



HR Wallingford

TIDAL TRANSPORT OF MUD/SAND MIXTURES

Laboratory tests

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CONTRACT

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ABSTRACT

An understanding of sediment transport in estuaries is important to enable greater control of processes such as siltation, dredging, and possible pollution. The bottom sediment contained in estuaries is generally a mud and sand mixture, and it is this mixture which is entrained into the water column during periods of higher flow and redeposited during slack flow conditions. This report covers laboratory tests performed on a wider range of mixed mud and sand beds. It extends previous work to include wave erosion tests and erosion tests on undisturbed samples.

Laboratory tests were carried out to investigate the consolidation of mud beds deposited with varying sand content and varying input rate. An increased percentage of sand increased the amount and rate of consolidation, resulting in higher densities. The higher input rate produced stepped density profiles, with a layer of sand at the bottom of the bed. The lower input rate produced more smooth profiles as the sand was held within the matrix.

Pore pressure measurements were taken for beds deposited at the higher input rate. During the early stages of consolidation, the effective stress did not appear to depend on density. During the later stages of consolidation, the effective stress increased with density. For a given density, the presence of sand decreased the effective stress in the bed.

Layered tests, in which a thin layer of mud/sand was deposited at the start of each day, indicated that the presence of sand increased the rate of consolidation. Layer thickness measurements showed that consolidation had not fully occurred between subsequent layers for the 0% sand test, and that water expulsion from lower layers inhibited consolidation of the overlying layers. The 20% and 55% sand tests were virtually consolidated between subsequent layers. The high density peak at each layer interface was greatest for the high sand content beds.

An erosion bell was used to obtain vertical shear strength profiles of under-consolidated mud/sand mixture beds in the top 7mm. The profiles obtained showed that shear strengths increased with both depth and sand content, with a range from 0.05Nm^{-2} to 2.0Nm^{-2} . Erosion tests in a reversing flume on blended mud/sand mixtures and natural mixtures indicated that the presence of sand increased the shear stress needed for erosion. The shear stresses were in the range 0.5Nm^{-2} to 2.2Nm^{-2} .

The characteristics of mud erosion under waves were investigated in the wave flume. Random waves of increasing significant wave heights were applied to mud beds of 0%, 20% and 40% added sand content. Immediately after the onset of the smallest waves, the density profiles of the bed during the tests became stepped, with a layer of high densities towards the bottom, and lower densities near the surface. This feature was more pronounced for the high sand content beds. Erosion occurred when a significant wave height of 0.12m was reached, when there was a substantial increase in mud concentrations throughout the water column. After 0.5 hours of this wave height, the measurements suggested that equilibrium had been reached. The erosion rates increased with decreasing sand content, from a range $5 \cdot 10^{-5}\text{kgm}^{-2}\text{s}^{-1}$ to $9 \cdot 10^{-5}\text{kgm}^{-2}\text{s}^{-1}$ (0% sand) decreasing to a range $0.5 \cdot 10^{-5}\text{kgm}^{-2}\text{s}^{-1}$ to $3 \cdot 10^{-5}\text{kgm}^{-2}\text{s}^{-1}$ (20% and 40% added sand). The bottom orbital velocity, U_{rms} , calculated for erosion in these tests (0.13ms^{-1}) compared well with the significant wave velocity, U_{sig} , measured in the field by COSEDS (Ref 4) (0.10ms^{-1} for erosion).

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1 INTRODUCTION

An understanding of sediment transport in estuaries is important to enable greater control of processes such as siltation, dredging, and possible pollution. The bottom sediment contained in estuaries is generally a mud and sand mixture, and it is this mixture which is entrained into the water column during periods of higher flow and redeposited during slack flow conditions. The characteristics of consolidation and erosion of either sand or mud have been studied separately in the laboratory by many researchers, but little work has been undertaken to assess these properties for combined mud and sand mixtures. Previous work was undertaken by HR Wallingford on the alluvial friction of sand-silt mixtures (Ref 1). This was done on a predominantly sand bed with only small amounts of riverine mud, which is appropriate to river flows above the tidal limit. This is not very representative of most estuaries, which often consist of mostly cohesive estuarine sediments with some sand. Laboratory tests on mud and sand mixtures carried out by Ockenden and Delo (Ref 2) indicated that the erosion constant, m_e , decreased even with only small (11%) percentages of sand added to a mud bed.

This report also suggested that the near surface layer of a consolidated mud and sand deposited bed was sand free and that the density of this layer increased with the percentage of sand. This report covers laboratory tests performed on a wider range of mixed mud and sand beds. It extends the previous work to include wave erosion tests and erosion tests on undisturbed samples.

The aim of this study is to increase understanding of the behaviour of mud and sand mixtures, with a view to improving the algorithms used in modelling sediment transport. At present these usually assume the sediment is comprised of either mud or sand.

The programme of work was:

i) Settling and consolidation tests on mud and sand mixtures, varying the sand content of a continuous mud and sand input, over periods of time representative of tidal slack water. Measurements of the bed thickness, density profiles and pore pressures within the beds were made as they settled and consolidated. Tests were also carried out on layered mud and sand mixture beds.

ii) Uni-directional erosion tests on mud and sand mixture beds after different times of consolidation to investigate the effect of an increasing percentage of sand on the shear strength of the bed.

iii) Wave erosion tests on mud and sand beds, investigating the erosion characteristics for a range of wave heights in a given water depth.

2 CONSOLIDATION TESTS

2.1 Objectives

The objective of the consolidation tests undertaken was to investigate the effect of an increasing percentage of sand on the deposition and subsequent consolidation of mud beds. The

input rate was varied in the tests to investigate whether a true mixture bed could be deposited under certain input conditions.

A constant mixture of mud and sand of known composition was pumped into a settling column, to simulate, as closely as possible, the deposition from the water column during typical periods of tidal slack water. Measurements of bed thicknesses and density profiles of the bed were taken, during both the input and consolidation phases.

A range of sand percentages in the input mud slurry were used so that the influence of sand amount on consolidation could be assessed. Three sets of tests were done, one series each for continuous slurry input over 2 and 4 hours, and another set of tests for regular intermittent inputs which produced layered beds. For some of the 2 hour continuous input tests pore pressure measurements were taken during the input and consolidation phases.

2.2 Description of Apparatus

The tests were run in a 2m high settling column of 92mm internal diameter. There was a port 0.5m above the base for the continuous input of the mud and sand suspension. A Harwell gamma ray transmission probe was used to measure density profiles of the bed during the tests. Pore pressure transducers were used to measure the dissipation of excess pore pressure in some of the beds, via ports situated in the lower section of the column. The consolidation test apparatus is described in detail in Appendix 1.

2.3 Continuous Input tests for mud/sand mixtures

2.3.1 Test Procedure

The mud used throughout the tests was Usk estuary mud. A size grading of this material showed that 98% of the mud was comprised of silt (less than 63 microns). To prepare the mud stock slurry, the mud was first sieved through a 200 μ m sieve to remove large particles, shells and debris which would block the input tubing, and to ensure a consistent slurry. A stock solution of 12kgm⁻³ Usk mud at 20kgm⁻³ salt was prepared and used throughout the tests with sand additions to achieve the desired percentage of sand by weight. The sand used was Kings Lynn 100 sand, with a median particle size of about 150 μ m, and 95% of material less than 200 μ m. This represented a fine sand suitable for tests.

In order to achieve a constant mixture of mud/sand slurry entering the column during the input phase the recirculating mixing tank was topped up at regular intervals, with the mud slurry and sand. This was done with 2 litres of mud slurry and the appropriate mass of sand. They were added frequently so that all of the sand could not be introduced to the column at one time, in the event of uneven mixing in the tank. During the input phase, bottle samples were taken at 30 minute intervals and analysed for mud and sand content, so that the total mass input entering the column could be calculated.

Prior to the tests the radioactive density probe was calibrated for each settling column used with saline solutions of known concentrations. The input pump was also calibrated for the setting

required for the desired input rates. The settling columns were cleaned and filled with 20kgm^{-3} saline solution to the height of the overflow outlet.

Density profiles and bed thickness readings were taken at half hour intervals during the input phase, at one hour intervals for the rest of the input day (up until about 5-7 hours after start of input), and at daily intervals thereafter (for about 4 days or until the bed had consolidated). Pore pressure measurements were taken at the same time as the density profiles for some 2 hour input tests. The visual appearance of the beds during their development was also noted.

The first series of tests carried out was for sand percentage inputs of 0 to 50% by weight, which was introduced into the columns over 2 hours with an input rate of 5.54 litres/hour. Three tests for sand contents of 0, 15, and 30% were carried out in this series which included pore pressure measurements and were tests PP1, PP2 and PP3 respectively.

The second series of tests was also carried out for sand percentages of 0 to 50%, but input over 4 hours at a rate of 2.77 litres/hour.

A summary of test names, input concentrations and input rates is shown in Table 1.

