<0.001 ***
II. 1×2 *sand & sand/gravel*	1, 28	36.84	P<0.001 ***
III. 1×2 *sand & gravel*	1, 28	15.21	0.001 ***
IV. 1×2 *sand/gravel & gravel*	1, 28	5.481	0.027 *

Table 6.6 Summary table from appendix III; table 4 1, 4.2, & 4.3. The table gives the F ratios and level of significance obtained from thirty-six 1×2 one-way analyses of variance for comparison of attached and released complexes in the three different types of sediment R1, R2 & R3 = replicate dish 1, replicate dish 2 and replicate dish 3. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns = not significant.

Factors	*Sand*			*Sand/gravel mix*			*Gravel*		
	R1 (DF 1, 6)	R2 (DF 1, 5)	R3 (DF 1, 6)	R1 (DF 1, 7)	R2 (DF 1, 5)	R3 (DF 1, 7)	R1 (DF 1, 6)	R2 (DF 1, 9)	R3 (DF 1, 8)
1. Number of byssus threads attached to animals	8.421 *	2.570 ns	0.810 ns	0.800 ns	1.889 ns	1.359 ns	1.968 ns	1.227 ns	3.391 ns
2. Number of byssus threads attached to grains (sediment)	✪	✪	✪	1.466 ns	0.147 ns	12.15 *	0.394 ns	1.152 ns	0.073 ns
3. Number of byssus threads unattached	1.250 ns	66.09***	2.759 ns	5.477 ns	1.661 ns	0.154 ns	0.009 ns	1.515 ns	1 000 ns
4. Number of grains (sediment) attached to threads.	✪	✪	✪	2.253 ns	3.889 ns	12.82 **	0.757 ns	0.671 ns	0.111 ns

✪ None of the byssus threads were attached to *sand* grain.

Discussion

7.1 General

Mountains and shorelines are used by human beings for recreational purposes. They are also a source of minerals and biological resources. The stability of mountains and shorelines are now under threat due to the exploitation of these environments and natural resources taken from them by man. Changes in weather around the globe, global warming and rising sea level now make our mountains and shorelines vulnerable, particularly shorelines in those parts of the world that are exposed to significant tidal action. There has therefore been growing interest in the protection and stability of mountains and the shoreline, with a wide range of studies on avalanching or slope stability (Takahashi 1981; Lowe 1982; Lee *et al.* 1983; Piper *et al.* 1985; Anderson & Richards 1987; Schwab & Lee 1988; Wetmiller & Evans 1989; Baraza *et al.* 1990; Paterson *et al.* 1990; Lee *et al.* 1991; Owen 1991; Bromhead 1992; Van Rhee & Bezuijen 1992; Auer & Shakoor 1993; Cochonat *et al.* 1993; McCarthy 1993; Alkema *et al.* 1994; Brooks & Richards 1994; Dijkstra *et al.* 1994; Anderson & Sitar 1995; Duperret *et al.* 1995; Thorne *et al.*1995; Roberts & Cramp 1996; Bromhead 1997; Coleman & Garrison 1997; Meadows & Meadows 1999). The above studies are concerned either with the factors contributing to avalanching, with the effects of geotechnical properties on avalanching, or with soil or sediment movement after an avalanche has taken place.

Sediments in the sea and in rivers have also been studied by many research workers. Turbidites in the sea damage communication cables, oil and gas pipe lines and other installations and also affect biological activity. In rivers, slowly settling sediment on the river bed causes environmental and navigational problems. Sediment once settled (stabilized) on the river bed becomes difficult to erode and results in a huge dredging cost. Furthermore, chemical contaminants dumped by industry and contaminants dumped by humans in river systems are readily adsorbed by sediments and remain in the river bed. There is therefore a considerable literature on marine and riverine sediments (Hampton 1972; Dyer 1979, 1980; Prior & Coleman 1982; Faas 1984; Kranck 1984; McCave 1984; Moon & Hurst 1984; Wetzel 1984; Dollan *et al.* 1990; Hollister & Nowel 1991; Mitchell 1993, 1995; Fass *et al.* 1993; Mehta & Srinivas 1993; Montague *et al.* 1993; Scarlatos & Mehta 1993; Alexander & Morris 1994; Bromhead & Beckwith 1994;

Perret *et al.* 1995; Sohn 1997). Much of the above work is concerned with the geomechanics and physics of sediment transport, and about sediment erosion, deposition and movements of turbidites.

Many workers have studied the characteristics of granular flow and avalanching of granular sediments in the laboratory (Bagnold 1954, 1966; Major & Pierson 1990, 1992; Allen 1970; Evesque 1991; Evesque *et al.* 1993; Greve & Hutter 1993; Hunger 1995; Chu *et al.* 1995; Metcalfe *et al.* 1995). Some workers have also recorded the angle of repose of granular material (Burkalow 1945; Jopling 1965; Statham 1974). However few scientists have studied the initiation of avalanches by recording the angle of avalanche (critical angle at which the slope begins to avalanche). Scientists have used different terms such as critical angle of repose, angle of sliding and maximum angle of repose to describe the critical angle at which slope begins to avalanche. Meadows *et al.* (1994), Muir Wood *et al.* (1994) and Shaikh *et al.* (1998) use the term "angle of avalanche" to mean what is described as the "critical or maximum angle of repose" by Bagnold (1966), Allen (1969 & 1970), Carrigy (1970) and Mehta (1985).

The main factors contributing to an avalanche or slope failure are earthquake, water and an alteration in slope inclination by natural or human activity. The alteration in slope inclination may be due to the deposition of excess sediment at the top of a slope or removal of excess sediment at the toe (bottom) of a slope. Because of the vast nature of the subject it has not been possible for me to cover every factor triggering avalanching or causing slope failure. In this thesis I have assessed slope stability by avalanching. I have investigated the effects of medium, fluid medium viscosity and biological activity on avalanching. The test procedure has consisted of inducing sediments to avalanche, measuring the angles at which they avalanche, and measuring the subsequent angle of repose once the avalanching process has terminated. In some of the experiments I have also recorded the duration of avalanche, change in volume of sediment after an avalanche and the slope failure mechanism.

7.2 Geotechnical Properties

Geotechnical properties of sediment such as grain size, density, shear strength, permeability and settling velocity are controlling parameters in avalanching and transporting mechanisms (Yallin 1977; Dyer 1979; Lowe 1982; McCave 1984; Dyer 1986; Anderson & Richards 1987; Shiati 1990; Baraza *et al.* 1992; Auer & Shakoor 1993; Dijkstra *et al.* 1994; Kenneth 1994; Robert & Cramp 1996; Wang & Zhang 1996; Coleman & Garrison 1997).

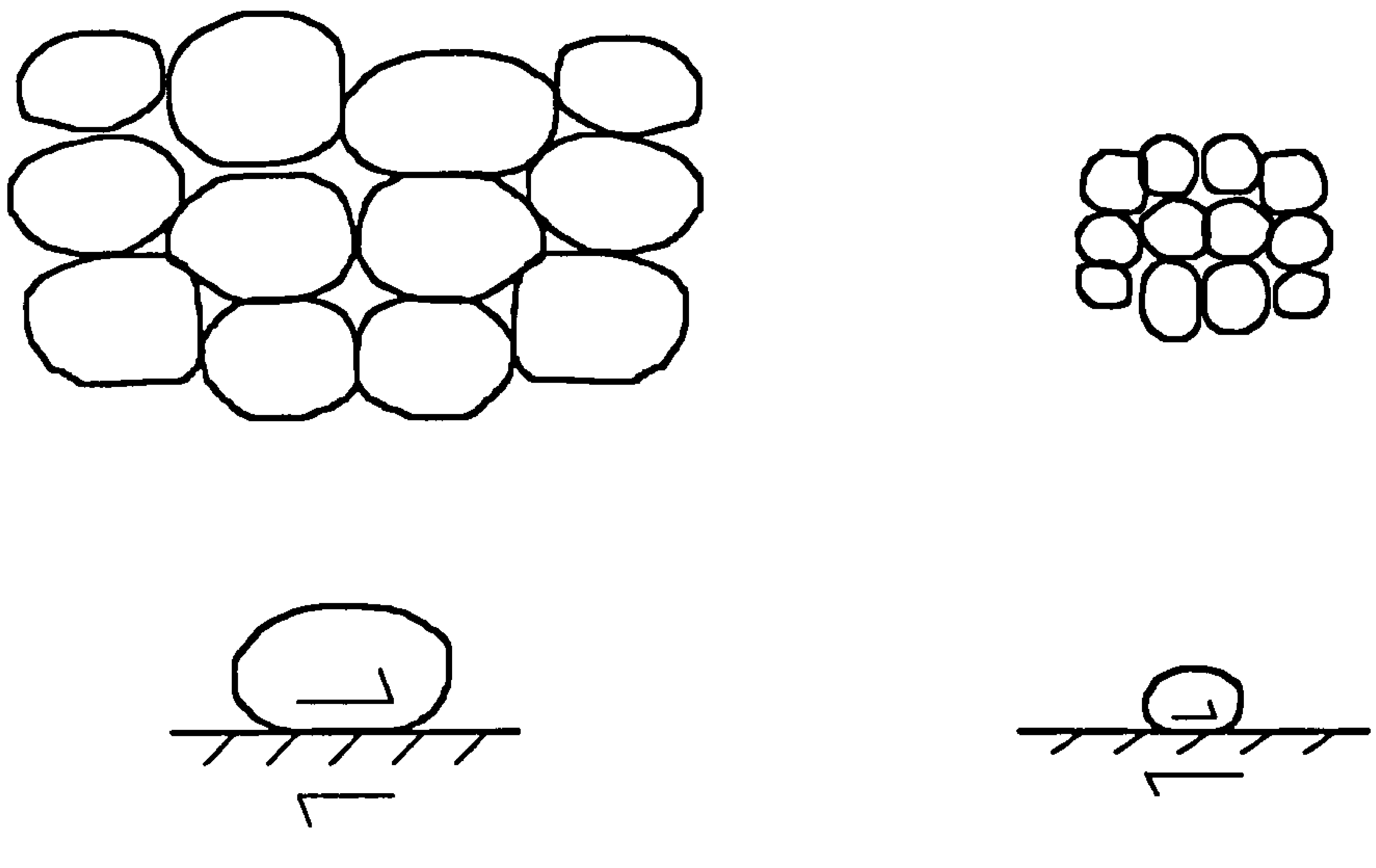
The results of section 1 show how the different geotechnical properties of sediments are related to each other and are important in quantifying the stability of slopes. The stability of sediment increases with increase in dry density and bulk density. It is known that soils and sediments of a higher water content have a lower bulk density and shear strength (Lee *et al.* 1993; Jepsen *et al.* 1997). The stability of soils and sediments are related to their shear strength and increase with shear strength (Jones *et al.* 1993; Tian *et al.* 1994; Perret *et al.* 1995; Rahardjo *et al.* 1995). These studies also show that marine sediments with higher densities and lower water content occur at a higher gradient whereas sediments with lower densities and higher water content occurred at a lower gradient.

Grain Size

There is evidence that grain size decreases downslope (Baraza *et al.* 1990; Auer & Shakoor 1993; Lee *et al.* 1993; Baraza & Ercila 1994). Coarser sediment rests at a higher slope gradient and finer sediment rests at a lower slope gradient. My results broadly confirm this.

The avalanching experiments in section 3 show that higher angles of avalanche and repose occurred in coarser sediments and lower angles of avalanche and repose occurred in finer sediments. These results were more obvious in well-sorted sediments. The direct relationship between angles of repose and mean particle size was also significant. My results broadly agree with the results of the work done by Burkalow (1945), Carrigy (1970) and Evesque *et al.* (1993). Burkalow (1945) in a laboratory study of the formation of sediment piles produced by dropping loose non-cohesive sediment from above, showed that the angle of repose increased with increase in grain size, angularity, roughness and compaction. The direct relationship of angles of avalanche and repose with grain size was also reported by Carrigy (1970) and Evesque *et al.* (1993).

The possible explanation for higher angles of avalanche and repose of coarser sediment is that the coarser sediments offer more frictional resistance and shear force during avalanching than the finer sediment. The frictional resistance depends on the surface contact area of sediment. The coarser sediment has larger surface contact area as compared to the finer sediment (Fig. 7.1).



(a) (b)

Figure 7.1 Illustration of surface contact area and frictional resistance offered by a grain of similar shape but of different size. a) Coarser grain. b) finer grain.

Sediment Phase Relations

Grain size distribution has a direct effect on the phase properties of sediment. Void ratio and density of a sediment depends on its grain size distribution (Denekamp & Tsur-Lavie 1981). The presence of fine sediment, for example, decreases porosity and permeability (Bennett *et al.* 1990). The decrease in the porosity of a sediment, in turn, results in an increase in dry density and bulk density (Lamb & Whitman 1979; Smith 1981; Craig 1992). In my work bulk density was directly proportional to the dry density and specific gravity, and was inversely proportional to porosity and void ratio (Fig 1.10).

My results in section 1 show that bulk density and dry density of sediments increase with increasing grain size in well-sorted sediments. Furthermore the vibro packing experiment results show that bulk density and dry density increase with increasing compaction (Table 1.11 Fig 1.11).

My results also show that shear strength increases significantly as bulk density and dry density increases. The relationship between shear strength and density was non linear (Fig 1.12). There was a very small increase in shear strength at the lower values of bulk density and dry density. At higher values of bulk density and dry density the shear strength increased at a higher rate. The reason for this may be as follows. At lower densities, the inter-granular friction between the sediment particles is low, while at higher densities, inter-granular friction between the sediment particles increases very rapidly.

In a rotating drum experiment, Statham (1974) showed that lower angles of avalanche occurred in sediment mixtures of higher porosity. Similar effects were also reported by Evesque (1991) and Evesque *et al.* (1993). The results of avalanching experiment 2 in section 3 shows similar effects to the results of Statham (1974). The results of avalanching experiment 2 show that angles of avalanche and angles of repose of sediments vary with porosity and bulk density of sediments. Higher angles of avalanche occurred in sediments of higher dry and bulk densities, and in well sorted sediments. However, in poorly sorted sediments higher angles of avalanche occurred in sediments having lower dry and bulk densities (Table 1.4, Table 1.5 and Table 3.1). The possible explanation for this is that, when fine sediment is mixed with the coarse sediments in a proportion sufficient just to fill the pore spaces between the coarse sediment, it causes dilatation (Bagnold 1954; Statham 1974; Takahashi 1981). Therefore the mixture of fine and coarse sediments avalanche and rests at a lower angle. In general, therefore, slopes of well sorted sediments of a similar density and porosity are more stable than slopes of poorly sorted sediments.

7.3 Supporting Medium

Fluid Medium:

Carrigy (1970) studied the effect of air and water on angles of avalanche and repose. He showed that angles of avalanche in air were higher than in water, however angles of repose remained the same in both air and water. Field observations of dry natural slopes (slopes in air) and slopes submerged in water of the same soil and sediment also show that angle of avalanche is greater in air than under water, but the angle of repose is the same in both media (Carrigy 1970).

My results in section 3 only partly agree with the results of Carrigy (1970). In contrast to Carrigy's results, in my experiments the angles of avalanche in air were similar to the angles of avalanche in water. However in agreement with Carrigy's results, I observed a lack of difference between the angles of repose in air and water. This suggests that the slope failure mechanism in air may be similar to the slope failure mechanism in water. The possible explanation for slope failure mechanisms being similar in air and water is that the water in the container was static (not flowing) during my experiments. There are therefore no seepage forces acting within the sediment. In the absence of flow of water, the angle of avalanche of submerged sediment will be the same as of completely dry unsubmerged sediment (Lambe & Whitman1979; McCarthy 1993).