3.3.2 Results

For the 2 hour inputs, with slurry pumped into the column at twice the rate of the 4 hour inputs, the bed was of a fluffy, loose appearance during the input phase, and there appeared to be

a circulatory movement of mud in suspension. For the 4 hour input tests, this feature was much less pronounced, and the beds were more tightly packed and with a clearer surface boundary.

It was found that for higher percentages of sand in the beds the bed thickness settled down more quickly for sandy beds than for mud only beds. The initial beds created were of the order 230-280mm thick after the initial input of 2 hours or 160-230mm thick after the 4 hour input. In both sets of tests this consolidated to 80-100mm after a few days. This was more noticeable for the 4 hour input, where the maximum bed thickness at the end of the input was lowest (160mm) for the higher percentage of sand. For the higher percentages of sand the bed thickness decreased rapidly during the first 40 hours, with little subsequent change, whereas the bed with lower percentages of sand was still changing in thickness after this time (Fig 1). This indicates that the presence of sand increases the rate of consolidation in the bed. This is more obvious for the 4 hour input which allowed more consolidation during the input phase, thus keeping the sand more evenly distributed throughout the bed.

Even during the input phase, for both the 2 hour and 4 hour tests with sand, the sand appeared to have influenced the bottom of the profiles, and increased the density. This was most likely to have been due to the presence of sand at the bottom of the bed, and the increased consolidation due to the mass of sand in the bed. Figure 2 shows the development of the density profiles in test A1 (0% sand, 2 hour input) and test E1 (47% sand, 2 hour input). In test A1 the

bed density was $50-100\text{kgm}^{-3}$ during the input phase. After 48 hours the surface density was still around $50-100\text{kgm}^{-3}$, whilst the bottom had increased to around 300kgm^{-3} . In comparison, for test E1 the sand was noticeable even during the input phase, and this was shown as a step in the density profile towards the bottom of the bed. During the input phase, the bottom of the bed showed a density of around 600kgm^{-3} , which had increased to 1100kgm^{-3} after 48 hours. A step in the density profile was still evident, and indicated that the sand was falling through the bed during the 2 hour input phase. Figure 3 shows the density profiles for the corresponding 4 hour input tests, and the maximum bed densities were lower for the high percentage sand test, E2, than for the corresponding 2 hour input test. The 4 hour input test did not show as pronounced a density step near the bottom of the bed as the 4 hour test, and the density gradient suggests that the sand content was increasing towards the bottom but was still held within the mud matrix. There was little difference, however, between the mud-only beds for the 2 and 4 hour input times, with densities and bed development being similar in both cases. The bottom densities reached around 300kgm^{-3} in both tests. As time progressed, the bottom density increased for both mud and mud/sand mixtures (Figs 2,3).

For the 2 hour input tests, there was little difference in the rate of consolidation between the 47% sand test (E1) and the 0% sand test (A1). The reduction in bed thickness was approximately the same for both tests over the time period of 24-72 hours, and this is illustrated in Figure 4. However, for the corresponding 4 hour tests with 45% sand (E2) and 0% sand (A2), the rate of

consolidation was faster for the E2 test bed, and this is shown in Figure 5. For the 0% sand bed, the bed level was still dropping after 120 hours, but for the 45% sand bed the bed level had largely settled after 72 hours (Fig 5). The difference in consolidation characteristics between these beds indicates that for the 2 hour input tests, the sand is dropping through the mud matrix before the mud matrix has consolidated, leaving a compacted sandy layer and a looser mud layer above. For the corresponding 4 hour input tests, the mud matrix is settling sufficiently during the input phase to hold the sand within it, and the effect of the sand is then to increase the rate of consolidation of the entire bed.

The density range within the bed increased with an increase in sand percentage, with maximum densities at the bottom of the beds. Figure 6 shows the density profiles for the 2 hour input tests after 2, 24, and 48 hours. The densities after 2 hours ranged from 50kgm^{-3} , at the surface, to 100kgm^{-3} at the bottom, for a 0% sand bed, and 50kgm^{-3} (surface) to 800kgm^{-3} (bottom) for a 47% sand bed. Figure 7 shows the density profiles after 2, 24 and 48 hours for the 4 hour input tests. For these tests, the densities after 2 hours ranged from 50kgm^{-3} at the surface, to 150kgm^{-3} at the bottom, for a 0% sand bed, and 50kgm^{-3} (surface) to 600kgm^{-3} (bottom) for a 45% sand bed.

As time progressed for both 2 and 4 hour input tests, the slope of the density profiles increased as the sand fell through the bed and consolidation occurred. The 2 hour input tests exhibited stepped profiles for high sand inputs,

with a sudden density increase in the lower bed, but this feature was not evident for the 4 hour tests. This is shown by comparison of Figures 6 and 7, where 4 hour input tests exhibit more smoothly sloping density profiles, even for high sand percentages, but the 2 hour tests show a sharp increase in density with depth near the base for sandy beds. The stepped 2 hour input density profiles indicate that most of the sand is at the bottom of the bed, whereas the 4 hour input density profiles indicate that the sand is more evenly distributed throughout the bed. This becomes even more prominent for the higher percentage sand tests, and more pronounced with time. The development of these density profiles indicated again that for the faster rate of input, (5.54 litres/hour for 2 hours), the sand was not supported by the mud matrix and fell through, whereas for the slower rate of input, (2.77 litres/hour for 4 hours), the mud matrix had enough time to consolidate sufficiently during settling for the sand to have been largely held within the mud matrix.

For the 2 hour input tests the stepped nature of the density profile was more pronounced with high sand percentages. This may have been due to the fact that at smaller sand percentages the resulting sand-rich layer was thinner and thus not so easily picked up by the resolution of the density probe. It could also be attributed to the capacity of the bed to hold the sand within the matrix, which is exceeded at the highest percentage sand (47%) and thus sand fell through the matrix forming a sand-rich layer at the bottom of the bed (Fig 6). This is shown by the density profiles in Figure 6, where the stepped

profile is only evident for the highest sand percentage.

The cumulative mass plots for the beds, for 2 hours and 4 hours input periods respectively, are shown in Figures 8 and 9. The figures show that for the slower 4 hour input (Fig 9), the plot is more linear, indicating that the mass was more evenly spread throughout the bed. But for the faster rate of input over 2 hours, the corresponding plot is of curved nature, indicating that there was more mass in the lower part of the bed, particularly for increased percentages of sand. This supports the hypothesis for the sand sinking through the mud matrix in the 2 hour tests.

The pore pressure measurements for the 2 hour input tests were analysed to yield the effective stress against dry density plots for the 0, 15 and 30% sand tests. Effective stress is defined as the total stress minus the excess pore pressure, ie

$$\sigma' = \sigma - u$$

where

σ' = effective stress

σ = total stress

u = excess pore pressure

The total shear stress at a point in the bed is calculated from the submerged weight of material in the bed above that point.

Figure 10 shows the results of the effective stress against time and density for the 2 hour tests. For all the tests the effective stress

during the tests was between 0 and 60Nm^{-2} . However, for the 0% sand test up until 24 hours consolidation the slope of effective stress against density was nearly vertical which suggested that the effective stress was not dependent on density during this period. But after 24 hours there was a change in the profile characteristics, which became of sloped nature, which indicated that effective stress did increase with density.

Earlier work with mud only suggested that there may be a unique relationship between effective stress and density regardless of the consolidation time. However, these results with mud/sand mixtures show that this is not true here particularly in the early stages of consolidation.

For the 15 and 30% sand tests the effective stress increased with density throughout the tests and the gradient of the slope decreased with time. The highest effective stresses for the tests occurred from 4 to 24 hours and were on average $50\text{-}60\text{Nm}^{-2}$ in the high density region of the bed. These results indicate that for a bed in the later stages of consolidation (>48 hours) at a given density, the presence of the sand tends to decrease the effective stress. For example, for a dry density of 300kgm^{-3} , 72 hours consolidation, the effective stress was approximately 45Nm^{-2} for 0% sand, 35Nm^{-2} for 15% sand, and 25Nm^{-2} for 30% sand. However, these results are only based on these three tests, so further tests would be necessary to support this trend.

It is recommended that more tests are carried out in order to determine how the effective stress with density relationship changes during consolidation particularly in the first few hours, both for mud beds and for combined mud/sand beds.

Observations of the beds during the tests revealed that, for high percentage sand beds, there were visible near-vertical channels (of the order 0.25mm thick and up to 3mm long) near the top of the beds, some of which ended in small volcano-like structures at the surface. The bottom of these channels appeared to open into teardrop-shaped pockets filled with sand (Plate 1). The dome-like structures at the surface were visible over the whole bed, so it is assumed that this was not just an edge effect at the perspex column. These features were not visible on the low percentage sand beds, although there were some small gaps in the sediment mostly of a horizontal nature (of the order 0.25 to 0.5mm wide and 50mm long) during the input and early consolidation phase. The vertical channels could indicate that the sand was dropping through the mud matrix and leaving small channels which were then used for pressure release during further consolidation. Another explanation could be that the sand was accumulating into small pockets in the bed, creating pressure which was then released up through the bed, and created the vertical channels and the small dome-like structures at the surface.

Dyer (Ref 3) also reports this "piping" effect for cohesive sediment, resulting from the water being expelled through regions of highest

permeability which join together to form a series of "pipes".

2.4 Layered mud/sand consolidation tests

2.4.1 Test Procedure

A series of consolidation tests was conducted with varying amounts of sand content in which the beds were deposited intermittently over a period of 4 days and which resulted in layered mud/sand mixture beds. The muds that were used for these tests were natural muds which had been collected from the Usk and Mersey estuaries. The sand contents of the muds were 0% (Usk), 20% (Eastham, Mersey), and 55% (Runcorn, Mersey).

A suspension of 16kgm^{-3} mud and 20kgm^{-3} salt was prepared for each mud. For each mud, layers were deposited from suspension at 24 hour intervals at an input rate of 5.54 litres/hour for 0.5 hours. The layers were deposited on 4 consecutive days, and density profiles of the layered beds were taken 24 hours after each input and 7 days after the initial input. Two tests were performed on each mud type, and the development of the density profiles and cumulative mass against time was plotted. The details for the tests are shown in Table 2.

2.4.2 Results

The development of the density profile structure was analysed for the 0, 20 and 55% sand layered mud beds. Figure 11 shows the density profile development of the layered beds with time for one of each mud type. All of the profiles showed stepped density profiles corresponding to the

layering with a density peak at the bottom interface of each layer. This peak may not be solely attributed to the sand accumulation at the bottom of a layer as it may also include the intrusion of sand into the underlying layer and associated compaction. Thus the high density peak is considered more as the layer interface region.

The 55% sand mud type showed the greatest density peak in the profile structure, with densities in excess of 500kgm^{-3} in this region. The corresponding densities for the 0 and 20% sand mud types were 300 and 400kgm^{-3} respectively (Figure 11). The maximum value of the density interface region increases downward through the bed, and increases more rapidly for the higher sand content (maximum densities range from $300\text{-}350\text{kgm}^{-3}$ for the 0% sand to $500\text{-}770\text{kgm}^{-3}$ for the 55% sand). This is probably due to the increased consolidation because of the increased weight of the mud matrix with the sand, and the longer consolidation time for the lower peaks.

The rate of consolidation for the layered bed was also greatest for the 55% sand mud type and this is reflected in the bed level changes with time. After 96 hours the surface bed level was approximately 60mm for the 55% mud type, but was approximately 100mm for the 0 and 20% sand tests (Figure 11). Figure 12 shows the thicknesses of individual layers during the tests, for a 0%, 20% and 55% sand content mixture. The thickness measurements for each layer were taken 24 hours after the input of that layer and at 24 hour intervals thereafter. It can be seen that, for the 0% sand, the thickness of layer 1 (the first layer that was deposited)

is still decreasing after layer 4 has been added, which indicates that layer 1 is still consolidating for the 0% sand test. For the 55% sand test the thickness of layer 1 has reached a fairly stable level after 48 hours, which implies that this layer has nearly reached full consolidation after 48 hours. This feature is even more noticeable for later layers, where layers 1, 2 and 3 are of very different thickness for test A2, 0% sand, and the corresponding layers are of nearly the same thickness for test C1, 55% sand. This result implies that the high content sand has a major effect on the consolidation rate, which is not observed at lower sand contents in these tests. The consolidation rate is faster for layers where sand is in the bed, and this is shown to a lesser extent in test B2.

The lower layers appear to inhibit the consolidation of upper layers where sand is not present in the bed (Figure 12). This is evident in test A2 (0% sand), where the consolidation of each layer is not complete before the addition of the next layer. The result of this is to increase the thickness of the top layer because water expelled from the lower layers has to pass through this layer. This feature is not so evident in tests B2 (20% sand) and test C1 (55% sand) as consolidation is more nearly complete before the addition of the next layer (Figure 12). Also the thickness of the layers in test C2 (55% sand) are much lower with a value of approximately 20mm instead of 30mm the for tests A2 (0% sand) and test B2 (20% sand). This result is due to the presence of sand in the bed because the mass of material in each layer is similar (see Table 3).

The results of the layered tests were also analysed to yield the integral mass of each 'layer' during the tests. For this analysis, the layer was defined as the region between two high density peaks which were considered as the interface region between two layers. This definition of a layer meant the integration of mass in this region allowed for the inclusion of sand infiltration into the top of the layer from the layer above and for some dropping out of sand into the layer below. The mass in each layer at each time was calculated from the density profiles taken throughout the tests. Table 3 shows the mass in each layer for all tests. Layer 1 is the first layer deposited and layer 4 the final layer. (The mass in the bottom layer of the column is underestimated because the density at the absolute bottom cannot be measured.) The table shows that, in general, for all tests, the mass remains approximately equal in each layer; there may be some mixing in the interface region but that there is no net movement of sand downward through the layers. Each layer has consolidated enough after 24 hours to support the next layer.

3 UNI-DIRECTIONAL CURRENT EROSION TESTS

3.1 Objectives

The aim of the uni-directional current erosion tests was to investigate the effect of increasing sand in the erosional properties of muddy beds. Two types of investigations were carried out; one set of tests in the long reversing flume on placed beds; and the other

tests by use of a recently developed erosion bell on deposited beds in settling columns. Values for the applied shear stress required for erosion were obtained and examined to see how the presence of sand in mud beds affected the erosion characteristics.

Both the methods involved the use of freshwater as the eroding medium, so a series of tests was run to investigate the effect of changing the overlying water. These tests are reported in Appendix 4, and indicate that the overlying suspensions do not significantly alter the erosion characteristics of the bed.

3.2 Column erosion tests

3.2.1 Description of apparatus

The apparatus used for the column erosion of deposited beds is a new technique currently being developed at HR Wallingford under a contract with ETSU. It was used on prepared mud/sand beds in the settling columns to calculate erosional shear stresses. The apparatus is shown in Figure 13.

The erosion bell consists of an inverted, curved funnel which fits inside a settling column with a small gap around the edges. This is positioned just above the sediment bed. Water is drawn down the sides of the column and up through the centre of the bell by gravitational flow or pumping. The funnel is shaped so that the water flow across the bottom of the funnel is laminar and flows radially toward the funnel centre, exerting an approximately even shear stress across the whole of the bed. Water removed through the funnel is replaced into the column

through a diffuser filled with nylon matting, to minimise the circulations in the column. An ultrasonic probe is mounted flush with the bottom of the funnel and is used to measure the distance from the bottom of the funnel to the sediment surface to within $\pm 0.5\text{mm}$.

The erosion bell is carefully lowered down the settling column over a previously deposited bed, until the bottom of the funnel is approximately 3-8mm from the bed. Care is taken not to disturb the bed in the process. The flow across the funnel head is then gradually increased until the surface material just begins to erode. A measurement of bed-funnel distance is then taken as well as a measurement of flow through the outlet pipe. The readings of the bed-funnel distance and flow are used for calculation of applied shear stress. The funnel is lowered close to the bed so that erosion occurs and the funnel-bed distance and flow are held constant until no more bed erodes. At this point the shear strength of the bed is assumed equal to the applied shear stress. Measurements of flow and funnel-bed distance are taken for shear stress calculation. This procedure is repeated until the desired thickness of bed has been eroded and appropriate measurements taken (typically 2 to 5mm). The erosion bell can then be used to measure erosion shear strength vertically down the bed, and to relate this to the density of the bed measured previously with the gamma ray density probe.

Vertical density profiles of the bed can also be calculated by measuring the suspended mud concentration in the system, which contains the bed material for each layer eroded. Measurements

of the concentration are made with a nephelometer or Paar densiometer situated in the reservoir, and are used to equate the mass of material eroded from the bed. The concentration and volume of the muddy water eroded for each layer, together with the depth (hence volume) of bed eroded, are then used to calculate the average density of the eroded bed.

3.2.2 Calculation of shear stress

The erosion bell has been tested using hot wire flush-mounted shear stress probes in a flume at the Polytechnic South West. These were used to investigate the applied shear stress exerted on a fixed bed for different funnel-bed distances and flows at different radii in the column.

A relationship between shear stress and hot wire voltage was determined by calibrating the hot wire probes in a small flume with known flows and a known pressure gradient. The shear stress exerted on the bed by the erosion bell was then measured by flush-mounting the calibrated shear stress probes in a settling column base at different radii below the erosion device for a fixed bed, no sediment.

Two different funnel heads were calibrated by the use of the shear stress probes. A number of different flow rates and funnel-bed distances were tested, with the probes positioned at 12, 19, 25 and 31mm from the funnel centre. The log of shear stress was plotted against the log of the bed-funnel distance for four different flows for each of the four radii. The results for the first funnel head are shown in Figure 14. The relationship between the shear stress and the

bed-funnel distance was found to be a log-log dependence. For a fixed bed-funnel distance, the log of the shear stress was found to have a linear relationship with the flow rate. The relationship between the shear stress, the funnel-bed distance, and the flow was found to be virtually the same for the four radii used for each funnel head. The relationships derived for each funnel head were of the form:

$$\log \tau = \alpha.Q - \beta.\log(h) + \gamma \quad (3.3)$$

τ = applied shear stress to the bed (Nm^{-2})

Q = flow (litres s^{-1})

h = funnel bed distance (mm)

α , β , γ are constants which depend on the funnel head.