Viscosity of Fluid Medium

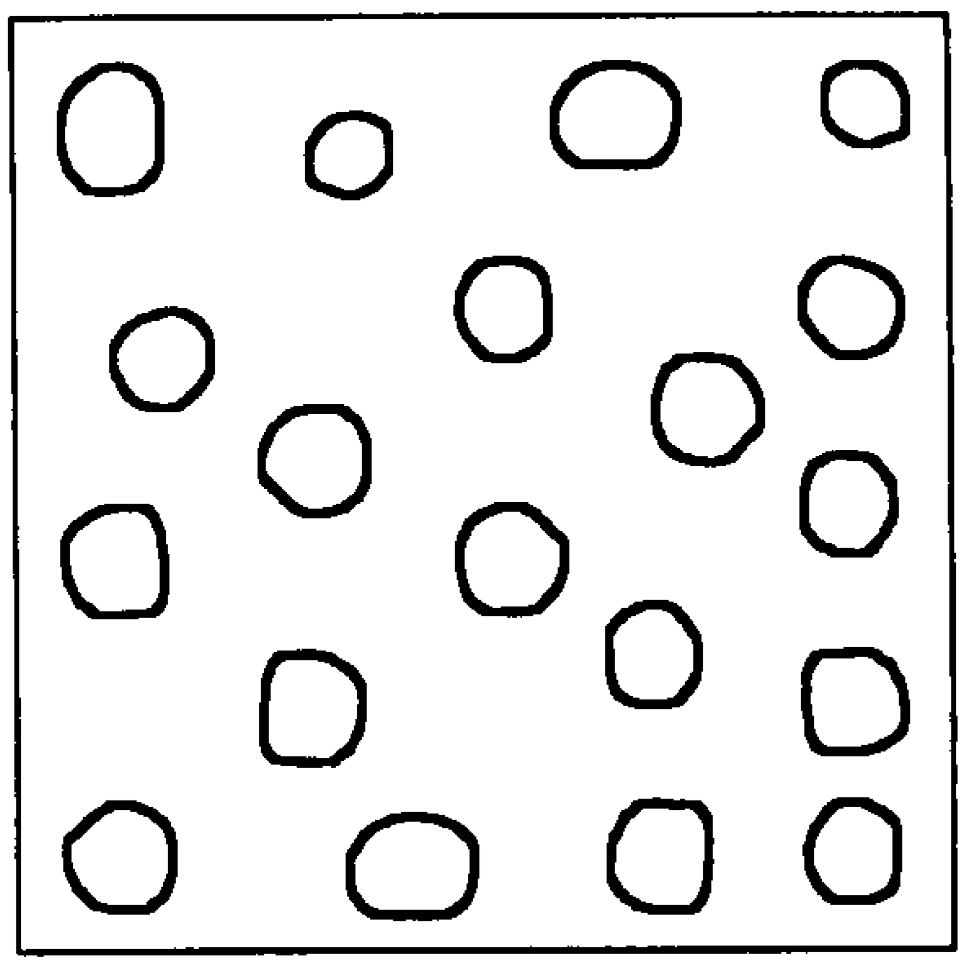
Studies of sediment movement, debris flows and debris flow deposits show that mud, clay and water slurries, and the fluid medium itself, may play an important role in sediment movement and debris flows (Bagnold 1954, 1966; Johnson 1970; Fisher 1971; Enos 1977; Hampton 1972, 1979; Takahashi 1978; Vallejo 1979; Takahashi 1981; Campbell 1990; Kusuda *et al.* 1993; Mehta & Srinivas 1993; Winterwerp *et al.* 1993; Bromhead & Beckwith 1994; Duperret *et al.* 1995). There are two schools of thought about the flow of sediment: one school thinks that in flow failure sediment behaves like a Bingham plastic (Johnson 1970; Fisher 1971; Enos 1977) and the other school following Bagnold thinks that in flow failure sediment behaves like a non-Newtonian fluid (Bagnold 1954; Hampton 1972; Takahashi 1978; Vallejo 1979; Campbell 1990).

In the Bingham plastic model, it is considered that during flow sediment behaves like a highly viscous mass that deforms slowly during failure. Since most of the debris flow moves as a plug containing clay and water slurry, Bingham plastic models explain the properties of debris flow containing clay slurries very well. However it is hard to understand the grain flow of a sediment that does not contain clay and water slurry in terms of a Bingham plastic model.

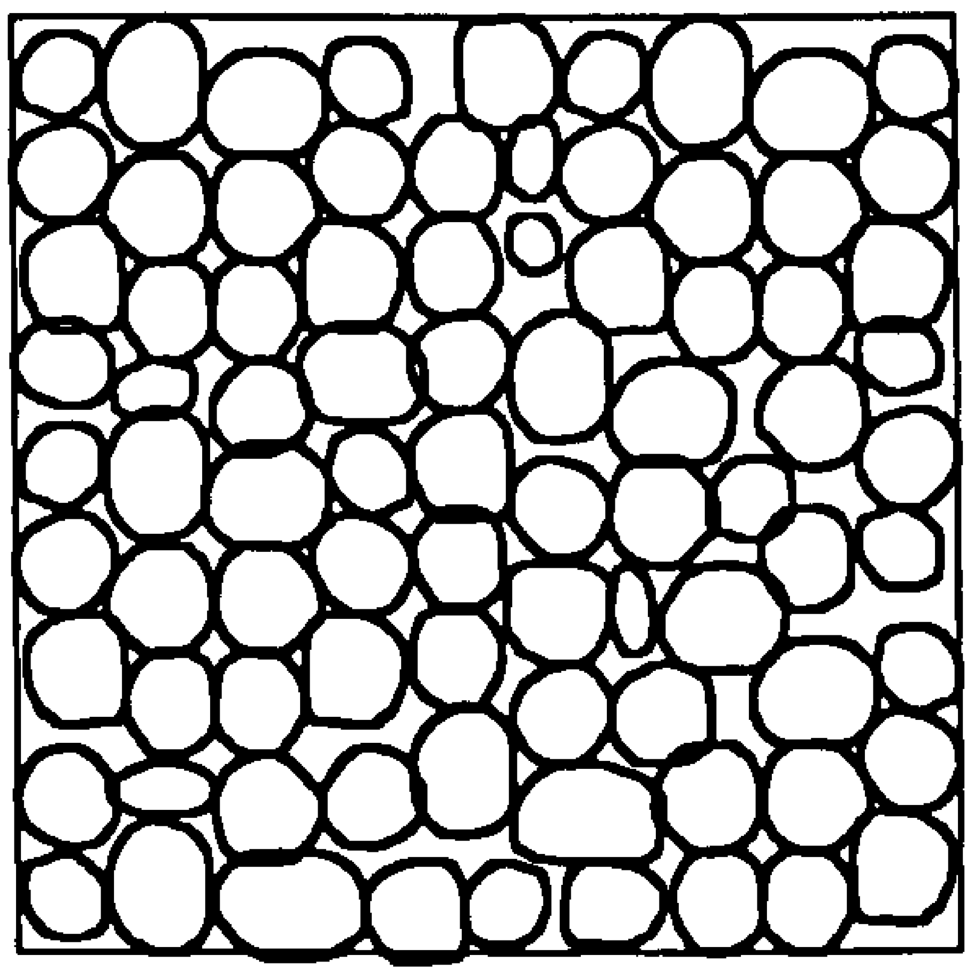
Bagnold's (1954) dilatant fluid concept attempts to explain grain flow of a non-cohesive sediment. According to the Bagnold dilatancy theory, during flow intergranular collisions between the sediment particles occur, and the whole failure mass expands due to the dispersive stresses induced by a highly viscous and dense interstitial fluid. In the absence of interstitial fluid, the coarser sediment moves from the higher energy position to the lower energy position (i.e. from the bottom to surface of flow) and the finer sediment moves from the lower energy position to the higher energy position (i.e. from surface to the bottom of flow) (Bagnold 1954; Leeder 1982).

Bagnold (1954) studied the effect of viscosity of interstitial fluid on sediment movement by using water and a mixture of glycerine-water-alcohol. In laboratory experiments, I have investigated the effect of viscosity of interstitial fluid by using GF/F filtered fresh water, alginic acid (low viscosity) and 100% glycerol. Therefore my results in section 4 can be compared with Bagnold's (1954) results. The results broadly agree with the Bagnold's (1954) dilatant theory. My results show that viscosity of the interstitial fluid and particle size distribution of the sediment play an important role in both the stabilisation and destabilisation process of sediment and soil. As mentioned previously, finer sediments mixed with coarse sediments in a proportion that just fills the pore spaces within the coarse sediment causes dilatation and the mixture of fine and coarse sediments avalanche and rests at a lower angle. A typical example in my experiments are the results for sediments F and H in viscous fluids. Furthermore the presence of fine sediment in 100% glycerol increases the glycerol's ability to support and drag coarser sediment. In my experiments, 100% glycerol and fine sediment behave like clay slurries behave in debris flow. In debris flow, clay slurries support and entrain granular solids (Hampton 1979).

There was an interesting difference in the angle of avalanche and repose of sediment in 100% glycerol between 15 minutes and 15 hours. The former were much lower than the latter. This may be because they were in a liquefied state (Fig 7.2 a). The liquefied sediment avalanched as a suspended load and at a liquefied stage there was no inter-granular friction between the sediment particles. However at 15 hours in 100% glycerol these sediments become packed (dense) and stabilised therefore they avalanched at a higher angle (Fig 7.2 b). The stabilised sediment at 15 hours avalanched as a bed load, due to the higher inter-granular friction between the sediment particles as they avalanched at a higher angle.



(a)



(b)

Figure 7.2 Schematic illustration of sediment in 100% glycerol. (a) Liquefied, unstable sediment at 15 minutes, avalanched at a lower angle. (b) Stable sediment at 15 hours, avalanched at a higher angle.

7.4 Factor of safety

Factors of safety are widely used in soil engineering to assess the stability of slopes. Their calculation for static non-avalanching slopes are often complex (Lee *et al.* 1983; Bromhead 1992). In the experiments reported in this thesis the stability of slopes has been assessed by a factor of safety which is defined as Tan (angle of avalanche)/Tan (angle of repose), following similar approaches referred to in Terzaghi 1948, Lambe & Whitman (1979, p 193), Lee *et al.* (1983, p 292, 303), and Craig (1992, p 377) and used by Muir Wood *et al.* (1994).

Figure 3.3 shows that there is a strong positive linear relationship between the factors of safety and the angle of avalanche and strong negative relationship between the factor of safety and angle of repose. The results of experiments in section 3 also show that different media do not affect the factor of safety. However the viscosity of the fluid medium affects the factor of safety. Results of experiments in section 4 show that at 15 minutes the factor of safety was higher in water than in alginic acid and 100% glycerol, whereas at 15 hours the factor of safety was higher in 100% glycerol than in alginic acid and water.

In the biological experiments, the highest factors of safety were exhibited by sediments containing *Nereis diversicolor* and *Corophium volutator* (Table 5.11; 2.29, 2.41). Sediments containing living microorganisms (LM) (Table 5.11 CNd, CCv; table 5.13 LM) had lower factor of safety values of 1.65, 1.73 and 1.65. These were higher than the factor of safety of the sediments containing dead (formalised) microorganisms (FM) (1.33). The lowest factor of safety was shown by ashed sediment avalanched in air (AA) (1.12). In my experiments, therefore, the two animal species have a major effect on slope stability as measured by the factor of safety, with microorganisms also being important - but to a lesser degree.

7.5 Duration of Avalanche

The results in section 3 show that the duration of avalanche increases with the decrease in grain size. Figure 3.8 shows a strong negative relationship between the duration of avalanche and mean particle diameter. The short avalanche duration of coarser sediments may be due to the higher frictional resistance in coarser sediment or it might be attributed to the scale effect, that is container size to particle size ratio. The ratio of the container width (75 mm) to the coarsest sediment (mean diameter 8 mm) was 9.375 in contrast to the ratio of the container width to the finer sediments (mean diameter 0.063 mm) was 1190.5.

The contrasting duration of avalanche in different fluids is almost certainly caused by the difference in their physical properties, in particular density and viscosity. Highly viscous 100% glycerol and alginic acid applies a higher drag force on the sediment particles. Density may also play a part by making the sediment particles more buoyant. But this can only be a mechanism in the glycerol experiments, since here density and viscosity both increase with increasing glycerol concentration. In contrast, alginic acid has a high viscosity but a density which is not different to that of water (see table 4.1).

7.6 Effects of Biological Activity on Avalanching

The effects of biological activity on soil and sediment stability on land have been well known for many years. Slopes on land can be made safer by bioengineering techniques such as growing trees (Dornald & Andrew 1982; Gray & Leiser 1982; Barker 1986; Bifan 1990; Bromhead *et al.* 1994; Collison *et al.* 1995; Morgan & Rickson 1995; Schiechtl & Stern 1996, 1997). However, there are only a few studies concerning the effect of biological activity on the stability of estuarine slopes (Mehta & Rao 1985; Meadows *et al.* 1994a; Muir Wood *et al.* 1997; Shaikh *et al.* 1998). Most of the work done on the interaction of estuarine sediment and biological activity is concerned with the effects of biological activity on sediment geotechnical properties and critical erosion velocity (McCall & Tevesz 1982, Meadows & Tufail 1986; Paterson 1987; Meadows & Tait 1989; Meadows & Meadows 1991; Yallop *et al.* 1994)

In this study I have explored the effects of biological activity on intertidal sandy sediments under laboratory conditions with special reference to slope stability. I have shown that biological activity in the form of burrows produced by two species of intertidal infaunal invertebrates (*Nereis diversicolor*, *Corophium volutator*) and microbiological activity produced by natural communities of microorganisms have dramatic effects on the angles at which slopes avalanche, and also on the avalanching process itself. The greatest increase in angles of avalanche occurred with *Nereis diversicolor* where angles in excess of 60° were regularly recorded (Table 5.1). These were followed closely by angles recorded for *Corophium volutator* of about 56°. Natural populations of microorganisms also had a significant effect, where angles of avalanche of 48° to 50° were recorded (CNd, CCv, LM). These angles should be compared with control values of 44° for ashed sediment in water and 37° for formalised sediment containing dead microorganisms (FM).

My results are relevant to work recently conducted by Meadows *et al.* (1994) and Muir Wood *et al.* (1994) on the effects of microbiological activity on avalanching. These authors showed that microbiological activity in the form of bacterial and fungal growth increased angles of avalanche. The biological and microbiological stabilisation of sediments reported in my thesis and in earlier published work is clearly of great significance where waves and water currents impinge on the intertidal zone and where steep sided run-off channels form on estuarine sediment banks.

Parallels between Engineering and Biological Stabilisation

The results are not only important for a sedimentological and geomorphological understanding of slope stability in the intertidal zone, but are also likely to have major implications in an environmental engineering context. This has recently been recognised by Muir Wood *et al.* (1990, 1994), Meadows *et al.* (1994), Pender *et al.* (1994) and Yallop *et al.* (1994) in studies on biological and microbiological effects on slope stability and on biological strengthening of sediments. In this context I wish to draw attention to parallels between engineering methods and biological stabilisation (Fig. 7.3). Engineers use vibration and compaction to pack and thus stabilise a sediment, infaunal invertebrates can have parallel effects by reworking and mixing the sediment. Engineers reinforce sediments using geomembranes, pilling and retaining structures (Craig 1992; McCarthy 1993). These are paralleled by biological activity in the form of biomembranes often formed by microorganisms and algal mats, armouring by large animals such as mussels, reinforcement by the roots of plants and reinforcement by burrows and tubes produced by infaunal animals. Engineering methods of stabilisation include the use of lime, cement, bitumen and bentonite. The biological equivalent is the production of extracellular polymeric material and other organic matter which binds particles together. In general, biological stabilisation tends to be more environmentally friendly but often acts on a smaller scale than conventional engineering methodology.