The regression procedure used to obtain these equations gave values for r^2 of around 0.9 for both funnel heads for flows between 0.02 and 0.12 litres per second for head 1, and flows between 0.1 and 0.4 litres per second for funnel head 2.

3.2.3 Test procedure

A stock suspension of 11.4kgm^{-3} of Usk mud with a salt concentration of 20kgm^{-3} was used throughout the tests. A settling column with a detachable top section was filled with saline water at 20kgm^{-3} . The prepared mud slurry was continuously pumped into the settling column at a height of 0.5m for a period of 24 minutes at a rate of 2.77 litres per hour to obtain a mud bed of between 10 and 20mm thickness. Sand additions of 0, 10, 30 and 50% by weight were added to the input slurry to create beds of varying sand content. The mud slurry was kept thoroughly mixed

by a mixing pump throughout the input phase to ensure even distribution of sand. The bed was then left to consolidate for 3 hours and a vertical density profile was taken with the gamma-ray probe.

The erosion bell was then carefully introduced into the column and the erosion bell system was allowed to recirculate until the water was well mixed. The funnel head was at a distance that did not erode the bed during this process.

The erosion bell pump was then turned off and the funnel head was brought down to about 8mm from the bed. The flow was gradually increased, and the funnel head carefully lowered in millimetre steps until surface erosion of the bed started to occur. At this point a measurement of the flow and the funnel to bed distance was taken for the calculation of the shear stress at the surface.

The erosion bell was then used to erode a layer of bed, typically 2 to 4mm thick, by successively increasing the flow and decreasing the funnel to bed distance. Measurements of suspended mud concentration in the system, visual bed height and funnel to bed distance were taken every 5 minutes during this period. At the base of each eroded layer, the conditions were kept constant until the bed was no longer eroding and the total suspended mud concentration in the closed system had equilibrated to a constant level.

Measurements were taken of the flow and funnel to bed distance for the calculation of shear stress at this depth. This procedure was continued to obtain the shear stress at levels in

the bed until the bed surface was considered too uneven for the laminar flow condition required to calculate the shear stress.

The erosion bell was used with the two funnel heads 1 and 2, to obtain shear stress profiles for deposited Usk mud beds with sand contents from 0 to 50% sand. A total of 12 beds were prepared and eroded in this manner.

3.3.4 Results

The results of the erosion device shear stress measurements are shown in Figures 15a and 15b, for erosion by funnel heads 1 and 2 respectively. There is some variation in the magnitude of the measured shear stress values between tests performed with funnel head 1 and head 2. This is largely considered to be due to the fact that the tests performed with head 1 and head 2 were carried out 6 months apart, and that the Usk mud used for the tests may have changed during this time. However, the results for both tests, when considered separately, show trends on the variation of shear stress profile with added sand.

The shear stress measurements were taken down to a maximum depth of 7mm below the surface of the bed. For funnel head 1 the shear stress values measured were between about 0.1 and 0.7Nm⁻², and for funnel head 2 between about 0.4 and 2.0Nm⁻². Three tests were done on a 0% sand bed with funnel head 1 and showed a maximum range of 0.3Nm⁻³ in the measured shear stress values (Fig 15a).

In general, there was an increase in shear stress with depth for all profiles (Fig 15a and 15b). There was a tendency for the measurements to be more inaccurate towards the bottom of the profile because the bed surface was more irregular and the assumption of laminar flow required for the shear stress calculation did not hold so well. There was also a general increase in measured shear stress with increasing sand content in the bed. It must be noted that a range of shear stress is expected as the mud beds created in these tests were not necessarily homogeneous.

3.3 Reversing flume tests

3.3.1 Description of apparatus

A reversing flume, 27m long, 600mm wide with a maximum depth of 200mm was used to test mud-sand samples.

Two types of mud bed were investigated in these tests; boxed core samples from the Mersey Estuary containing different natural sand contents, and artificially mixed mud and sand beds prepared using sieved Usk mud with sand additions.

Flow was produced by the rotation of an impeller driven by a constant discharge $0.14\text{m}^3\text{s}^{-1}$ axial pump. Altering the impeller-vane pitch caused the flow velocity to increase or decrease. The vane angle was changed at a constant rate in order to produce a constant acceleration over given periods of time. Measurements were also carried out when the flow was steady. Flows from -1 to 1ms^{-1} could be produced although flows were only used in one direction for these tests.

Screens and guide vanes were placed at the entrance to provide a uniform flow. Uniform flow was confirmed by velocity profiles measured at the working section, which was 19m downstream from the entrance. The flume had a removable sample box in the working section. A false bottom allowed the sample box to be placed below the flume floor with the mud sample surface flush with the flume bed. An ultra-sonic probe was mounted above the bed in a fixed position, and was used to measure the height of the bed surface during the Mersey mud tests, and thus the depth of erosion.

3.3.2 Calculation of shear stress

Shear stresses were calculated from the velocity profiles, by fitting a semi-logarithmic curve (to at least the bottom part of each profile) to calculate the shear velocity, u_* , according to an empirical relationship:

$$u/u_* = 1/k \ln(z/z_0) \quad (3.4)$$

where

u = horizontal velocity component (ms^{-1})

u_* = shear velocity (ms^{-1})

z = distance above the bed (m)

z_0 = the intercept of the semi log profile on the height axis

k = von Karman's constant (0.4)

The bed shear stress, τ , is then

$$\tau = \rho u_*^2 \quad (3.5)$$

where

ρ is the density of the fluid (kgm^{-3}).

3.3.3 Erosion of Mersey samples

Three tests were run on a mud-sand mixtures from the Mersey estuary; one test each on three different muds, each with a different percentage of sand (Eastham 20% sand, Runcorn 55% sand and Egremont 90% sand). The mud was used directly from the container in which it was collected, moulded by hand to fit into the flume sample box and the surface smoothed. The surface of the sample was approximately 0.46m by 0.42m. A propeller current meter at a fixed height above the bed measured a reference velocity throughout the test. An ultrasonic probe mounted above the bed measured the depth of erosion.

The depth of flow (150mm) was kept constant for all experiments. The flow was accelerated at a constant rate from zero until erosion was observed visually (within 10-15 minutes). The acceleration was stopped and the flow held constant for another 15-20 minutes to assess the effects of erosion and measure a velocity profile. Velocity profiles were measured using a propeller current meter of diameter 10mm. A vertical velocity profile was plotted for each set of flow conditions. A logarithmic fit to the lower part of each velocity profile yielded, for each test, the values of the shear velocity and the corresponding value of the bed shear stress (calculated from the slope of the line fitted to the bottom of the profile). This value of shear stress may be slightly higher than the actual critical shear stress for erosion because during the time taken to stop the flume from accelerating, the velocity would have still increased a little.

The results of these tests are shown in Figure 16. The erosion test for Eastham mud (20% sand) exhibited an increase in the local bed height prior to erosion, which did not appear to have been so prominent for higher sand percentage samples. The bed level rose from 0 to about 3mm during the first 23 minutes of the test before erosion started and then the level dropped sharply, when erosion started to occur. This rise in bed level could be due to movement of a softer layer on the surface, possibly with entrainment of water.

The Egremont (90% sand) and the Eastham (20% sand) samples started to erode at a shear stress of around 0.9Nm^{-2} . This is illustrated as the applied shear stress required to bring about a significant reduction in bed level. The Egremont (90% sand) sample eroded at a slower rate (approximately 2mm over 10 minutes), at the same applied shear stress of 0.9Nm^{-2} , than the Eastham (20% sand) sample which eroded at a rate of approximately 3mm over 7 minutes. This is shown by comparison of the 90% sand and 20% sand beds in the period between 20 and 30 minutes. The rates of erosion for Egremont (90% sand) sample and the Runcorn (55% sand) sample at the end of the tests were approximately the same but the applied shear stresses were 2.24 and 1.82Nm^{-2} respectively. A comparison of the Eastham (20% sand) sample and the Runcorn (55% sand) sample at around 30 minutes, shows that the same depth of erosion had been achieved for applied shear stresses of 0.9 and 1.1Nm^{-2} respectively. These results suggest that the higher sand content bed required a higher applied shear stress to erode the bed at the same rate.

A hypothesis for the slightly increased erosion depths and rates for the lower percentage sand samples may be that the presence of the sand is to compact the bed and to increase the density. A higher shear stress may then need to be applied for erosion to occur.

It must be noted that a range of shear stress values and erosion rates is expected as the placed mud beds in these tests were not necessarily homogeneous. There will be natural differences in the mud (different organic content, pH, mineralogy etc) which result from the muds being collected from sites a long way apart. The differences in erosion shear strength and erosion rate may be attributable to any of these factors as well as the varying sand content.

3.3.4 Erosion of blended mud and sand beds

Mud and sand mixture beds were prepared by sieving high density Usk mud and stirring in fine sand to a smooth, even consistency. The mixtures prepared were 0, 25 and 50% sand by weight and had average densities of 547kgm^{-3} , 562kgm^{-3} , and 611kgm^{-3} respectively. The mud and sand pastes of different sand content were put into a tray of dimensions $0.42 \times 0.46 \times 0.05\text{m}$, which was then mounted so that it was flush with the flume bottom. Clay was moulded around the tray edge to ensure smooth flow over the test section. The prepared beds were then subjected to increasing bottom shear stress by increasing the velocity in the flume in steps. Three tests were run on the 0% sand mixture and two tests were run on each of the 25 and 50% sand mixtures. An extra test was

performed on the 50% sand bed using a jet erosion method to erode the bed because the shear stresses applied in the flume were insufficient to erode this bed.

The depth of flow was kept constant at 150mm for all the erosion tests. The flow was increased from zero in small steps until erosion was observed visually on the surface of the mud/sand bed sample. A propeller current meter was then used to obtain a vertical velocity profile at the point of erosion. A vertical velocity profile at the point of erosion was plotted for each mud/sand mixture bed eroded. Logarithmic fits to the lower part of the profiles were used to obtain the values of the bottom shear velocity as in the previous Mersey mud tests.

The results of the erosion of the blended mud/sand beds are given in Table 4. The velocity profiles for representative 0%, 25% and 50% sand tests are given in Figure 17. In general, the shear strength and velocity for erosion increased with increasing sand content. The 50% sand beds did not erode at the maximum flows and shear stresses obtainable in the reversing flume, and thus the shear strength of the beds was greater than that derived from the final velocity profile. For test 8, the shear strength for erosion was obtained by the use of a water jet erosion method.

There was however, some considerable variation on the erosional shear stresses and velocities and this was considered attributable to slight irregularities in the mud surface and localised inhomogeneities in the mud/sand mixture.

4 WAVE EROSION TESTS

4.1 Objectives

The objective of the wave erosion tests was to investigate the effect of an increasing proportion of sand on the erosional character of a mud/sand bed under waves.

Mud slurries containing percentages of 0, 20 and 40% by weight sand were placed in a wave flume and subjected to increasing wave-induced shear stresses. This was achieved by generating 3 wave conditions over the beds with increasing significant wave height for time periods of 1, 1 and 2 hours respectively. Measurements of bed level, suspended mud concentration, and density profiles were taken throughout the tests. The suspended mud concentrations were analysed to obtain erosion rates for each half hourly period during tests. The measurements of bed level, erosion rates, density profiles and mud concentrations were analysed in order to establish the effect of increasing sand in the placed bed on wave erosion characteristics.

4.2 Test procedure

A full description of the wave flume apparatus is given in Appendix 3 and there is a diagram of the apparatus in Figure A3.1.

A slurry of Harwich mud with a density of about 400kgm^{-3} mud and 20kgm^{-3} salt was used as the base mud for the tests. The mud was placed in an 8m long, 0.3m wide and 0.07m deep trough in a 23m long wave flume such that the surface of the mud was at the same level as the bottom of the flume. The mud bed was then subjected to random waves

(JONSWAP spectrum) with significant wave height 0.03, 0.06 and 0.12m, for time periods of 1, 1, and 2 hours respectively.

Bed level measurements at 0.5m intervals along the test section were taken every half hour with an ultrasonic probe.

Suspended mud concentrations above the bed were taken with a nephelometer at 0.5m horizontal and 0.05m vertical intervals, and also at several points outside the test section. The concentration measurements were used to evaluate the total mass of mud in suspension. These measurements were taken before the tests and at half-hourly intervals during the tests. From this data the erosion rate of mass entrained into the overlying water was calculated.

Density profiles in the middle of the bed were taken with a conductivity probe before the test and then every hour. These density profiles were taken in slightly different places in the bed for each profile because the probe went into the bed during the measurement and thus destroyed the bed at this point. However the measurements were all close to the middle of the flume and were taken to be representative of the middle of the bed.

For every wave condition, water level measurements were taken at 2m intervals along the flume with pressure transducers and analysed to obtain the wave parameters for the tests.

The nephelometer, conductivity probe, ultrasonic probe and pressure transducers were calibrated before the tests and the nephelometer and conductivity probe were zeroed in distilled water

prior to each set of measurements. The logging of this data was controlled by computer and a 2-dimensional vertical profiler was used to position the instruments accurately during measurement.

Three wave tests for Harwich only mud slurry were carried out in tests A1, A2, A3 respectively, using the same slurry throughout and stirring thoroughly before each test. Two tests were carried out for sand additions of both 20% (tests B1, B2) and 40% (tests C1, C2) by weight.

Some preliminary tests using the Harwell density probe with Harwich mud of different densities showed that a 600kgm^{-3} slurry was capable of supporting an additional 20% or 40% sand within the mud matrix. At this density, the sand did not fall significantly through the bed. The sand mixture was prepared using Kings Lynn 100 sand (the same as that used for the consolidation tests).

For the wave erosion tests the 360kgm^{-3} mud slurry was first mixed thoroughly and 14.4kg of sand was evenly sprinkled onto the surface of the mud and the bed stirred well again to obtain a bed of 20% sand content. The sand addition process was repeated to obtain the 40% sand bed and mixed as before. A second test was performed on each of the 20 and 40% sand beds and the bed was mixed thoroughly before each test. Density bottle samples were taken from the bed from both end and the middle to check the bed consistency and the average density for each test was noted. The average densities determined for tests were A1 (400kgm^{-3}), A2 (377kgm^{-3}), A3

(360kgm^{-3}), B1 (430kgm^{-3}), B2 (450kgm^{-3}), C1 (452kgm^{-3}), and C2 (502kgm^{-3}).

4.3 Results

Consolidation tests without waves were performed on Harwich mud beds in tests A, B and C containing sand additions of 0, 20, and 40% sand respectively, and are shown in Figure 18. The density profiles showed that the sand was largely held within the mud matrix at a density of around 600kgm^{-3} . There was a slight variation in the slope of the density profiles as more sand was added, with the density gradient increasing from virtually homogeneous for bed A to an increase of about 25kgm^{-3} per 10mm depth for bed C (40% added sand). As time progressed, the bottom density increased slightly, particularly for the higher percentage sand. The bed thickness development with time did not appear to have varied much with sand content, and tests A, B and C showed a reduction of around 10mm for the consolidation period of 4 hours. There was no evidence for sand rapidly dropping through the mud matrix during these tests and the beds placed for wave erosion tests were assumed to be mixtures of mud and sand. (The beds placed for the wave erosion tests were of densities around 400kgm^{-3} but preliminary tests showed that these densities were also sufficient to hold the sand within the mud matrix in a similar way.)

The density profiles of the beds during the wave tests are shown in Figure 19. The form of the density profiles were different in shape and character to the beds which were not subjected to wave action. A reason for the non-homogeneity of the beds at 0 hours during a test can be

attributed to mud not being fully vertically mixed during stirring, and the slight disruption of the bed surface during the introduction of overlying water into the flume prior to a test. Instrument and flume calibrations need to be done before a test whilst the mud and water are in place, and these may take from 1 to 1.5 hours. Inevitably, during this time the placed bed will have consolidated so that at time '0 hours' (the beginning of the test) the bed is not necessarily homogeneous.

The most prominent feature was the layering of the beds with sand added during the wave tests which was not so evident for the 0% sand addition beds and for the beds not subjected to wave action. The bed developed into two distinct layers even after 1 hour of low wave height for the sandy beds, the surface layer at about 200kgm^{-3} and the bottom layer at about 500kgm^{-3} . The density step between the layers was highest for the high sand tests with density increases at around 420kgm^{-3} (test C1, 40% sand), 360kgm^{-3} (test B1, 20% sand), and 170kgm^{-3} (test A3, 0% sand). These density profiles suggest that the beds had developed a fluidised less dense upper layer early on during the tests, as the layered bed structure was evident after only 1 hour. The density of the upper layer decreased by about 100kgm^{-3} during the tests which was as expected with material going into suspension during erosion by wave action. The presence of the 2 layers during the tests indicates that the upper bed may be being fluidised prior to erosion which is also supported by the decrease in density. The bed height does not appear to have dropped when erosion occurred (after 3 hours) for tests B1 and C1, but instead the bed level seems to

have risen during erosion which indicates that the bed may have been lifted and fluidised during erosion.

The bed level changes during the tests A1 and C2 are shown in Figure 20. The x-axis is the distance along the flume from the spending beach. The ultrasonic probe suffered from interference during the 'B' tests and these tests are thus not included in the results. The net bed levels seem to rise slightly during the tests and there is no net reduction in bed height as may be expected during erosion. Erosion certainly occurred during this time, shown by a rise in concentration in suspension. There seems to be a rise in bed level towards the wave paddle and a reduction towards the spending beach. A possible explanation for this may be that the bed is fluidising during the test and that no distinct drop in bed level occurs at the point of erosion, more that the bed surface is first fluidised and then the fluidised mud is entrained into the overlying water. This effect would be most pronounced towards the wave paddle where wave energy has not been dissipated and thus fluidisation and subsequent erosion is more likely to occur.