Slope Failure Mechanisms

Visual observations of the avalanching process show that different slope failure mechanisms (Lee *et al.* 1983 p 284-487; Bromhead 1992; Craig 1992; McCarthy 1993 p 494) were associated with the different types of biological activity. These probably reflect specific mechanical and chemical stabilisation effects produced by the tubes of the animals, together with extracellular polymeric material produced by these animals and by microorganisms (Fig. 7.4). In particular, the processes taking place during avalanching in the sediment containing *Nereis diversicolor* are very similar to rotational failure of slopes. In rotational failure, the slip surface is curved forming a bowl shape trench after failure. The failed mass characteristically slumps to the toe area of the original slope. Rotational failure is associated with slopes of homogenous material possessing cohesion. The processes taking place during avalanching in the sediment containing *Corophium volutator* are very similar to block and wedge failure. In block and wedge failure an intact mass of sediment avalanches, subsequent to cracks developing over the surface of the sediment. The mechanisms taking place during the avalanching in the sediment containing living and dead microorganisms are very similar to translational failure. Translational failure is generally associated with slopes of layered material. It involves sliding of a thin layer of sediment over a stratum of significantly different strength. During failure the sliding surface remains roughly parallel to the slope, and the sliding mass either remains intact or breaks up into large slabs.

Implications of Biological Experiments for Slope Stabilisation under Field conditions

It would be interesting to know whether the slope failure mechanisms that have been observed in laboratory experiments can be detected on slopes in the field where abundant populations of *Corophium volutator* and *Nereis diversicolor* and abundant microbial growth occur. Our highest angle of avalanche was 62° (*Nereis diversicolor*) which is an increase of 62% over that for the formalised control sediment. Our highest factor of safety was 2.40 (*Corophium volutator*) which is an increase of 80% over that for the formalised control sediment. Slope in excess of 55° certainly occur on the banks of run-off channels in estuarine cohesive sediments where both *Corophium volutator* and *Nereis diversicolor* may be abundant. My results suggest that these high slope angles are maintained by biological and microbiological activity. The high values of the factor of safety suggest that the slopes are relatively stable. This appears to be so as many run-off channels, are semi-permanent features of the geomorphology of estuarine ecosystems. It would be extremely interesting to know the angles of avalanche and factors of safety of some of these naturally occurring slopes in the intertidal zone.

7.7 Mytilus edulis Bysuss Threads Attachment

In my laboratory experiments on *Mytilus edulis*, animals were seeded onto *sand*, a *sand/gravel* mix, and *gravel*. In *sand*, none of the *M. edulis* attached threads to sediment. They attached all the byssus threads to animal's shells as shown in figure 7.5 a. Sometimes *M. edulis* released a fully developed complex from its byssus stem and started building a new complex.

In the *sand/gravel* mix and *gravel*, *M. edulis* attached threads to shells and to gravel. The number of threads attached to sediment in *gravel* was more than the number of threads attached to gravel in the *sand/gravel* mix. On *gravel M. edulis* produced more threads than in *sand/gravel* mix and in *sand*.

The results of the experiments confirm that, *M. edulis* attached threads to hard substrata and produced higher number of threads in gravel. The results broadly agree with the work done by Meadows & Shand (1989).

The above results are highly relevant to the formation of mussel beds on sandy shores and in particular to the use of mussel beds as an environmentally friendly method of coastline protection. My experiments suggests that the initial formation of new in-situ mussel patches might be aided by prior seeding with gravel patches. These gravel patches would then serve as a focus for the subsequent attachment of mussels.

Figure 7.3 Parallels between Engineering and Biological Stabilisation

Process	**Stabilisation**		
	Engineering	**Biological**	
1. Mechanical			
a) *Packing*	Vibration, Compaction	Reworking or mixing of sediment	
b) *Reinforcement*	Geomembrane, Piling, Retaining	Biomembrane	
		Armouring	
		Roots, hyphal filaments	
		Burrows & Tubes	
2. Chemical	Lime, Cement, Bitumen, Bentonite	Exopolymer, Organic matter	

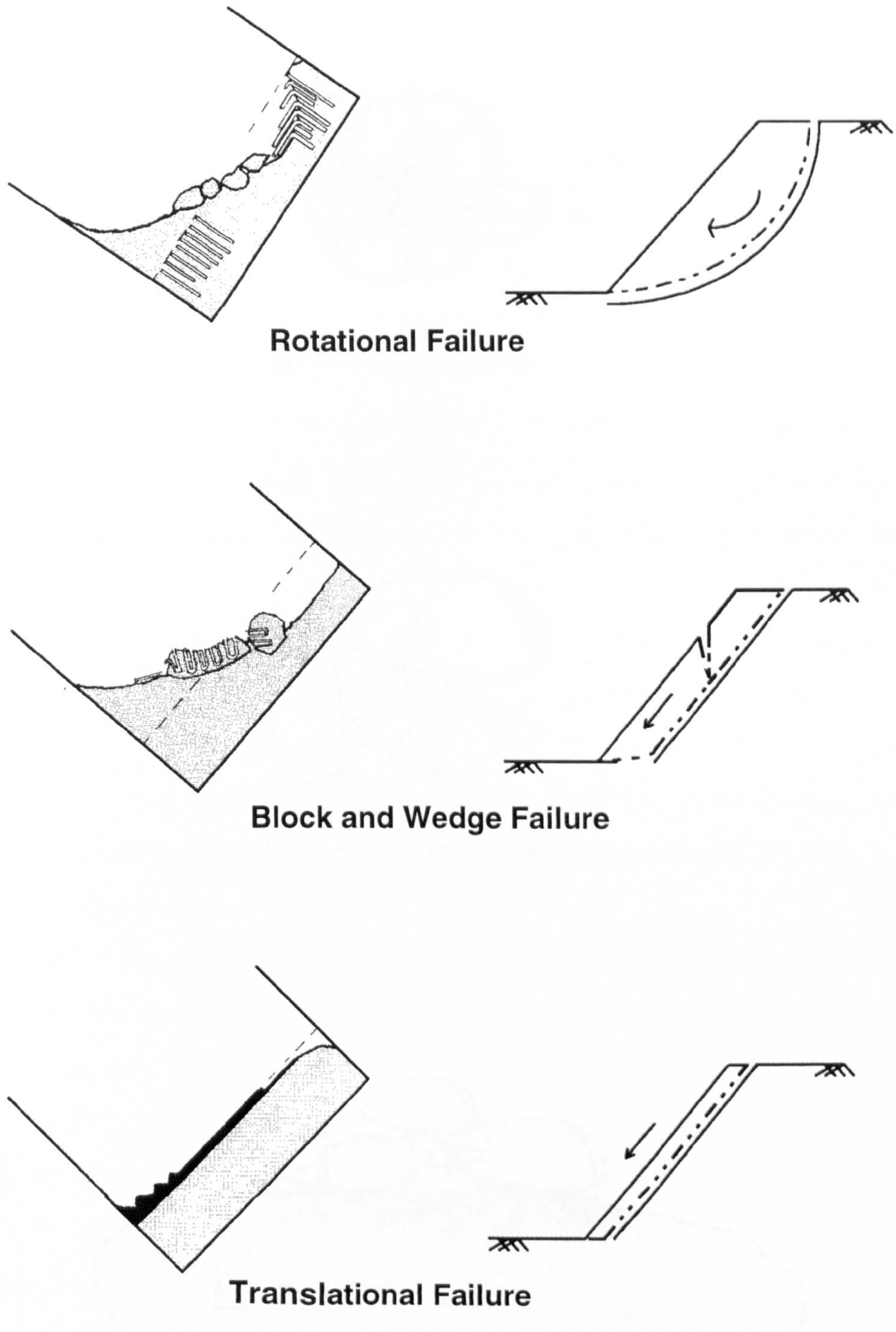
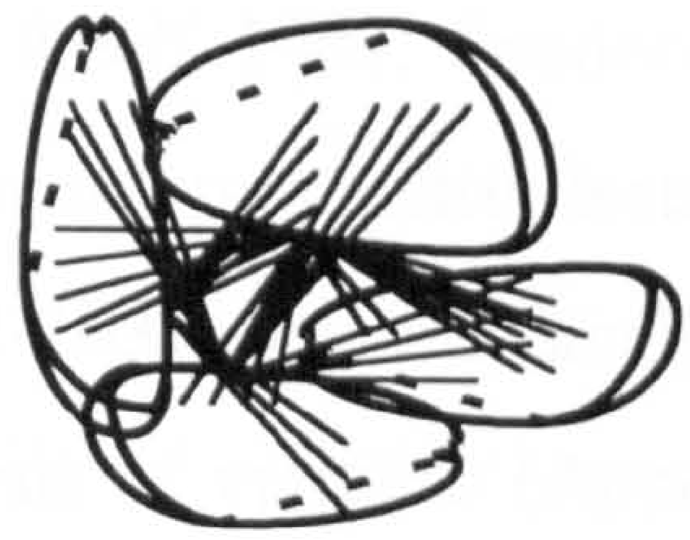
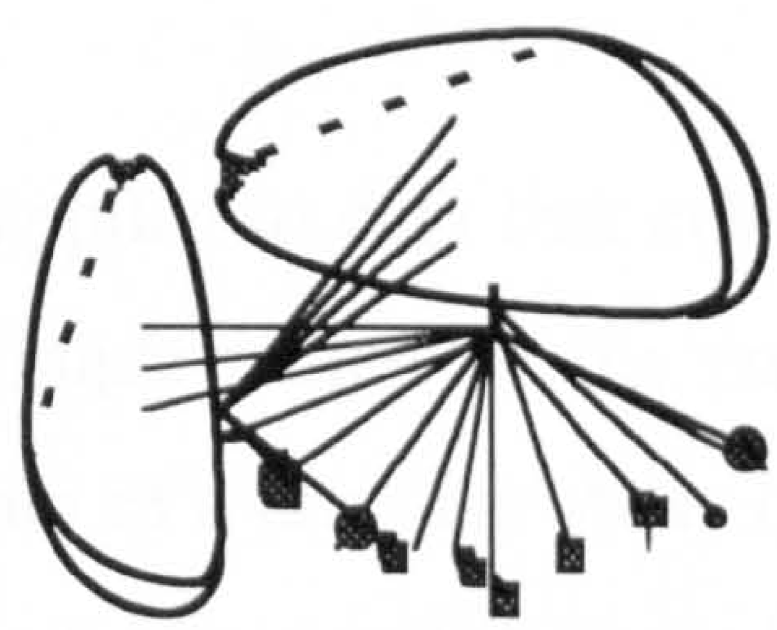


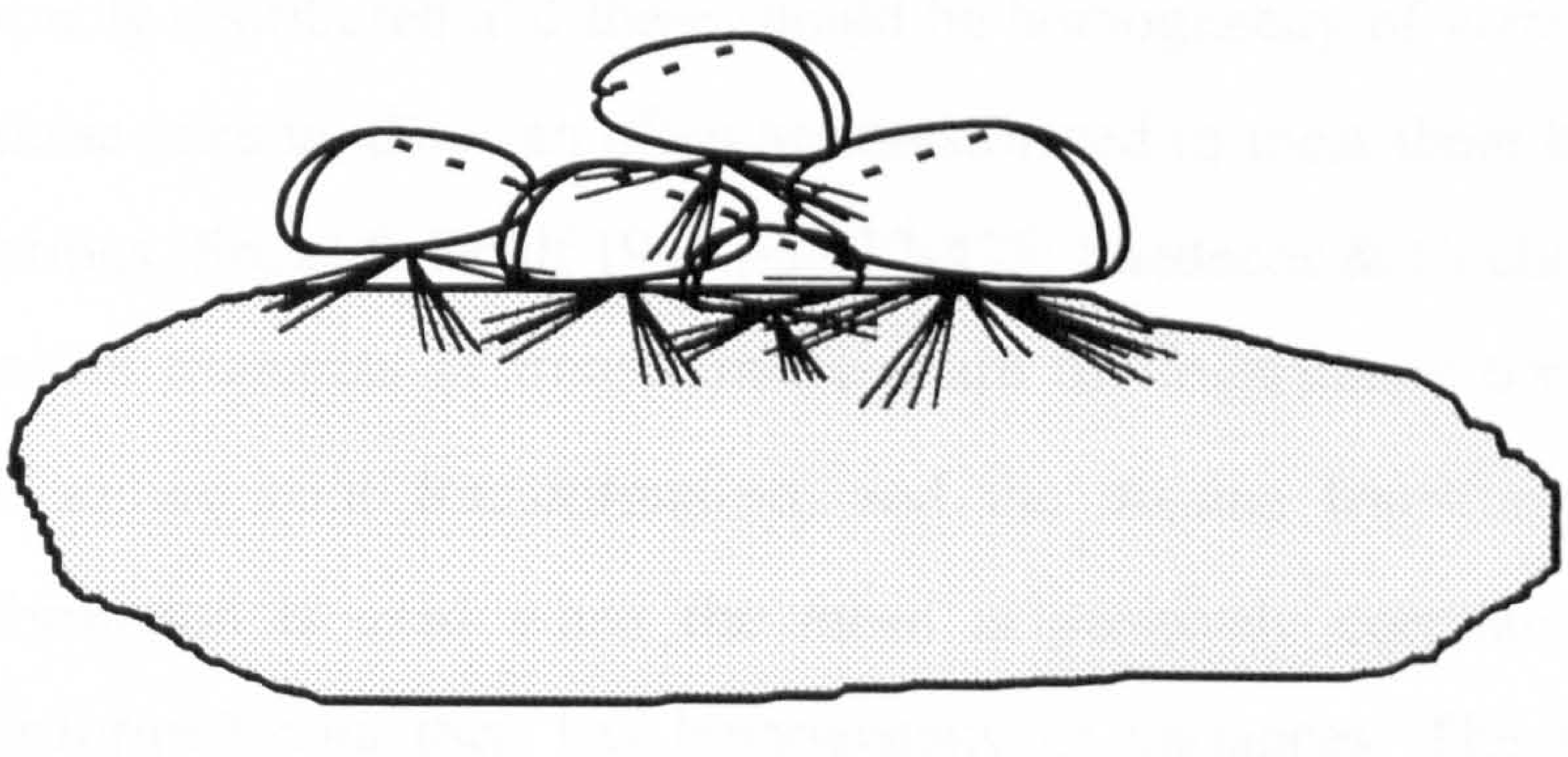
Figure 7.4 Slope failure mechanisms. **Top**: Left; shape of the slope after an avalanche in sediment containing *Nereis diversicolor* (Biological experiment 1). Right; illustration of rotational failure (Craig, 1992, McCarthy, 1993). **Middle**: Left; shape of the slope after an avalanche in sediment containing *Corophium volutator* (Biological experiment 2). Right; illustration of block and wedge failure (McCarthy, 1993). **Bottom**: Left; shape of the slope after an avalanche in sediment containing living meiofauna plus microorganisms (Biological experiments 3). Right; illustration of translational failure (Craig, 1992, McCarthy, 1993).



(a) *M. edulis* on Sand.



(b) *M. edulis* on Gravel.



(c) *M. edulis* on Rock.

Figure 7.5 *Mytilus edulis* byssus thread production. The distinct mechanism by which the *M. edulis* produced byssus threads in sand (a), sand/gravel mix or on gravel (b) and on rock (c).

7.8 Statistical Analyses of Data in Thesis

Most commonly used statistical methods are generally classified as parametric and nonparametric tests (Sokal & Rohlf 1981; Snedecor & Cochran 1989; Weiss & Hassett 1991). I have used the following parametric tests in my thesis: student's paired t test (e.g. Tables 3.8 and 3.9 pp102-103), one-way analysis of variance (e.g. Tables 1.5 p 47 and 1.7 p 51), two-way analysis of variance (Appendix I: Tables 3.2, 3.3 and 3.4 pp 261, 262), three-way analysis of variance (Appendix I: Table 3.1 p 260) and regression analysis (e.g. Figure 1.10 p 48, Table 3.13 p114).

A parametric test on a set of data can only be applied only if the data satisfy certain basic assumptions. The difference between nonparametric and parametric data and the criteria that are required to be satisfied before a parametric test can be applied are as follows.

Nonparametric tests are applied to data that consist of numbers of objects falling into different categories. An example would be the numbers of people killed by road traffic accidents during each month of a one year study in a particular town. The suitable test answering the question " Is there any difference between the numbers of people killed between the different months? " would be a chi-square test. The data is not continuous and not normal.

Parametric tests require that these two criteria are met, together with the criteria of independence. When performing the parametric tests of analyses of variance the data should also be normally distributed and there should be homogeneity of variances. If the data do not meet these criteria, they can often be transformed to meet them by applying suitable transformations (Sokal & Rohlf 1981 pp 417-428; Snedecor & Cochran 1989 pp 282-296). Well known examples of transformations are the logarithmic transformation ($\log_{10}$ or ln), the square root transformation, and the arcsine transformation. The logarithmic transformation is used when the mean is positively correlated with the variance. The transformed data then has homogeneity of variances. The square root transformation is used when the data has a Poisson distribution. This transformation transforms the data to a normal distribution. The arcsine transformation is used when the data consists of percentages, and transforms the data to a more normal distribution.

I have used the arcsine transformation in my thesis (p 185 Fig 5.12). This graph shows the relationship between the percentage increase in sediment volume (y-axis) and the angle of avalanche in degrees on the x-axis. The regression analysis referred to in the legend of figure 5.12 was performed on the arcsine of the percentage increase in volume. No other transformations were required of my data because they broadly satisfy the criteria needed for parametric tests.

The majority of statistical tests I have used in my thesis consisted of analyses of variance. These consisted of three-way, two-way and one-way analyses of variance. A three-way analysis of variance is shown in Appendix I Table 3.1 p 260. Examples of two-way analyses of variance are shown in Appendix I Tables 3.2, 3.3 and 3.4 pp 261, 262. In the three-way analysis of variance, and in three out of the eight two-way analyses of variance, the interactions were statistically significant. This means that no statement can be made about the main effects. For example in Appendix I Table 3.4 c the interaction effect was highly significant ($P<0.001$***). So nothing can be said about the two main effects of tube diameter and sediment length. I conducted a large number of two-way analyses of variance in which many of the interaction effects were significant. These are not presented in my thesis because of space limitations. When interaction occurs in a two-way analysis of variance, one-way analyses of variance are required on the data. I have done this throughout in my thesis. I have reported the one-way analyses of variance throughout.

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APPENDIX 1:

Geotechnical Properties of Soils and Sediments

Soils and sediment normally form due to the weathering of rocks on land. These sediments are later transported by water and ice, redistributed and deposited in the ocean. The avalanching process, both on land and in water also plays an important rule in sediment transportation and deposition into the ocean. It is well known that the sediment particle size, particle size distribution and density are controlling parameters in avalanching and transporting mechanisms. The other geotechnical properties such as packing of sediment, shear strength, permeability and the settling velocity are also important consideration in sediment avalanched and transported by the water and ice. The slopes of beach faces are, to a certain extent, controlled by the permeability of the beach sand whereas settling velocity is fundamental to sedimentation and suspension. These areas are of great significance for civil engineers, geologists and sedimentologists as we move into the 21st century.

Soil and sediment classification, and grain size distribution

Sediments are generally classified as gravel, sand and mud. The particle size and particle size distribution are frequent variables that determine most sediment properties (density, permeability, shear strength, avalanching and settling velocity). Particle shape is also important in all classification systems. It is assumed that particles are approximately spheroids, although they are not (Dyer 1979, p 97). Among the several systems of classification exist, engineers commonly follow the BS-1377:1675 classification system based on the metric scale. However sedimentologists and geologists follow the metric scale introduced by Wentworth (1922) and the phi (ϕ) scale devised by Krumbein (1934).

The base of the Wentworth metric scale is a 1 mm size and the other grades follow by dividing or multiplying by two. This avoids large number of decimal places while describing smaller particle size. Krumbein (1936) defined phi (ϕ) unit as the negative logarithm to the base two of the particle diameter in millimetre.

$$\phi = -\log_2 \text{(particle size in mm)}$$

A brief description of the metric (mm) scale and the phi (ϕ) scale of sediment classification is given in Table. 1 (Folk 1980).

Advantages and Disadvantages of the phi (ϕ) scale: The phi (ϕ) scale is used to simplify the calculation of statistical parameters of sediment. The phi (ϕ) scale also simplifies plotting of frequency distributions and cumulative frequency curves. When the particle size in phi units is plotted as an independent variable instead of the particle size in mm, against percentage weight, the frequency distribution curves of sediments become more symmetrical (Dyer 1979).

The phi notation has the disadvantage that the large grain sizes have negative values and the small grain sizes have positive values. However, this is not normally a problem if care is taken

Statistical parameters and their significance in particle size distribution

Mean Size and Median: Mean size and median (D_{50}) are the measure of central tendency. The mean is the centre of gravity of the cumulative distribution curve, whereas median (D_{50}) is the 50th percentile value dividing the cumulative frequency curve into two parts (Inman 1952). For a perfectly normal and symmetrical particle size distribution the mean, median and mode are the same and are represented by the size of the 50th percentile. If the distribution is skewed there may be difference between them. For a negatively skewed distribution, the mean is greater than the median (D_{50}) and for a positively skewed distribution, the mean is smaller than the median (Dyer 1986 p 26).

Standard deviation (Sorting): In particle size analysis, sorting is a measure of standard deviation. A higher value of standard deviation indicates a lower sorting of the sediment. Sorting is used to determine factors like sediment source, grain size and their transportation and depositional mechanisms (Tucker 1981 p 15).

Skewness: Skewness is a measure of the symmetry of the distribution. For a normal distribution, the coefficient of skewness is zero. If the grain size distribution measured in mm has its peak towards the coarse end of the distribution and the tail of the curve towards the finer end of the curve, then the sediment is said to be negatively skewed (mean > median). If the grain size distribution measured in mm has its peak towards the finer end of the distribution and its tail at the coarser end of the distribution, the sediment is said to be positively skewed.

Since the phi scale is opposite to the mm scale, the above two statements have to be reversed. A positively skewed distribution has its peak at the coarse end of the distribution and its tail in the fine end of the distribution, and a negatively skewed distribution has its peak at the fine end of the distribution and its tail in the coarser end of the distribution.

When discussing skewness parameters of sediments, therefore, great care needs to be taken to identify which scale is being used - the millimetre scale or the phi scale.

Skewness reflects depositional processes. Beach sand for example tends to have a negative skewness coefficient (positively skew in case of phi (ϕ) scale) as fine particles have been remove by persistent wave action. On the other hand river sand is positively skewed (negatively skew in case of phi (ϕ) scale); since clay and silt are not removed by currents (Tucker 1981 p 15).

Kurtosis: Kurtosis shows the peakedness of the distribution curve. If the coefficient of kurtosis is greater than three, the distribution has a higher central peak than the normal distribution falling rapidly on either side of the mean to longer tails. This is called leptokurtosis. If the coefficient of kurtosis is less than three the distribution has a lower central peak than the normal distribution. This is called platykurtosis. The platykurtosis curve has a flat top and tends to be convex with little or no tails (Dyer 1986 p 28).

Methods for calculation of statistical parameters

Generally there are two methods that exist for statistical analysis of particle size distribution. One is a graphical method and the other is the algebraic method of moments.

Graphical Method: The particle size at a particular percentile value is taken from a cumulative frequency curve (cumulative weight percentage against particle size plot). The percentile value is the size of particle for which a certain percentage of the sample is finer. In graphical method, Trask formulae for the mm scale are based on 25th, 50th and 75th percentile values. The method introduced by Krumbein (1936) on the phi (ϕ) scale uses the 5th, 16th, 84th and 95th percentile. Other statistical parameters using the points phi scale introduced by Inman (1952) and by Folk & Ward (1957) are based on 5th, 16th, 50th, 84th and 95th percentile values. (for detail see Dyer 1979 p 117; Tucker 1981 p 14).

Advantages and disadvantages of the Graphical method: The graphical method can be applied to both sieving and pipette methods and can be used for any type of sediment. The method requires a particle size distribution chart to be produced which takes time.

Method of Moments

Krumbein (1936) adopted the method of moments for use on the phi (ϕ) scale. In method of moment calculations are based on the percentage fraction of the total weight in each class interval and the mid-point value of each class interval (Table 2). This assumption is very important, because a very small weight with a large mean can play an important role in the calculation. Because of this, some authors advise the use of sieves set at quarter (1/4) phi intervals. (Dyer 1986 p 27).

In the method of moments, the mean size is calculated by taking the moment of the percentages in each of the constant particle size increments. Sorting is the second moment about the mean. Skewness is the third moment about the mean deviation divided by the cube of the standard deviation. Kurtosis is the fourth moment about the mean deviation divided by the fourth power of standard deviation.

Advantages and disadvantages of Method of moments: Since the method of moments uses entire population, therefore it can only be applied to a particle size distribution which is fully determined and there is a constant interval between the sieve sizes.

The method of moments is suitable for sandy sediments (sediments of intertidal flat or sediment at entrance of beaches) and can only be applied by using the sieving method. The method of moments cannot be used for finer sediment, for example clay and silt using the pipette method. Since most estuarine sediments contain clay or silt fractions, the method of moments is not suitable for estuarine sediments (Folk 1966; Dyer 1979 p 120).

Table 1 Particle size classification (Folk 1980).

Sediment Type		Range of Particle Size metric (mm)	phi (ϕ)
GRAVEL	Boulder	4096 to 256	-20 to -8
	Cobble	256 to 64	-8 to -6
	Pebble	64 to 4	-6 to -2
	Granules	4 to 2	-2 to -1.0
SAND	Very coarse sand	2 to 1.0	-1.0 to 0.0
	Coarse sand	1.0 to 0.5	0.0 to 1.0
	Medium sand	0.5 to 0.25	1.0 to 2.0
	Fine sand	0.210 to 0.125	2.0 to 3.0
	Very fine sand	0.125 to 0.0625	3.0 to 4.0
MUD	Coarse silt	0.0625 to 0.031	4.0 to 5.0
	Medium silt	0.031 to 0.0039	5.0 to 8.0
	Clay	> 0.0039	< 8.0

Table 2 Particle size calculation. f = percentage fraction of the total weight in each class interval. m_ϕ = mid-point value of each class interval in phi unit (Tucker 1981; Dyer 1986).

Parameter	Formulae
Mean size	$\bar{x} = \sum \frac{\text{Percentage} \times \text{grain size}}{100} = \sum \frac{f\, m_\phi}{100}$
Sorting (Standard deviation)	$\sigma_\phi = \sqrt{\frac{\sum f(m_\phi - \bar{x})^2}{100}}$
Skewness	$\alpha_{3\phi} = \frac{1}{100} \frac{\sum f(m_\phi - \bar{x})^3}{\sigma_\phi^3}$
Kurtosis	$\sigma_{4\phi} = \frac{1}{100} \frac{\sum f(m_\phi - \bar{x})^4}{\sigma_\phi^4}$

Coefficient of Uniformity (Cu) and Coefficient of Curvature (Cz)

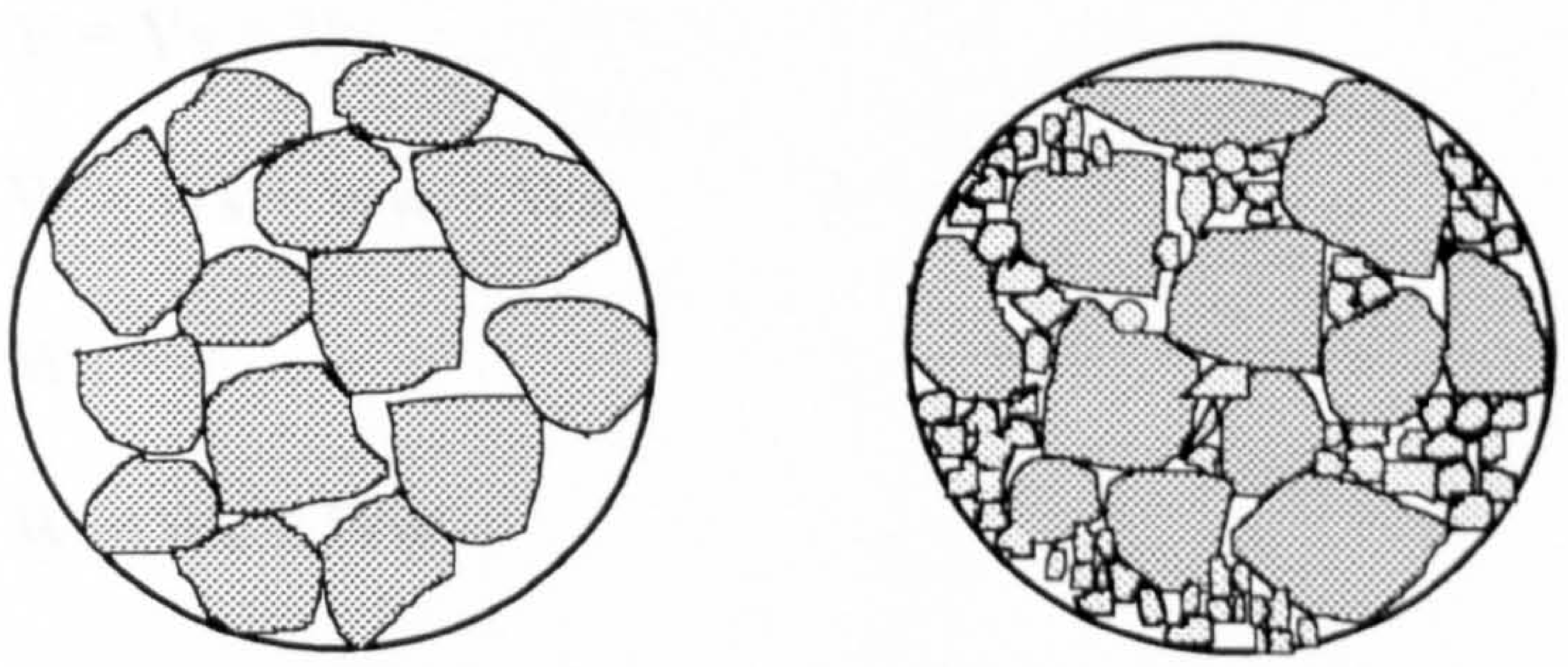
The coefficient of uniformity (Cu) and coefficient of curvature are used to describe the sediment texture (Fig. III). A uniform soil or sediment will have coefficient of uniformity (Cu) value approaching to 1 and an almost vertical distribution curve. A well-graded soil or sediment has a coefficient of curvature (Cu) between 1 and 3 with a smooth, concave distribution curve. A poorly graded sediment has a wide distribution curve which is deficient in intermediate particle sizes. If a sediment has intermediate particle sizes in a higher proportion than the larger and smaller particle sizes, the sediment can be described as gap-graded (Smith 1981; Craig 1992).

The coefficient of uniformity (Cu) and coefficient of curvature (Cz) are calculated by the following formulae (Bowels 1978; Craig 1992).

$$\text{Coefficient of uniformity (Cu)} = \frac{D_{60}}{D_{10}} \qquad \text{---(1)}$$

$$\text{Coefficient of Curvature (Cz)} = \frac{{D_{30}}^2}{D_{60}\, D_{10}} \qquad \text{---(2)}$$

The particle size D_{10}, D_{30} and D_{60} are taken from the particle size distribution chart. D_{10} is the particle diameter below which 10% of sediment lies. Similarly D_{30} and D_{60} are the particle diameters below which 30% and 60% of the sediment lies.



a) Uniform Sediment b) Graded Sediment

Figure III Sediment texture (Rankilor 1981).