Figures 21, 22 and 23 show the development of the mud concentration in suspension for tests A3, B2 and C1 respectively. All tests show low concentrations in the upper water column until erosion started to occur when the highest wave height was applied (after time 2 hours). Before substantial erosion had occurred, at 1.5 hours, the concentration at 0.05m above the bed had risen to about 0.25kgm^{-3} for tests A3 and C1 whilst the upper layers remained low. This was

not so pronounced for test B2, but this may have been because the mud-rich lower waters were too close to the bed to have been detected by the nephelometer. This feature is evident again at 2.5 hours when the overall concentrations in the overlying waters have increased for all tests and concentrations are highest at 0.05m height. At this time of highest applied wave height, the concentrations are greatest for the bed with no added sand, with concentrations exceeding 1kgm^{-3} . Between times 1.5 hours ($H_s=0.06\text{m}$) and 2.5 hours ($H_s=0.12\text{m}$) the concentrations in the whole water column had increased for all tests and substantial erosion had occurred. It was deduced that erosion of the bed had not occurred at the applied wave heights of 0.03 and 0.06m and that a significant wave height of 0.12m was required to achieve erosion of all beds.

There was no substantial further increase in water concentrations after about 0.5 hours duration of the highest applied wave height (time 3 hours onwards) for the tests and it was considered that this was because equilibrium had been reached for this wave height. The highest water concentrations, particularly at 0.05m above the bed were obtained for the lowest sand content beds, which indicated that the presence of sand decreased the erosion rate. A possible explanation for these observations would be that the bed is first fluidised and then is eroded and mixed into the water column. The high concentrations observed at 0.05m above the bed also agree with this hypothesis because the fluidised mud would be entrained into the lower water column. The presence of sand within the mud matrix may have increased the strength of the

bed making it more resistant to fluidisation and subsequent erosion.

Figure 24 shows the increase in suspended mass during each half hour for all tests. There was little change in suspended mass and no substantial erosion until the wave height of 0.12m had been reached. At this wave height there was a rapid increase in suspended mass for all beds during the first 30 minutes of this wave height but no further increase afterwards, and some tests showed a decrease. The erosion rates calculated half-hourly during the first $H_s = 0.12\text{m}$ period (2-2.5 hours) were of an order of magnitude greater for the 0% sand tests than for the 20% and 40% added sand tests, with erosion rates of $5 \cdot 10^{-5}\text{kgm}^{-2}\text{s}^{-1}$ to $9 \cdot 10^{-5}\text{kgm}^{-2}\text{s}^{-1}$, and $0.5 \cdot 10^{-5}\text{kgm}^{-2}\text{s}^{-1}$ to $3 \cdot 10^{-5}\text{kgm}^{-2}\text{s}^{-1}$ respectively. During the period 3.5-4 hours however, there was no substantial change in the suspended mass and it was considered that equilibrium had been reached. The total masses of mud in suspension during the wave tests under increasing significant wave height are given in Table 5. There is a large increase in the total suspended mass at 2.5 hours and then the concentration levels out. This indicated that all the erodible bed material had gone into suspension and that no further erosion had occurred. The rates of erosion were of an order of magnitude higher for the mud-only beds than for the beds with added sand. This indicates that the sand inhibits erosion and reduces the erosion rate.

In comparison with these laboratory experiments, field measurements have been carried out in Marsden Bay by the COSEDS group (Ref 4).

Measurements of beam attenuation of light were taken at a height of 2m above the bed, and velocity measurements were taken 0.32m above the bed. The velocity data was analysed to calculate values of the significant wave velocity, U_{sig} . The results indicated that a value of U_{sig} exceeding 0.10ms^{-1} (at a height 0.32m above the bed) was required for erosion and suspension of sediment, which resulted in an increase in beam attenuation. This compares well with the laboratory tests for which the root mean squared bottom orbital velocity, U_{rms} , was calculated by linear wave theory. For the eroding significant wave height of 0.12m, U_{rms} was calculated to be 0.13ms^{-1} .

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. Laboratory tests were carried out to investigate the consolidation of mud beds deposited with varying sand content and varying input rate. An increased percentage of sand increased the amount and rate of consolidation, resulting in higher densities (Figs 2 to 9). The higher input rate (5.54 litres/hour over 2 hours) produced stepped density profiles, with a layer of sand at the bottom of the bed. The lower input rate (2.77 litres/hour over 4 hours) produced more smooth profiles as the sand was held within the matrix.
2. Pore pressure measurements were taken for beds deposited at the higher input rate (5.54 litres/hour over 2 hours) (Fig10). During the early stages of consolidation, the effective

stress did not appear to depend on density. During the later stages of consolidation, the effective stress increased with density. For a given density, the presence of sand decreased the effective stress in the bed.

3. Layered tests, in which a thin layer of mud/sand was deposited at the start of each day, indicated that the presence of sand increased the rate of consolidation (Figs 11 and 12). Layer thickness measurements showed that consolidation had not fully occurred between subsequent layers for the 0% sand test, and that water expulsion from lower layers inhibited consolidation of the overlying layers. The 20% and 55% sand tests were virtually consolidated between subsequent layers. The high density peak at each layer interface was greatest for the high sand content beds, due to compaction of the mud matrix.
4. An erosion bell was used to obtain vertical shear strength profiles of under-consolidated mud/sand mixture beds in the top 7mm (Fig 15). The profiles obtained showed that shear strengths increased with both depth and sand content, with a range from 0.05Nm^{-2} to 2.0Nm^{-2} .
5. Erosion tests in a reversing flume on blended mud/sand mixtures and natural mixtures indicated that the presence of sand increased the shear stress needed for erosion (Figs 16 and 17). The shear stresses were in the range 0.5Nm^{-2} to 2.2Nm^{-2} .

6. The characteristics of mud erosion under waves were investigated in the wave flume. Random waves of increasing significant wave heights of 0.03m, 0.06m and 0.12m were applied to mud beds of 0%, 20% and 40% added sand content. Immediately after the onset of the smallest waves, the density profiles of the bed during the tests became stepped, with a layer of high densities towards the bottom, and lower densities near the surface (Fig 19). This feature was more pronounced for the high sand content beds. Erosion occurred when a significant wave height of 0.12m was reached, when there was a substantial increase in mud concentrations throughout the water column (Figs 21-24). After 0.5 hours of this wave height, the measurements suggested that equilibrium had been reached. The erosion rates increased with decreasing sand content, from a range $5 \times 10^{-5} \text{kgm}^{-2}\text{s}^{-1}$ to $9 \times 10^{-5} \text{kgm}^{-2}\text{s}^{-1}$ (0% sand) decreasing to a range $0.5 \times 10^{-5} \text{kgm}^{-2}\text{s}^{-1}$ to $3 \times 10^{-5} \text{kgm}^{-2}\text{s}^{-1}$ (20% and 40% added sand). The bottom orbital velocity, U_{rms} , calculated for erosion in these tests (0.13ms^{-1}) compared well with the significant wave velocity, U_{sig} , measured in the field by COSEDS (Ref 4) (0.10ms^{-1} for erosion).

5.2 Recommendations

Previous work carried out by HR Wallingford (Ref 5) showed that the behaviour of mud and sand mixtures is dependent on locality. Many factors may affect the behaviour of the mud eg. pH, salinity, mineralogy, cation exchange capacity, density, consolidation time, sand content etc. The tests in this report were not all carried out with mud from the same location, nor necessarily with the same

chemical and physical characteristics. Therefore trends which have been identified may be due as much to some other variable as to the sand content. It is recommended that similar tests are performed on mud/sand mixtures collected from one area of an estuary where different sand contents are found. This should eliminate many of these other variables affecting the behaviour of the sediment and allow for easy comparison of results.

In order to minimise the variables which affect mud behaviour, many of the tests carried out have been with beds which have been artificially created in the laboratory environment. This has resulted in beds with two distinct bands of grain size (one mud, one sand) rather than a smooth grain size distribution. Although great care has been taken to simulate real environmental conditions, this is not always possible and it is recommended that further measurements are taken in the field in order to investigate the behaviour of mud and sand mixtures in the natural environment.

The tests described in this report have involved the measurement of mud concentration in suspension during the wave tests. It is recommended that measurements of both suspended mud and sand are made in future, both in the field and in the laboratory in experiments of this nature. A start has been made by the COSEDS group using both optical and acoustic devices in the field to measure the suspended concentrations, but the same type of development needs to be done for the measurement of mud and sand content on the estuary bottom (Ref 4).