Phase Relationships

Soils and sediments are either a two-phase or a three-phase system depending on the composition of solid particles, air and water present in it. The soils and sediments are a two-phase system if the voids (pore spaces) between the solid particles, are either completely occupied by air or completely occupied by water. In the three-phase system, voids are partly occupied by air and partly occupied by water (Fig. IV).

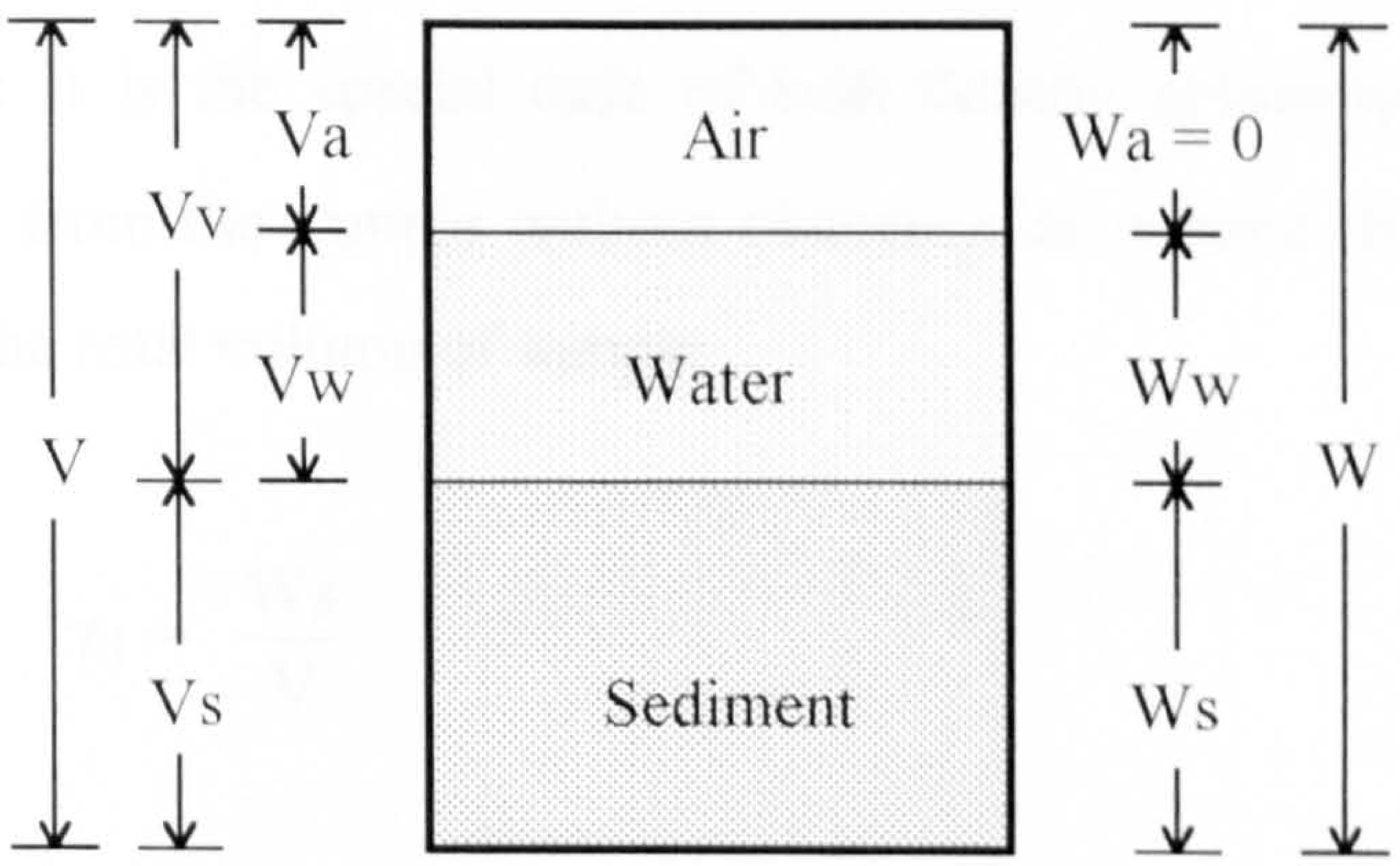


Figure IV Sediment three phase system.

$V = Vs + Vw + Va$

$Vv = Vw + Va$(for completely saturated sediment $Vv = Vw$)

$$V = Vs + Vv \quad \text{---(3)}$$

$$W = Ws + Ww + Wa \quad \text{---(4)}$$

$Wa = 0$

$$W = Ws + Ww \quad \text{---(5)}$$

where

V = Total volume of sample, Vs = Volume of solid, Vw = Volume of water, Va = Volume of air, W = Total weight of sample, Ws = Weight of solid, Ww = Weight of water, Wa = weight of air (negligible).

Void Ratio (e): It is the ratio of volume of voids to the volume of solids.

$$e = \frac{Vv}{Vs} \qquad \text{---(6)}$$

Porosity (n): The porosity is the ratio of volume of voids to the total volume.

$$n = \frac{Vv}{V} \qquad \text{---(7)}$$

Dry Density (γ_d): It is the special case of bulk density assuming that the water is completely remove from the sample without changing its volume. It is the ratio of the weight of solid to the total volume of sample.

$$\gamma_d = \frac{Ws}{V} \qquad \text{---(8)}$$

Bulk Density (γ_b): It is the ratio of the total weight to the volume of sample.

$$\gamma_b = \frac{W}{V} \qquad \text{---(9)}$$

Specific Gravity (Gs): The specific gravity of any material is defined as the ratio of the weight of a given volume of that material to the weight of an equal volume of water.

$$Gs = \frac{Ws}{Ww} \qquad \text{---(10)}$$

Permeability

Permeability is a measure of flow of water through a sediment. In the measurement of permeability it is assumed that the flow of water follows the Darcy's law.

$$\frac{Q}{t} = k\,A\,\frac{H}{L} \qquad \text{---(11)}$$

Where k = coefficient of permeability, L = length of sediment (mm), H = hydraulic head across the sediment (mm), Q = quantity of water flowing, t = time for flow of water.

Coefficient of Permeability: According to Darcy's law coefficient of permeability (k) is the rate of flow (Q) through a unit cross section (A) of a sediment under the influence of the hydraulic gradient (i = H/L).

$$k = \frac{Q/t}{A\,i} \qquad \text{---(12)}$$

The coefficient of permeability not only depends on the properties of the sediment, but also on the properties of the water. The coefficient of permeability varies with the temperature and hence viscosity of water. Darcy's law is valid only if the:

- sediment is 100 percent saturated with water.
- flow of water is steady and laminar.
- volume of sediment remains constant during the test.

The coefficient of permeability depends on the particle size, particle shape and average size of the pores. The smaller the particle size the smaller is the pore size and the lower is the coefficient of permeability. For a perfect sediment sample having no fissures, the coefficient of permeability is a function of void ratio (Craig 1992 p 38). The permeability of coarse sediment is determined by using constant head permeameter and the permeability of fine sediment is determined by using falling head permeameter.

Constant Head Permeameter: In constant head permeameter the volume of water passed through a sample in a specific time is recorded. During the measurement the head of water remains constant in this method. Permeability and coefficient of permeability are determined by using the above equations (11 & 12). This method is suitable for measuring the permeability of coarse sediment.

Falling Head Permeameter: Since water passes slowly through a fine sediment and it is not possible to obtain a measurable amount of water within a reasonable time period. Therefore the permeability of fine sediment is measured by using a falling head permeameter. In a falling head permeameter the time and the variation in continuously falling head is recorded. Here the coefficient of permeability is determined by the equation (13) given below (Smith 1981 p44; Craig 1992 p 40).

$$k = \frac{L}{t} \times 2.3 \log_{10} \frac{h_1}{h_2} \qquad \text{---(13)}$$

Where k = coefficient of permeability, L= length of sediment (mm), h_1 = initial water level (mm), h_2 = final water level (mm), t = time for water level to fall from h_1 to h_2.

Shear strength

Shear strength is the maximum resistance offered by sediment to the shearing stresses under any given condition.

For the determination of slope stability a knowledge of sediment shear strength is necessary (Dill & More 1965). There are generally four basic techniques available for measuring shear strength of soil and sediment. In first technique the soil and sediment sample (held in shear box) is caused to shear at a constant rate by applying a shearing force. In the second technique the soil and sediment sample is caused to fail under a compressive force (Tri-axial test). The above two tests are laboratory tests and can be done under both drained and undrained conditions. In the third technique the sediment shear strength is determined by using different size and shapes of penetrometer (cone penetration & pile load tests). The undrained shear strength of sediment in the laboratory as well as in the field can be determined by a penetrometer technique (Terzaghi & Peek 1948; Bowels 1978; Smith 1981; Cheng & Jack 1990; Cernica 1995; Craig 1992). The use of an electronic cone for soil and sediment field testing is now increasing. The electronic cone is cost and time effective and can record shear resistance at a micro scale level (Meigh 1987; Lunne & Robertson 1997). In the fourth technique, shear strength is measured by applying a torque on a soil or sediment sample (vane test). The vane is normally used to measure the shear strength of in-situ soil or sediment. However vanes can also be used to measure the shear strength of sediment in laboratory (Dill & More 1965).

Cone Penetrometer: In my laboratory experiments, undrained shear strength of sediment S2 was measured by using a Geonor Fall-Cone Penetrometer and a Pilcon Hand Van Tester.

The following equation was applied to the results of the Geonor fall-cone penetrometer (Hansbo 1957).

$$\tau_f = \frac{k\,Q\,9.81}{h^2} \qquad \text{---(14)}$$

Where τ_f = Shear strength in kN m^{-2} or kPa, k = constant depend on the apex angle of cone, Q = weight of cone in gm, h = penetration of cone in mm.

Hand Van Tester: The equipment consists of a torque-head, an adjustable stainless steel rod and a stainless steel vane. The vane is made up of four thin rectangular blades. The torque head and vane are connected by the rod. The vane is driven into the soil or sediment and the torque is applied to the vane by gradually rotating the torque-head. During shear failure a cylinder of soil or sediment fails, equal to the width (d) and depth (h) of vane. The shear strength of soil or sediment (c) is calculated as follows (Smith 1981)

$$T = c\,(\pi dh)\,\frac{d}{2} + c\left(\pi\frac{d^2}{4}\right)\frac{1}{3}\,d \times 2 \qquad \text{---(15)}$$

Where T = torque applied on vane (Nm), c = cohesion of soil or sediment (kN m^{-2}), d = width of the vane (mm), h = height of vane (mm).

According to the Mohr-Coulomb theory, shear strength of soil or sediment is given by

$$\tau = c + \sigma \tan \phi$$

In the vane test, it is assumed that ϕ is zero (Smith 1981). Therefore the shear resistance of the soil or sediment cylinder is equal to the cohesion (c) of sediment.

$$\tau = c \qquad \text{---(16)}$$

Appendix I : Table 3.1
Three-way analysis of variance testing differences in permeability coefficients (k) between tube diameters, sediment lengths and water heads. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Source	Sum of Squares	Mean Square	D F	F ratio	P
Tube diameter	0.00492	0.00246	1 36	182.2	0.005 **
Sediment length	0.00694	0.00694	2 36	2.238	0.107 ns
Water head	0.00011	0.00005	2 36	78.84	0.001 **
Tube diameter × Sediment length	0.00248	0.00124	2 36	34.96	0.003 **
Tube diameter × Water head	0.00013	0.00003	4 36	1.410	0.250 ns
Sediment length × Water head	0.00008	0.00004	2 36	1.720	0.193 ns
Tube diameter × Sediment length × Water head	0.00014	0.00004	4 36	1.600	0.195 ns
Residual	0.00079	0.00002			
Total	0.01559				

Appendix I : Table 3.2

Two-way analyses of variance testing differences in permeability coefficients (k) between different sediment lengths and water heads for a given tube diameter. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Source	Sum of Squares	Mean Square	D F		F ratio	P
a) Tube Diameter 20 mm						
Sediment length	0.00636	0.00636	1	12	105.0	< 0.001 ***
Water head	0.00013	0.00006	2	12	1.061	0.50 > P < 0.25
Interaction	0.00022	0.00011	2	12	1.784	0.25 > P > 0.10
Residual	0.00073	0.00006				
Total	0.00743					
b) Tube Diameter 25 mm						
Sediment length	0.00296	0.00296	1	12	1232	< 0.001 ***
Water head	0.00007	0.00003	2	12	13.63	< 0.001 ***
Interaction	0.00000	0.00000	2	12	0.2083	> 0.75
Residual	0.00003	0.00000				
Total	0.00305					
c) Tube Diameter 54 mm						
Sediment length	0.00010	0.00010	1	12	31.42	< 0.001 ***
Water head	0.00004	0.00002	2	12	5.454	0.025 > P > 0.01
Interaction	0.00000	0.00000	2	12	0.1515	> 0.75
Residual	0.00004	0.00000				
Total	0.00018					

Appendix I : Table 3.3

Two-way analyses of variance testing differences in permeability coefficients (k) between different tube diameters and water heads for a given sediment length.

Source	Sum of Squares	Mean Square	D F		F ratio	P
a) Sediment Length 100 mm						
Tube diameter	0.00663	0.00331	2	18	467.1	< 0.001 ***
Water head	0.00008	0.00004	2	18	5.451	0.025 > P >0.01
Interaction	0.00002	0.00000	4	18	0.563	0.75 > P > 0.5
Residual	0.00013	0.00001				
Total	0.00685					
b) Sediment Length 200 mm						
Tube diameter	0.00077	0.00038	2	18	10.30	0.005 >P> 0.001 ***
Water head	0.00010	0.00005	2	18	1.398	0.5 > P > 0.25
Interaction	0.00067	0.00006	4	18	1.683	0.75 > P > 0.10
Residual	0.00067	0.00004				
Total	0.00179					

Appendix I : Table 3.4

Two-way analyses of variance testing differences in permeability coefficients (k) between different tube diameters and sediment lengths for a given water head. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Source	Sum of Squares	Mean Square	D F		F ratio	P
a) Water Head (H_1 = 450 mm to 400 mm)						
Tube diameter	0.00237	0.00118	2	12	28.22	
Sediment length	0.00174	0.00174	1	12	41.59	
Interaction	0.00052	0.00026	2	12	6.234	0.025 > P > 0.01*
Residual	0.00050	0.00004				
Total	0.00513					
b) Water Head (H_2 = 400 mm to 350 mm)						
Tube diameter	0.00119	0.00059	2	12	27.60	
Sediment length	0.00292	0.00292	1	12	135.9	
Interaction	0.00123	0.00061	2	12	28.57	< 0.001 ***
Residual	0.00026	0.00002				
Total	0.00560					
c) Water Head (H_3 = 350 mm to 300 mm)						
Tube diameter	0.00149	0.00075	2	12	257.2	
Sediment length	0.00235	0.00235	1	12	811.3	
Interaction	0.00087	0.00044	2	12	150.1	< 0.001 ***
Residual	0.00004	0.00000				
Total	0.00475					

Appendix I: Table 3.5

One-way analyses of variance testing differences in permeability coefficients (k) between different tube diameters for a given sediment length and water head. Probability: 0 05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Source	Sum of Squares	Mean Square	D F	F ratio	P
a) **Sediment Length 100 mm**					
I) Water Head (H_1 = 450 mm to 400 mm)					
Tube diameter	0.0039777	0.0019888	2	157.6	< 0.001 ***
Residual	0.0000757	0.0000126	6		
Total	0.0040534		8		
II) Water Head (H_2 = 400 mm to 350 mm)					
Tube diameter	0.0043087	0.0021544	2	558.8	< 0.001 ***
Residual	0.0000231	0.0000039	6		
Total	0.0043319		8		
III) Water Head (H_3 = 350 mm to 300 mm)					
Tube diameter	0.0041582	0.0020791	2	483.3	< 0.001 ***
Residual	0.0000258	0.0000043	6		
Total	0.0041840		8		
a) **Sediment Length 200 mm**					
I) Water Head (H_1 = 450 mm to 400 mm)					
Tube diameter	0.0000256	0.0000128	2	4.810	0.057 ns
Residual	0.0000159	0.0000027	6		
Total	0.0000415		8		
II) Water Head (H_2 = 400 mm to 350 mm)					
Tube diameter	0.000301	0.000150	2	1.390	0.320 ns
Residual	0.000651	0.000108	6		
Total	0.000951		8		
III) Water Head (H_3 = 350 mm to 300 mm)					
Tube diameter	0.0000129	0.0000065	2	7.860	0.021 *
Residual	0.0000049	0.0000008	6		
Total	0.0000179		8		

Appendix I : Table 3.6
One-way analyses of variance testing differences in permeability coefficients (k) between different sediment lengths for a given tube diameter and water head. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Source	Sum of Squares	Mean Square	D F	F ratio	P
a) **Tube Diameter 20 mm**					
I) Water Head (H_1 = 450 mm to 400 mm)					
Sediment length	0.001256	0.001256	1	11.02	0.0290 *
Residual	0.000456	0.000114	4		
Total	0.001712		5		
II) Water Head (H_2 = 400 mm to 350 mm)					
Sediment length	0.0031602	0.0031602	1	51.37	0.0020 **
Residual	0.0002461	0.0000615	4		
Total	0.0034063		5		
III) Water Head (H_3 = 350 mm to 300 mm)					
Sediment length	0.0021622	0.0021622	1	348.1	< 0.001 ***
Residual	0.0000248	0.0000062	4		
Total	0.0021870		5		
a) **Tube diameter 25 mm**					
I) Water Head (H_1 = 450 mm to 400 mm)					
Sediment length	0.0009779	0.0009779	1	279.9	< 0.001 ***
Residual	0.0000140	0.0000035	4		
Total	0.0009919		5		
II) Water Head (H_2 = 400 mm to 350 mm)					
Sediment length	0.0009475	0.0009475	1	470.6	< 0.001 ***
Residual	0.0000081	0.0000020	4		
Total	0.0009556		5		
III) Water Head (H_3 = 350 mm to 300 mm)					
Sediment length	0.0010323	0.0010323	1	569.3	< 0.001 ***
Residual	0.0000073	0.0000018	1		
Total	0.0010395		5		

Appendix I : Table 3.7

One-way analyses of variance testing differences in permeability coefficients (k) between different sediment lengths for a given tube diameter and water head. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Source	Sum of Squares	Mean Square	D F	F ratio	P
a) **<u>Tube diameter 54 mm</u>**					
I) <u>Water Head (H_1 = 450 mm to 400 mm)</u>					
Sediment length	0.0000313	0.0000313	1	3.800	0.123 ns
Residual	0.0000329	0.0000082	4		
Total	0.0000642		5		
II) <u>Water Head (H_2 = 400 mm to 350 mm)</u>					
Sediment length	0.0000443	0.0000443	1	44.80	0.003 ***
Residual	0.0000040	0.0000010	4		
Total	0.0000482		5		
III) <u>Water Head (H_3 = 350 mm to 300 mm)</u>					
Sediment length	0.0000290	0.0000290	1	36.38	0.004 ***
Residual	0.0000032	0.0000008	4		
Total	0.0000322		5		

Appendix I : Table 3.8

One-way analyses of variance testing differences in permeability coefficients (k) between different water heads for a given tube diameter and sediment length. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Source	Sum of Squares	Mean Square	D F	F ratio	P
a) **Sediment length 100 mm**					
I) Tube Diameter 20 mm					
Water Head	0.0000439	0.0000220	2	1.730	0.2550 ns
Residual	0.0000762	0.0000127	6		
Total	0.0001202		8		
II) Tube Diameter 25 mm					
Water Head	0.0000256	0.0000128	2	4.810	0.0570 ns
Residual	0.0000159	0.0000027	6		
Total	0.0000415		8		
III) Tube Diameter 54 mm					
Water Head	0.0000239	0.0000120	2	2.040	0.2110 ns
Residual	0.0000351	0.0000059	6		
Total	0.0000590		8		
a) **Sediment length 200 mm**					
I) Tube Diameter 20 mm					
Water Head	0.000301	0.000150	2	1.390	0.3200 ns
Residual	0.000651	0.000108	2		
Total	0.000951		8		
II) Tube Diameter 25 mm					
Water Head	0.0000408	0.0000204	2	9.180	0.0150 *
Residual	0.0000133	0.0000022	6		
Total	0.0000542		8		
III) Tube Diameter 54 mm					
Water Head	0.0000129	0.0000065	2	7.860	0.0210 *
Residual	0.0000049	0.0000008	6		
Total	0.0000179		8		

Appendix I: Table 4.1
One-way analyses of variance testing difference between amplitude of packing and bulk density, dry density, and void ratio. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Source	Sum of Squares	Mean Square	D F	F ratio	P
a) Bulk Density					
Amplitude	66654.4	11109.1	6	179.0	< 0.0001 ***
Residual	434.5	62.1	7		
Total	67088.9		13		
b) Dry Density					
Amplitude	121605	20267	6	163.2	< 0.0001 ***
Residual	869	124	7		
Total	122474		13		
c) Void Ratio					
Amplitude	0.09574	0.01596	6	63.65	< 0.0001 ***
Residual	0.00176	0.00025	7		
Total	0.09750		13		

Appendix I : Table 4.2
One-way analyses of variance testing difference between amplitude of packing and shear strength measured by using cone for a given core. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Source	Sum of Squares	Mean Square	D F	F ratio	P
a) Core S_1 (shear strength measured by using small cone)					
Amplitude	12.4473	2.0746	6	56.03	< 0.001 ***
Residual	0.5183	0.0370	14		
Total	12.9656		20		
b) Core S_2 (shear strength measured by using large cone)					
Amplitude	151.284	25.214	6	179.1	< 0.001 ***
Residual	1.971	0.141	14		
Total	153.255		20		

Appendix I : Table 4.3

One-way analyses of variance testing difference between shear strength measured by using small cone, small vane, large cone, and large vane for a given amplitude of packing. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

Source	Sum of Squares	Mean Square	D F	F ratio	P
a) Amplitude 1					
Shear strength	0.89817	0.29939	3	126.4	< 0.001***
Error	0.01895	0.00237	8		
Total	0.91712		11		
b) Amplitude 1.5					
Shear strength	1.30872	0.43624	3	324.2	< 0.001***
Error	0.01076	0.00135	8		
Total	1.31948		11		
c) Amplitude 2					
Shear strength	1.29489	0.43163	3	353.3	< 0.001***
Error	0.00977	0.00122	8		
Total	1.30467		11		
d) Amplitude 2.5					
Shear strength	1.002828	0.334276	3	598.7	< 0.001***
Error	0.004467	0.000558	8		
Total	1.007294		11		
e) Amplitude 3					
Shear strength	299.2888	99.7629	3	20000	< 0.001***
Error	0.0390	0.0049	8		
Total	299.3278		11		
f) Amplitude 3.5					
Shear strength	914.2228	304.7409	3	20000	< 0.001***
Error	0.1235	0.0154	8		
Total	914.3463		11		
g) Amplitude 4					
Shear strength	724.842	241.614	3	846.8	< 0.001***
Error	2.283	0.285	8		
Total	727.125		11		

Appendix II:

Factor of Safety

The factor of safety is the ratio of stabilising forces resisting movement to destabilising forces encouraging it. A slope is stable if its factor of safety is equal to or greater than 1.5 ($F \geq 1.5$) and the stability of slope is its marginal if the factor of safety is equal to or greater than 1.15 ($F \geq 1.15$). A slope is consider to be unstable if factor of safety is less than one ($F < 1$) (Schiechtl & Stern 1996). The factor of safety of a slope is determined by limit equilibrium methods of slope stability analysis. In limit equilibrium methods it assumed that the slope might fail by the sliding of a mass of sediment on a well-defined failure plane (failure surface) as the shear strength of the sediment at the failure plane reaches its limit (Lamb and Whitman 1979; Anderson and Richards 1987). The shear strength of sediment at a failure plane of slope is determined by Mohr-Coulombs theory as follows

$$\tau = C + \sigma \tan \phi$$

Where τ = maximum shearing resistance, C = cohesion of soil or sediment, σ = effective compressive stresses, ϕ = angle of internal friction (Lamb and Whitman 1979; Bromhead 1992; Craig 1992; McCarthy 1993).

Limit Equilibrium Methods of Slope Stability Analysis

Limit equilibrium methods of slope stability analysis concentrate on the equilibrium of forces at a potential failure plane. The location and shape of the potential failure plane vary according to the assumed failure conditions, for example rotational or translational. In rotational failure, the depth of the failure plane is greater than the length of the slope and the failure plane may be a circular arc or a non-circular curve shape. However in translational failure, the depth of the failure plane is small as compared to the length of the slope, and the failure plane is parallel to the slope surface. The two limiting equilibrium methods used to test the stability of a slope under potential rotational failure conditions are the *method of moments* and the *method of slices* (Brunsden & Prior 1984; Craig 1992). Slightly different approaches are used to calculate the equilibrium of stabilising and destabilising forces for each of the three types of slope failure (rotational slide, translational slide and block and wedge slide). Factors of safety for each of the three types of potential failure are calculated, and the slope is declared safe or unsafe with respect to a particular type of failure.

In the method of moments and the method of slices, the potential failure surface is assumed to be a circular arc. In the method of moments,the equilibrium of forces acting on a unit section or slice of slope is considered and the factor of safety for potential slope failure is determined. However in the method of slices, the potential failure slope is divided into slices. The equilibrium of forces for each of the slices is considered separately and the factor of safety for each slice is calculated.

The stability of a slope in translational failure is analysed by ***infinite slope analysis*** and the stability of slope in block and wedge failure is analysed by ***sliding block analysis***. In these analyses the equilibrium of forces acting on a unit section or slice of slope is considered, and the factor of safety for the whole failure slope is calculated.

Stability Analysis

The stability of a slope is analysed by cutting a slice (free body element) of sediment from the slope and considering the equilibrium of forces on the slice (Lambe & Whitman 1979; Brunsden & Prior 1984; Bromhead 1992; Craig 1992). The forces acting on the slice of a uniform slope composed of dry cohesionless sediment is shown in figure V. Generally in infinite slope analysis of the limit equilibrium method it is assumed that

- the slope is very wide in the direction normal to the cross-section (slice).
- the slope is infinite (the thickness of the unstable moving material is small as compared to the height of the slope).

On the basis of the first assumption, only stresses on the slope that act in the plane of the cross-section (slice) are considered. According to the second assumption, it is assumed that the stresses on the two vertical faces of the slice are equal and exactly balance each other. The tangential forces (τ_l and τ_r) and the lateral forces (σ_l and σ_r) acting on the two vertical faces AC and BD of the slice cancel each other. Therefore the effective normal force (*N*) and the shearing resistance (*T*) on face CD of the slice only enters into the equilibrium when slope is on the verge of avalanche.

For a uniform slope of infinite extent

$$\sigma_l = \sigma_r \text{ and } \tau_l = \tau_r$$

For a slope surface parallel to the failure plain therefore ($\beta = \phi$), the slope is in equilibrium and:

$$\Sigma H = 0 \qquad T = W \sin \phi \qquad \text{--- (1)}$$

$$\Sigma V = 0 \qquad N = W \cos \phi \qquad \text{--- (2)}$$

From equation (1) and (2) the relation between *T* and *N* is therefore

$$\frac{T}{N} = \frac{W \sin \phi}{W \cos \phi}$$

$$\boxed{T = N \tan \phi} \qquad \text{--- (3)}$$

According to the Mohr-Coulomb theory, the shear strength of a soil or sediment is given by:

$$\tau = C + \sigma \tan \phi$$

or for a cohesionless sediment where C= 0

$$\tau = \sigma \tan \phi \qquad \text{--- (4)}$$

The angle of avalanche is a maximum stable slope angle at which full shear resistance is mobilised and avalanching begins. The inclination of a maximum stable slope should be equal to the angle of internal friction when full shear strength is mobilised and sliding commences (Lambe & Whitman 1979 p 192, 193; Evesque *et al.* 1993). Therefore from equation 4 the maximum shearing resistance for the slice to be on the verge of avalanche is

$$T_m = N \tan \phi \qquad \text{--- (5)}$$

Where ϕ = angle of avalanche, T_m = maximum or peak shearing resistance on the failure plane, *N* = effective normal stress on the failure plane

During an avalanche the internal friction between the particles is either zero if the sediment moves as a suspended load or minimal if the sediment moves as a bed load or a mass. The avalanching begins to cease when internal friction between the particles begins to develop. The inclination of the slope once avalanching has ceased is known as the angle of repose (θ). The angle of repose for sand and gravel is about equal to the angle of internal friction for the loose state (Lambe & Whitman 1979 p 193). Therefore from equation 4 the shearing resistance of loose cohesionless sediment or its residual shearing resistance is:

$$T_r = N \tan \phi \qquad \text{--- (6)}$$

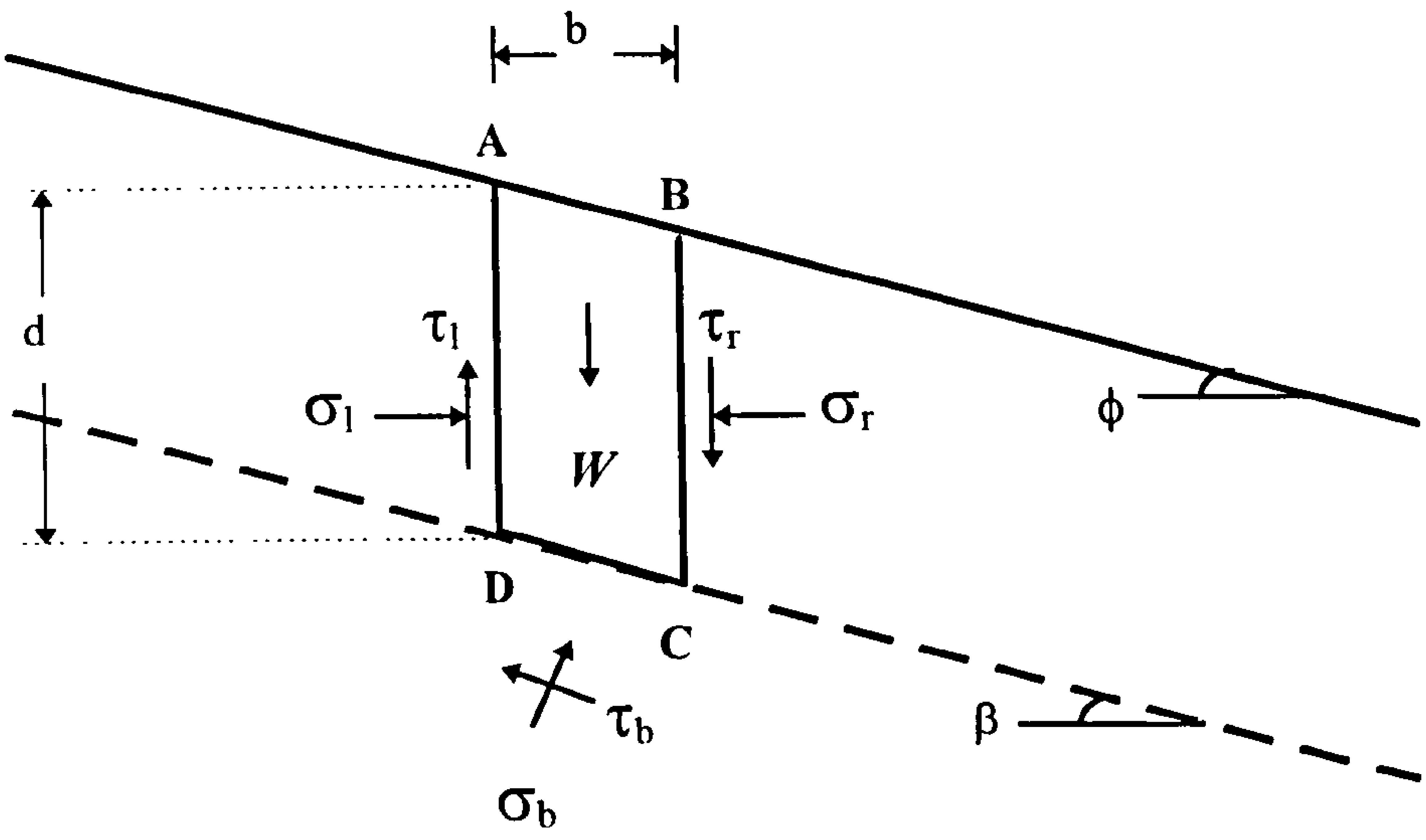
Where T_r = residual shearing strength or resistance on the failed plane, N = effective normal stress on the failed plane, θ = angle of repose (inclination of the slope when avalanching has ceased).