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TABLES

TABLE 1 : Actual concentrations and input conditions for consolidation tests

TEST	MUD CONC. (kgm ⁻³)	SAND %	INPUT RATE (litres hr ⁻¹)	INPUT TIME (hours)
A1	12	0	5.54	2
B1	11.4	6	5.54	2
C1	11.4	7	5.54	2
D1	11.4	14	5.54	2
E1	11.4	50	5.54	2
PP1	11.4	0	5.54	2
PP2	11.4	15	5.54	2
PP3	11.4	30	5.54	2
A2	12	0	2.77	4
B2	11.4	4	2.77	4
C2	11.4	9	2.77	4
D2	11.4	19	2.77	4
E2	11.4	45	2.77	4

**TABLE 2 : Test details for layered bed
consolidation tests**

Test	% Sand	Time of layer input (days)	Time of density profiles (days)
A1	0	1,2,3,4	2,3,4,5,7
A2	0	1,2,3,4	2,3,4,5,7
B1	20	1,2,3,4	2,3,4,5,7
B2	20	1,2,3,4	2,3,4,5,7
C1	55	1,2,3,4	2,3,4,5
C2	55	1,2,3,4	2,3,4,5

TABLE 3 : Mass of individual layers with time for layered bed consolidation tests.

	Time (hours)			
	24	48	72	96
Test A1 (0% sand)				
Layer	Mass of layers (kgm^{-2})			
1	40.4	39.6	41.1	36.7
2		34.3	40.2	38.9
3			41.2	37.9
4				41.5
Test A2 (0% sand)				
Layer	Mass of layers (kgm^{-2})			
1	35.8	45.6	36.8	37.3
2		31.4	41.2	46.4
3			42.8	44.7
4				42.6
Test B1 (20% sand)				
Layer	Mass of layers (kgm^{-2})			
1	34.2	48.2	40.2	50.0
2		44.4	34.6	45.6
3			36.7	58.1
4				42.9

TABLE 3 (continued)

		Time (hours)			
		24	48	72	96
Test B2 (20% sand)					
Layer		Mass of layers (kgm ⁻²)			
1	39.5	41.8	36.0	40.3	
2		49.3	38.6	55.3	
3			36.4	46.1	
4				51.6	
Test C1 (55% sand)					
Layer		Mass of layers (kgm ⁻²)			
1	30.7	39.6	41.3	34.5	
2		38.5	53.1	47.8	
3			37.9	44.6	
4				36.7	
Test C2 (55% sand)					
Layer		Mass of layers (kgm ⁻²)			
1	28.3	34.4	36.1	35.5	
2		27.3	33.8	38.7	
3			48.0	39.4	
4				44.2	

TABLE 4 : Results of uni-directional erosion tests on blended mud and sand mixture beds.

% Sand	Test	Erosion Shear Strength (Nm ⁻²)	Erosion Shear velocity (ms ⁻¹)
0	1	0.3 - 0.4	0.018 - 0.021
0	2	0.7 - 1.0	0.027 - 0.032
0	3	0.9	0.030
20	4	0.3 - 0.8	0.018 - 0.028
20	5	0.5 - 0.6	0.023 - 0.025
50	6	>0.6	>0.024
50	7	>1.0	>0.032
50	8	2.0	

TABLE 5: Total mass of mud in suspension for wave erosion tests under increasing significant wave height.

Hs (m)	Time (hours)	Mass of mud in suspension (kg)						
		Test						
		A1	A2	A3	B1	B2	C1	C2
0	0	0.016	0.010	0.105	0.060		0.073	0.118
0.03	0.5	0.024	0.011		0.071		0.048	0.101
0.03	1.0	0.009	0.011		0.030	0.034	0.065	0.101
0.06	1.5	0.038	0.039	0.125	0.026	0.034	0.061	0.108
0.06	2.0	0.042	0.036	0.143	0.035	0.026	0.092	0.092
0.12	2.5	0.415	0.361	0.388	0.095	0.141	0.129	0.150
0.12	3.0	0.462	0.564	0.249	0.074	0.143	0.200	0.127
0.12	3.5	0.491	0.284	0.216	0.106	0.204	0.207	
0.12	4.0	0.336	0.167	0.087	0.158	0.250		

FIGURES

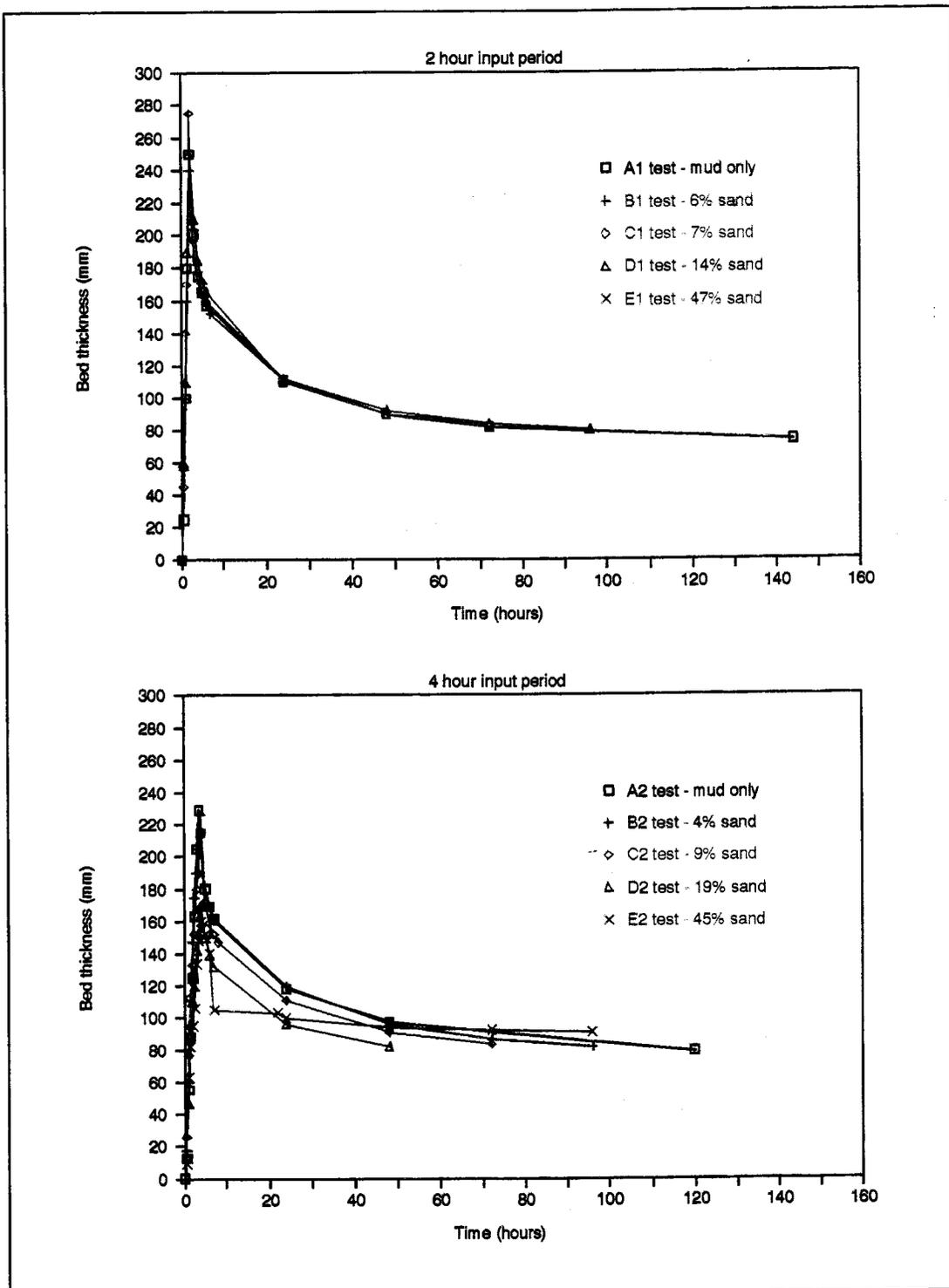


Fig 1 Comparisons of bed thickness against time for tests with 2 and 4 hour inputs