The factor of safety of a slope against sliding is the ratio of peak shear strength to the residual shear strength (Terzaghi & Peek 1948; Lambe & Whitman 1979; Craig1992 McCarthy 1993). Therefore from equations 5 and equation 6:

$$\text{Factor of Safety} = \frac{\text{Peak shear strength}}{\text{Residual shear strength}}$$

$$\text{Factor of Safety} = \frac{T_m}{T_r} = \frac{N \tan \phi}{N \tan \theta}$$

$$\therefore \quad \boxed{\text{Factor of Safety} = \frac{\tan \phi}{\tan \theta}}$$



For a uniform slope of infinite extent

$$\sigma_l = \sigma_r \text{ and } \tau_l = \tau_r$$

For slope surface parallel to the failure plain $\beta = \phi$

Stresses on plane **CD** of the slice (i) and equilibrium of free body (ii)

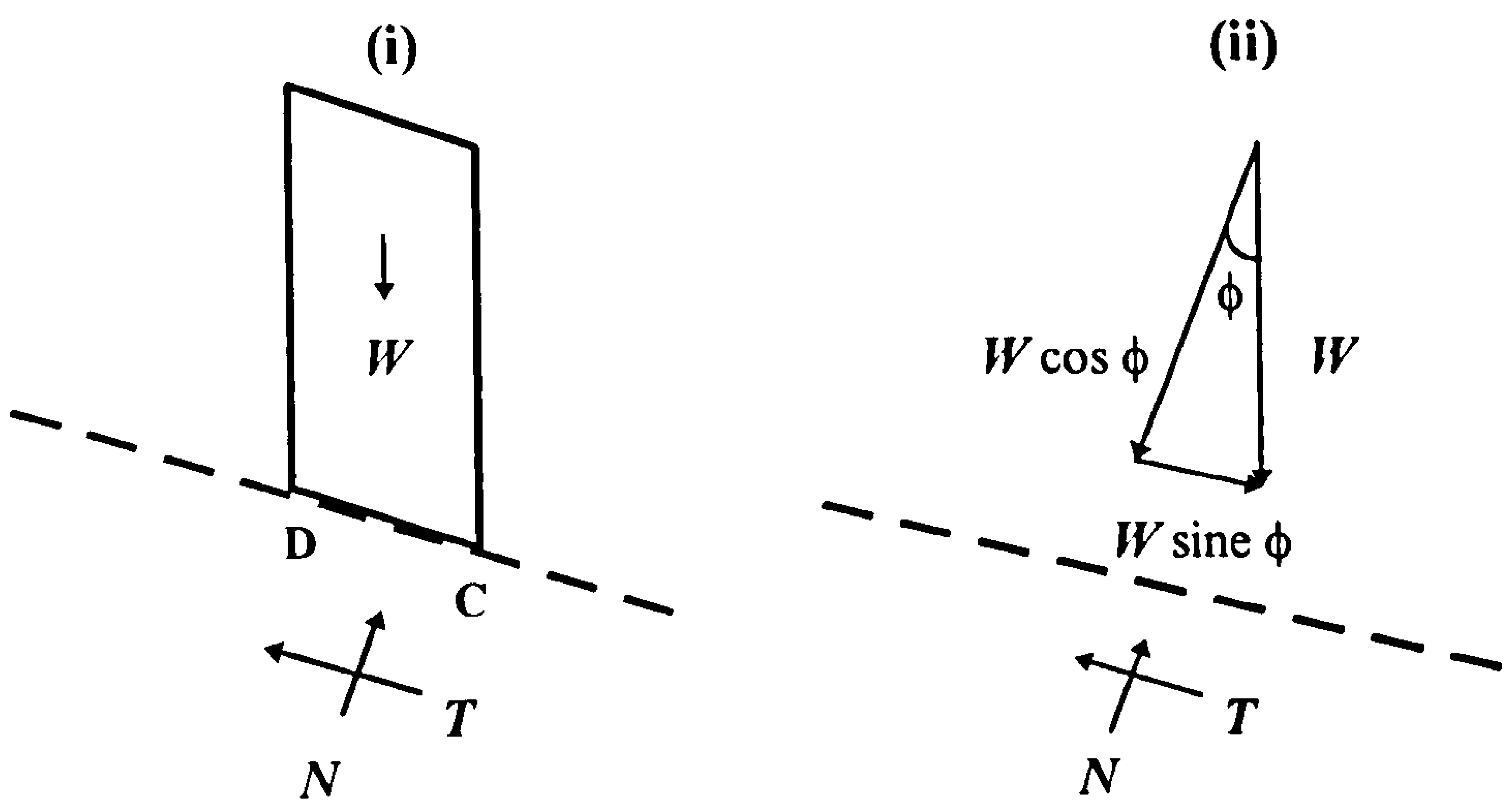


Figure V Free body diagram of the slice. τ_l and τ_r are tangential stresses and σ_l and σ_r are lateral stresses on the slice. When the slope is on the verge of avalanche, $\sigma_b = N$ (maximum effective normal stress on assumed failure plane) and $\tau_b = T$ (maximum shearing resistance along assumed failure plane). W = weight of soil or sediment. β = angle of assumed plane of sliding. ϕ = angle of slope at avalanching (angle of avalanche). (Lambe & Whitman 1979; McCarthy 1993)

APPENDIX. III

Appendix III: Table 1.1

M. edulis byssus thread production in *Sand* (63 μm to 500 μm). Replicate dish 1. Attached byssus complexes: I to V are the complexes produced by and attached to each of the five individual animals in the dish. Released byssus complexes: I to III are the three released complexes in the dish.

Observations.	Attached Byssus Complexes					Released Byssus Complexes		
	I	II	III	IV	V	I	II	III
Number of Byssus Threads:								
a) attached to its own Shell.	0	0	2	7	2			
b) attached to other Animals shells.	8	11	6	9	17			
c) total threads attached to shells.	8	11	8	16	19	3	1	6
d) attached to Grains.	0	0	0	0	0	0	0	0
e) Unattached or Broken.	0	4	3	5	8	7	6	5
Total number of byssus threads.	8	15	11	21	27	10	7	11
Number of Grains attached to threads.	0	0	0	0	0	0	0	0

Appendix III: Table 1.2

M. edulis byssus thread production in *Sand* (63 μm to 500 μm) Replicate dish 2 Attached byssus complexes: I to V are the complexes produced by and attached to each of the five individual animals in the dish Released byssus complexes: I to II are the two released complexes in the dish.

Observations.	**Attached Byssus Complexes**					**Released Byssus Complexes**	
	I	**II**	**III**	**IV**	**V**	**I**	**II**
Number of Byssus Threads a) attached to its own Shell.	2	6	0	0	0	10	9
b) attached to other Animals shells.	0	2	2	2	10		
c) total threads attached to shells.	2	8	2	2	10		
d) attached to Grains.	0	0	0	0	0	0	0
e) Unattached or Broken.	2	3	0	0	6	18	17
Total number of byssus threads.	4	11	2	2	22	28	26
Number of Grains attached to threads.	0	0	0	0	0	0	0

Appendix III: Table 1.3

M. edulis byssus thread production in *Sand* (63 μm to 500 μm). Replicate dish 3. Attached byssus complexes: I to V are the complexes produced by and attached to each of the five individual animals in the dish. Released byssus complexes: I to III are the three released complexes in the dish.

Observations.	**Attached Byssus Complexes**					**Released Byssus Complexes**		
	I	**II**	**III**	**IV**	**V**	**I**	**II**	**III**
Number of Byssus Threads a) attached to its own Shell.	0	0	0	0	2	8	5	6
b) attached to other Animals shells.	5	4	2	8	4			
c) total threads attached to shells.	5	4	2	8	6			
d) attached to Grains.	0	0	0	0	0	0	0	0
e) Unattached or Broken.	2	3	0	3	2	3	15	3
Total number of byssus threads.	7	7	2	11	8	11	20	9
Number of Grains attached to threads.	0	0	0	0	0	0	0	0

Appendix III: Table 1.4

M. edulis byssus thread production in *Sand gravel mix* (sand & gravel mixed in 1:1 ratio). Replicate dish 1. Attached byssus complexes: I to V are the complexes produced by and attached to each of the five individual animals in the dish. Released byssus complexes: I to IV are the four released complexes in the dish.

Observations.	Attached Byssus Complexes					Released Byssus Complexes			
	I	II	III	IV	V	I	II	III	IV
Number of Byssus Threads a) attached to its own Shell.	0	2	4	0	0	4	0	0	0
b) attached to other Animals shells.	3	0	7	0	0				
c) total threads attached to shells.	3	2	11	0	0				
d) attached to Grains.	5	4	10	5	1	3	20	5	10
e) attached to Glass.	0	0	0	13	10	0	0	0	0
f) Unattached or Broken.	4	1	0	2	1	3	3	4	7
Total number of byssus threads.	12	7	21	20	12	10	23	9	17
Number of Grains attached to threads.	5	3	7	5	1	3	20	5	10

Appendix III: Table 1.5

M. edulis byssus thread production in *Sand gravel mix* (sand & gravel mixed in 1:1 ratio). Replicate dish 2. Attached byssus complexes: I to V are the complexes produced by and attached to each of the five individual animals in the dish. Released byssus complexes: I to II are the two released complexes in the dish.

Observations.	**Attached Byssus Complexes**					**Released Byssus Complexes**	
	I	**II**	**III**	**IV**	**V**	**I**	**II**
Number of Byssus Threads a) attached to its own Shell.	0	0	0	0	0	7	0
b) attached to other Animals shells.	5	13	9	4	9		
c) total threads attached to shells.	5	13	9	4	9		
c) attached to Grains.	6	2	11	4	9	6	9
d) Unattached or Broken.	0	5	2	0	4	0	0
Total number of byssus threads.	11	20	22	8	22	13	9
Number of Grains attached to threads.	3 ▼	1 ▼	6	4	6	6	9

▼ Grain shared by attached complexes.

Appendix III: Table 1.6

M. edulis byssus thread production in *Sand gravel mix* (sand & gravel mixed in 1:1 ratio) Replicate dish 3. Attached byssus complexes: I to V are the complexes produced by and attached to each of the five individual animals in the dish. Released byssus complexes: I to IV are the four released complexes in the dish.

Observations.	**Attached Byssus Complexes**					**Released Byssus Complexes**			
	I	**II**	**III**	**IV**	**V**	**I**	**II**	**III**	**IV**
Number of Byssus Threads a) attached to its own Shell.	0	0	0	0	0	3	4	0	8
b) attached to other Animals shells.	0	5	25	7	11				
c) total threads attached to shells.	0	5	25	7	11				
d) attached to Grains.	3	0	2	3	2	7	3	8	10
e) Unattached or Broken.	0	1	0	1	2	0	9	0	0
Total number of byssus threads.	3	6	27	11	15	10	16	8	18
Number of Grains attached to threads.	3	0	1	3	2	7	3	8	10

Appendix III: Table 1.7

M. edulis byssus thread production in *Gravel* (4 mm to 8 mm). Replicate dish 1. Attached byssus complexes: I to V are the complexes produced by and attached to each of the five individual animals in the dish. Released byssus complexes: I to III are the three released complexes in the dish.

Observations.	**Attached Byssus Complexes**					**Released Byssus Complexes**		
	I	**II**	**III**	**IV**	**V**	**I**	**II**	**III**
Number of Byssus Threads								
a) attached to its own Shell.	0	4	0	0	0	0	0	0
b) attached to other Animals shells.	0	4	0	4	2			
c) total threads attached to shells.	0	8	0	4	2			
d) attached to Grains.	27	8	0	14	2	36	10	3
e) Unattached or Broken.	8	4	0	8	2	4	2	8
Total number of byssus threads.	35	20	0	26	6	40	12	11
Number of Grains attached to threads.	21 ▼	8	0	12 ▼	2	36	10	3

▼ Grain shared by attached complexes only.
Note: Animal III did not produce threads.

Appendix III: Table 1.8

M. edulis byssus thread production in *Gravel* (4 mm to 8 mm). Replicate dish 2. Attached byssus complexes: I to V are the complexes produced by and attached to each of the five individual animals in the dish. Released byssus complexes: I to VI are the six released complexes in the dish.

Observations.	**Attached Byssus Complexes**					**Released Byssus Complexes**					
	I	**II**	**III**	**IV**	**V**	**I**	**II**	**III**	**IV**	**V**	**VI**
Number of Byssus Threads: a) attached to its own shell.	0	0	0	0	0	0	0	0	0	0	0
b) attached to other Animals shells.	0	0	0	0	3						
c) total threads attached to shells.	0	0	0	0	3						
d) attached to Grains.	6	23	1	1	16	10	14	13	12	21	14
e) Unattached or Broken.	1	2	1	0	9	18	4	1	9	3	4
Total number of byssus threads.	7	25	2	1	25	28	18	14	21	24	18
Number of Grains attached to threads.	4 ■	20 ■	1	1	16 ■	9 ■	11 ■	8	10	18 ■	14 ■

■ Grain shared by attached complex and released complex.

Apendix III: Table 1.9

M. edulis byssus thread production in *Gravel* (4 mm to 8 mm). Replicate dish 3. Attached byssus complexes: I to V are the complexes produced by and attached to each of the five individual animals in the dish. Released byssus complexes: I to V are the five released complexes in the dish.

Observations.	**Attached Byssus Complexes**					**Released Byssus Complexes**				
	I	**II**	**III**	**IV**	**V**	**I**	**II**	**III**	**IV**	**V**
Number of Byssus Threads:										
a) attached to its own shell.	0	0	0	0	0					
b) attached to other Animals shells.	0	2	0	0	0	0	6	9	1	2
c) total threads attached to shells.	0	2	0	0	0					
d) attached to Grains.	10	6	35	6	0	15	20	16	10	5
e) Unattached or Broken.	4	7	8	1	5	2	8	0	3	3
Total number of byssus threads.	14	15	43	7	5	17	34	25	14	10
Number of Grains attached to threads.	10 ▼	5 ▼	27	4	0	13	20	7	10	5

▼ Grain shared by attached complexes only.

Appendix III: Table 2.1

One-way analyses for the differences between the replicate dishes. Total twelve one way analyses are presented in the table: (a) four 1×3 one way analyses on *sand*; (b) four 1×3 one-way analyses on *sand/gravel mix*; (c) four 1×3 one-way analyses on *gravel*. One 1×3 analysis for each of the attachment categories. Each cell in these analyses contained 5 observations. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

(a) Analysis of variance on replicate dishes in *sand*.

(I) 1×3 one-way analysis on replicates for threads attached to animals own shell.

Source	DF	SS	MS	F ratio	Probability	Significance
Replicate dishes	2	8.40	4.20	0.797	0.473	ns
Residual	12	63.20	5.27			
Total	14	71.60				

(II) 1×3 one-way analysis on replicates for byssus threads attached to other animals.

Source	DF	SS	MS	F ratio	Probability	Significance
Replicate dishes	2	137.2	68.6	5.444	0.021	*
Residual	12	150.8	12.6			
Total	14	288.0				

(III) 1×3 one-way analysis on replicate for byssus threads attached to grains.

Note :- None of the threads attached to sand grains.

(IV) 1×3 one-way analysis on replicates for byssus threads unattached.

Source	DF	SS	MS	F ratio	Probability	Significance
Replicate dishes	2	12.13	6.07	1.124	0.357	ns
Residual	12	64.80	5.40			
Total	14	76.93				

(b) Analyses of variance on replicate dishes in *sand/gravel mix*.

(I) 1×3 one-way analysis on replicates for threads attached to animals own shell.

Source	DF	SS	MS	F ratio	Probability	Significance
Replicate dishes	2	4.80	2.40	2.243	0.148	ns
Residual	12	12.80	1.07			
Total	14	17.60				

(II) 1×3 one-way analysis on replicates for byssus threads attached to other animals.

Source	DF	SS	MS	F ratio	Probability	Significance
Replicate dishes	2	160.5	80.3	2.147	0.160	ns
Residual	12	449.2	37.4			
Total	14	609.7				

(III) 1×3 one-way analysis on replicates for byssus threads attached to grains.

Source	DF	SS	MS	F ratio	Probability	Significance
Replicate dishes	2	50.53	25.27	2.998	0.088	ns
Residual	12	101.20	8.43			
Total	14	151.73				

(IV) 1×3 one-way analysis on replicates for byssus threads unattached.

Source	DF	SS	MS	F ratio	Probability	Significance
Replicate dishes	2	4.93	2.47	0.905	0.431	ns
Residual	12	32.80	2.73			
Total	14	37.73				

(c) Analysis of variance on replicate dishes in *gravel*.

(I) 1×3 one-way analysis on replicates for threads attached to animals own shell.

Source	DF	SS	MS	F ratio	Probability	Significance
Replicate dishes	2	2.13	1.07	1.000	0.397	ns
Residual	12	12.80	1.07			
Total	14	14.93				

(II) 1×3 one-way analysis on replicates for byssus threads attached to other animals.

Source	DF	SS	MS	F ratio	Probability	Significance
Replicate dishes	2	7.60	3.80	1.727	0.219	ns
Residual	12	26.40	2.20			
Total	14	34.00				

(III) 1×3 one-way analysis on replicates for byssus threads attached to grains.

Source	DF	SS	MS	F ratio	Probability	Significance
Replicate dishes	2	10	5	0.038	0.963	ns
Residual	12	1601	133			
Total	14	1611				

(IV) 1×3 one-way analysis on replicates for byssus threads unattached.

Source	DF	SS	MS	F ratio	Probability	Significance
Replicate dishes	2	15.6	7.8	0.696	0.517	ns
Residual	12	134.4	11.2			
Total	14	150.0				

Appendix III: Table 2.2

One-way analyses for the differences between the attachment categories (number of byssus threads attached to animals own shells, number of byssus threads attached to other animal's shells, number of byssus threads attached to grains, number of byssus threads unattached) in the three sediment types. Three different analyses are presented in the table: (a) attachment categories in *sand*; (b) attachment categories in *sand/gravel mix*; (c) attachment categories in *gravel*. Each sets of data were analysed by a 1×4 one-way analysis of variance. Each cell in these analyses contained 60 observations, 15 from each of the attachment categories. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

(a) 1×4 one-way analysis on attachment categories in *sand*.

Source	DF	SS	MS	F ratio	Probability	Significance
Attachment categories	3	296.40	98.80	12.67	P<0.0001	***
Residual	56	436.53	7.80			
Total	59	732.93				

(b) 1×4 one-way analysis on attachment categories in *sand/gravel mix*.

Source	DF	SS	MS	F ratio	Probability	Significance
Attachment categories	3	349.9	116.6	7.986	P<0.0001	***
Residual	56	816.8	14.6			
Total	59	1166.7				

(c) 1×4 one-way analysis on attachment categories in *gravel*.

Source	DF	SS	MS	F ratio	Probability	Significance
Attachment categories	3	945.1	315.0	9.752	P<0.0001	***
Residual	56	1810.3	32.3			
Total	59	2755.4				

Appendix III: Table 2.3

One-way analyses of variance comparing attachment categories (number of byssus threads attached to animals own shells, number of byssus threads attached to other animals shells, number of byssus threads attached to grains, number of byssus threads unattached) in the three sediment types (sand, sand/gravel mix, gravel). Fifteen observations per cell (five from each of the replicate dish). Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

(a) Number of threads attached to animals own shell

(I) 1×3 one-way analysis on *sand*, *sand/gravel mix* and *gravel*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	2	11.51	5.76	2.322	0.111	ns
Residual	42	104.13	2.48			
Total	44	115.64				

(II) 1×2 one-way analysis on *sand* and *sand/gravel mix*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	7.50	7.50	2.351	0.136	ns
Residual	28	89.20	3.19			
Total	29	96.70				

(III) 1×2 one-way analysis on *sand* and *gravel*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	9.63	9.63	3.117	0.088	ns
Residual	28	86.53	3.09			
Total	29	96.17				

(IV) 1×2 one-way analysis on *sand/gravel mix* and *gravel*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	0.13	0.13	0.112	0.737	ns
Residual	28	32.53	1.16			
Total	29	32.67				

(b) Number of threads attached to other animals shells

(I) 1×3 one-way analysis on *sand*, *sand/gravel mix* and *gravel*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	2	279.5	139.8	6.297	0.004	***
Residual	42	931.7	22.2			
Total	44	1211.2				

(II) 1×2 one-way analysis on *sand* and *sand/gravel mix*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	2.1	2.1	0.065	0.798	ns
Residual	28	897.7	32.1			
Total	29	899.9				

(III) 1×2 one-way analysis on *sand* and *gravel*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	187.5	187.5	16.30	P<0.0001	***
Residual	28	322.0	11.5			
Total	29	509.5				

(IV) 1×2 one-way analysis on *sand/gravel mix* and *gravel*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	229.6	229.6	9.983	0.004	***
Residual	28	643.7	23.0			
Total	29	873.4				

(c) Number of threads attached to sediment (grains)

(I) 1×3 one-way analysis on *sand, sand/gravel mix* and *gravel.*

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	2	805.7	402.9	9.593	P<0.0001	***
Residual	42	1763.1	42.0			
Total	44	2568.8				

(II) 1×2 one-way analysis on *sand* and *sand/gravel mix.*

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	149.63	149.63	27.61	P<0.0001	***
Residual	28	151.73	5.42			
Total	29	301.37				

(III) 1×2 one-way analysis on *sand* and *gravel.*

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	800.8	800.8	13.92	0.001	**
Residual	28	1611.3	57.5			
Total	29	2412.2				

(IV) 1×2 one-way analysis on *sand/gravel mix* and *gravel.*

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	258.1	258.1	4.097	0.053	ns
Residual	28	1763.1	63.0			
Total	29	2021.2				

(d) Number of byssus threads unattached

(I) 1×3 one-way analysis on *sand*, *sand/gravel mix* and *gravel*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	2	45.64	22.82	3.622	0.035	*
Residual	42	264.67	6.30			
Total	44	310.31				

(II) 1×2 one-way analysis on *sand* and *sand/gravel mix*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	10.80	10.80	2.634	0.116	ns
Residual	28	114.67	4.10			
Total	29	125.47				

(III) 1×2 one-way analysis on *sand* and *gravel*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	12.03	12.03	1.485	0.233	ns
Residual	28	226.93	8.10			
Total	29	238.97				

(IV) 1×2 one-way analysis on *sand/gravel mix* and *gravel*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	45.63	45.63	6.810	0.014	*
Residual	28	187.73	6.70			
Total	29	233.37				

Appendix III: Table 3

One-way analyses of variance comparing number of grains (sediment) attached to byssus threads in the three sediment types. Fifteen observations per cell five from each of the replicate dish. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

(I) 1×3 one way analysis on *sand*, *sand/gravel mix* and *gravel*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	2	582.7	291.4	10.96	P<0.0001	***
Residual	42	1116.3	26.6			
Total	44	1699.0				

(II) 1×2 one way analysis on *sand* and *sand/gravel mix*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	83.33	83.33	36.84	P<0.0001	***
Residual	28	63.33	2.26			
Total	29	146.67				

(III) 1×2 one way analysis on *sand* and *gravel*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	572.0	572.0	15.21	0.001	**
Residual	28	1052.9	37.6			
Total	29	1625.0				

(IV) 1×2 one way analysis on *sand/gravel mix* and *gravel*.

Source	DF	SS	MS	F ratio	Probability	Significance
Sediment types	1	218.7	218.7	5.481	0.027	*
Residual	28	1116.3	39.9			
Total	29	1335.0				

Appendix III: Table 4.1

One-way analyses of variance testing differences between the attached complexes and released complexes. Number of threads and number of grains in attached and released complexes were compared by thirty-six 1×2 one-way analyses. Probability: 0.05>P>0.01*; 0.01>P>0.001**; P<0.001***. ns= not significant.

(1.1) Comparison of attached & released complexes in replicate dish 1 of *Sand.*

(I) 1×2 one-way analysis of on threads attached to shells.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	154.1	154.1	8.42I	0.027	*
Residual	6	109.9	18.3			
Total	7	264.0				

(II) 1×2 one-way analysis of on threads attached to grains.
Note: None of the byssus thread were attached to sand grains.

(III) 1×2 one-way analysis of on threads unattached.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	7.50	7.50	1.250	0.306	ns
Residual	6	36.00	6.00			
Total	7	43.50				

(IV) 1×2 one-way analysis of on number of grains (sediment) attached to threads.
Note: None of the byssus thread were attached to sand grains.

(1.2) Comparison of attached & released complexes in replicate dish 2 of *Sand.*
(I) 1×2 one-way analysis of on threads attached to shells.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	31.6	31.6	2.570	0.170	ns
Residual	5	61.3	12.3			
Total	6	92.9				

(II) Analysis of variance on byssus threads attached to grain.
Note: None of the byssus thread were attached to sand grains.

(III) 1×2 one-way analysis of on threads unattached.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	334.41	334.41	66.09	P<0.0001	***
Residual	5	25.30	5.06			
Total	6	359.71				

(IV) 1×2 one-way analysis of on number of grains (sediment) attached to threads.
Note: None of the byssus thread were attached to sand grains.

(1.3) Comparison of attached & released complexes in replicate dish 3 of *Sand.*

(I) 1×2 one-way analysis of on threads attached to shells.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	3.33	3.33	0.810	0.403	ns
Residual	6	24.67	4.11			
Total	7	28.00				

(II) 1×2 one-way analysis of on threads attached to grains.
Note: None of the byssus thread were attached to sand grains.

(III) 1×2 one-way analysis of on threads unattached.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	46.9	46.9	2.759	0.148	ns
Residual	6	102.0	17.0			
Total	7	148.9				

(IV) 1×2 one-way analysis of on number of grains (sediment) attached to threads.
Note: None of the byssus thread were attached to sand grains.

Appendix III: Table 4.2

(2.1) Comparison of attached & released complexes in replicate 1 of *sand/gravel mix*.

(I) 1×2 one-way analysis of on threads attached to shells.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	10.8	10.8	0.800	0.402	ns
Residual	7	94.8	13.5			
Total	8	105.6				

(II) 1×2 one-way analysis of on threads attached to grains.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	45.0	45.0	1.466	0.265	ns
Residual	7	215.0	30.7			
Total	8	260.0				

(III) 1×2 one-way analysis of on threads unattached.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	15.61	15.61	5.477	0.052	ns
Residual	7	19.95	2.85			
Total	8	35.56				

(IV) 1×2 one-way analysis of on number of grains (sediment) attached to threads.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	62.4	62.4	2.253	0.177	ns
Residual	7	193.8	27.7			
Total	8	256.2				

(2.2) Comparison of attached & released complexes in replicate 2 of *sand/gravel mix*.

(I) 1×2 one-way analysis of on threads attached to shells.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	28.9	28.9	1.889	0.228	ns
Residual	5	76.5	15.3			
Total	6	105.4				

(II) 1×2 one-way analysis of on threads attached to grains.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	1.7	1.7	0.147	0.715	ns
Residual	5	57.7	11.5			
Total	6	59.4				

(III) 1×2 one-way analysis of on threads unattached.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	6.91	6.91	1.661	0.254	ns
Residual	5	20.80	4.16			
Total	6	27.71				

(IV) 1×2 one-way analysis of on number of grains (sediment) attached to threads.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	17.50	17.50	3.889	0.106	ns
Residual	5	22.50	4.50			
Total	6	40.00				

(2.3) Comparison of attached & released complexes in replicate 3 of *sand/gravel mix*.

(I) 1×2 one-way analysis of on threads attached to shells.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	76.1	76.1	1.359	0.282	ns
Residual	7	392.0	56.0			
Total	8	468.0				

(II) 1×2 one-way analysis of on threads attached to grains.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	55.56	55.56	12.15	0.010	*
Residual	7	32.00	4.57			
Total	8	87.56				

(III) 1×2 one-way analysis of on threads unattached.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	4.67	4.67	0.514	0.496	ns
Residual	7	63.55	9.08			
Total	8	68.22				

(IV) 1×2 one-way analysis of on number of grains (sediment) attached to threads.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	60.09	60.09	12.82	0.009	**
Residual	7	32.80	4.69			
Total	8	92.89				

Appendix III: Table 4.3

(3.1) Comparison of attached & released complexes in replicate dish 1 of *gravel.*

(I) 1×2 one-way analysis of on threads attached to shells.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	14.70	14.70	1.968	0.210	ns
Residual	6	44.80	7.47			
Total	7	59.50				

(II) 1×2 one-way analysis of on threads attached to grains.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	71	71	0.394	0.554	ns
Residual	6	1077	180			
Total	7	1148				

(III) 1×2 one-way analysis of on threads unattached.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	0.1	0.1	0.009	0.918	ns
Residual	6	69.9	11.6			
Total	7	70.0				

(IV) 1×2 one-way analysis of on number of grains (sediment) attached to threads.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	112	112	0.757	0.417	ns
Residual	6	888	148			
Total	7	1000				

(3.2) Comparison of attached & released complexes in replicate dish 2 of *gravel.*

(I) 1×2 one-way analysis of on threads attached to shells.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	0.982	0.982	1.227	0.297	ns
Residual	9	7.200	0.800			
Total	10	8.182				

(II) 1×2 one-way analysis of on threads attached to grains.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	57.7	57.7	1.152	0.311	ns
Residual	9	451.2	50.1			
Total	10	508.9				

(III) 1×2 one-way analysis of on threads unattached.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	41.5	41.5	1.515	0.250	ns
Residual	9	246.7	27.4			
Total	10	288.2				

(IV) 1×2 one-way analysis of on number of grains (sediment) attached to threads.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	29.1	29.1	0.671	0.434	ns
Residual	9	390.5	43.4			
Total	10	419.6				

(3.3) Comparison of attached & released complexes in replicate dish 3 of *gravel.*

(I) 1×2 one-way analysis of on threads attached to shells.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	25.60	25.60	3.391	0.103	ns
Residual	8	60.40	7.55			
Total	9	86.00				

(II) 1×2 one-way analysis of on threads attached to grains.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	8	8	0.073	0.793	ns
Residual	8	882	110			
Total	9	890				

(III) 1×2 one-way analysis of on threads unattached.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	8.10	8.10	1.000	0.347	ns
Residual	8	64.80	8.10			
Total	9	72.90				

(IV) 1×2 one-way analysis of on number of grains (sediment) attached to threads.

Source	DF	SS	MS	F ratio	Probability	Significance
Byssus complex	1	8.1	8.1	0.111	0.748	ns
Residual	8	584.8	73.1			
Total	9	592.9				