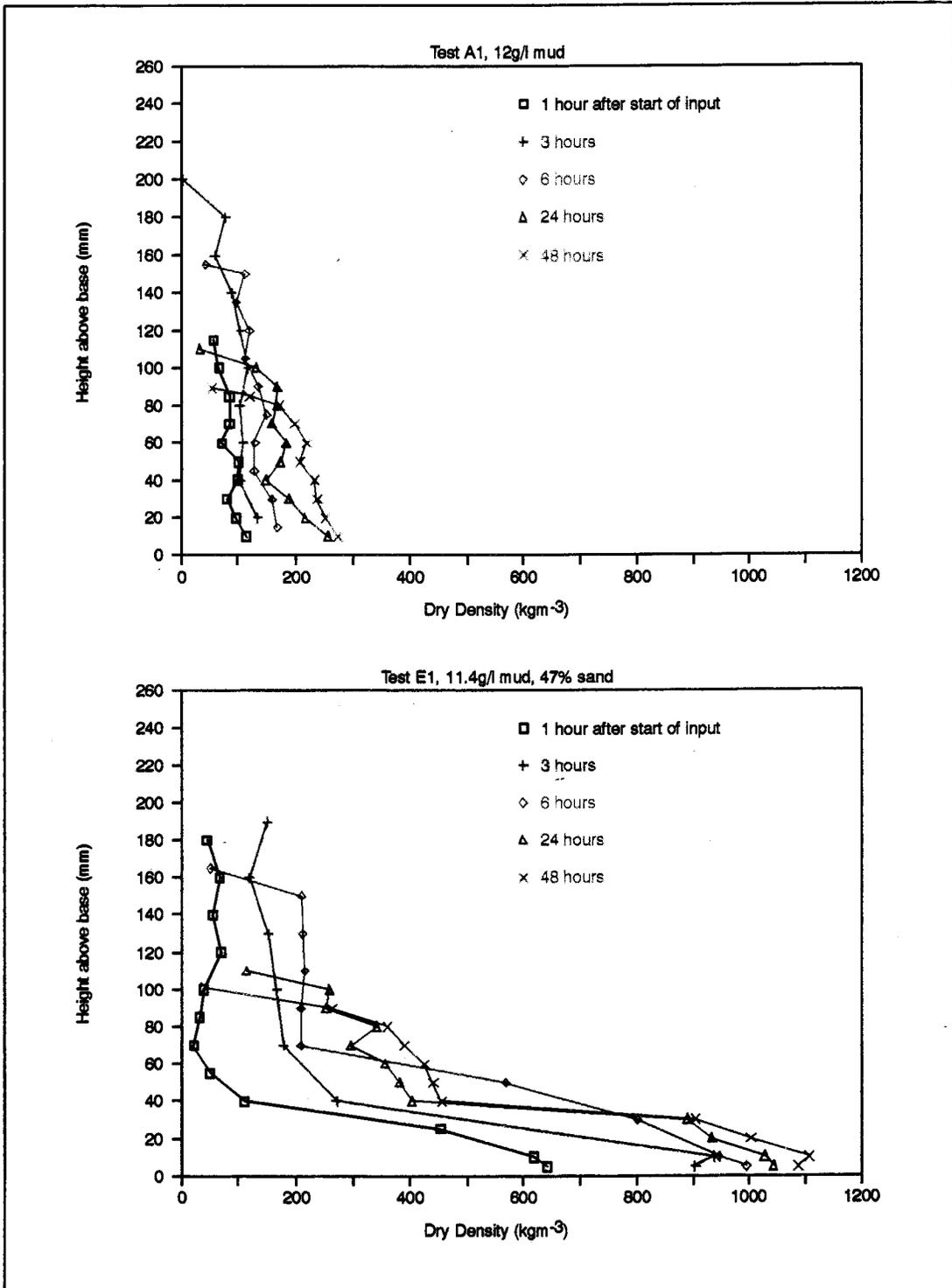


Fig 2 Density profile development test A1 (0% sand) and test E1 (47% sand), for an input of 2 hours

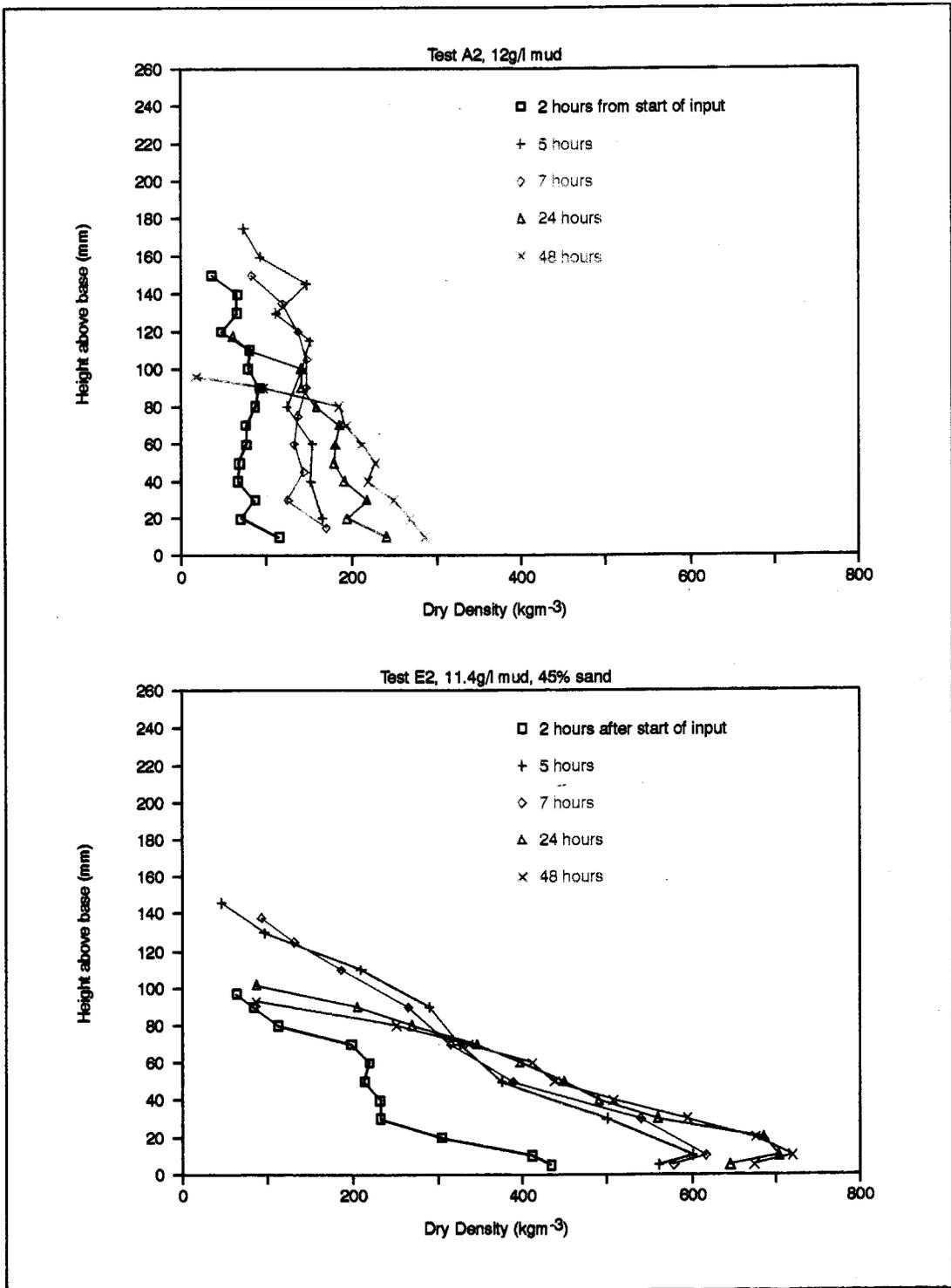


Fig 3 Density profile development test A2 (0% sand) and test E2 (45% sand), for an input of 4 hours

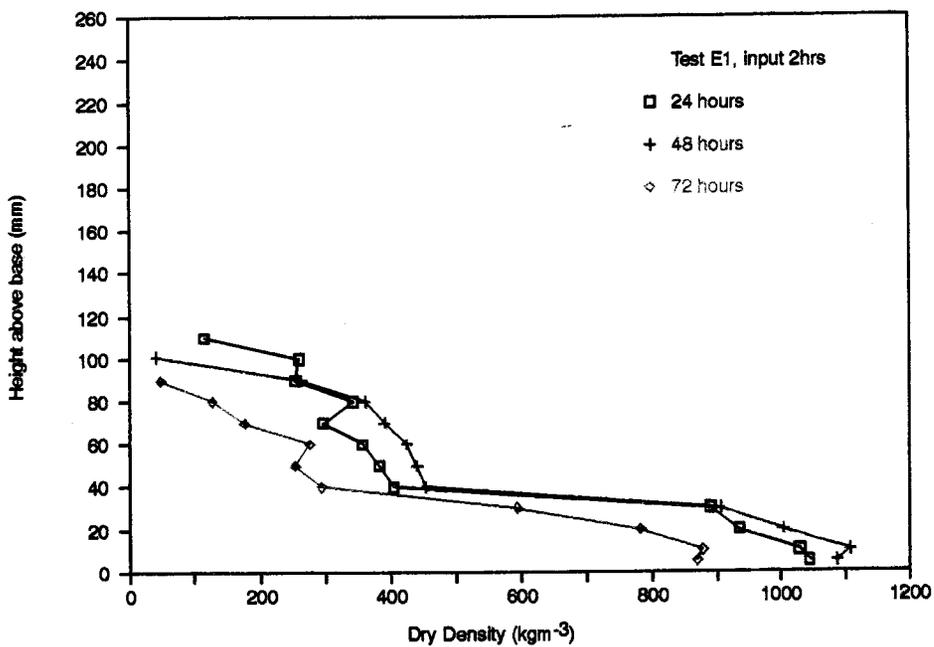
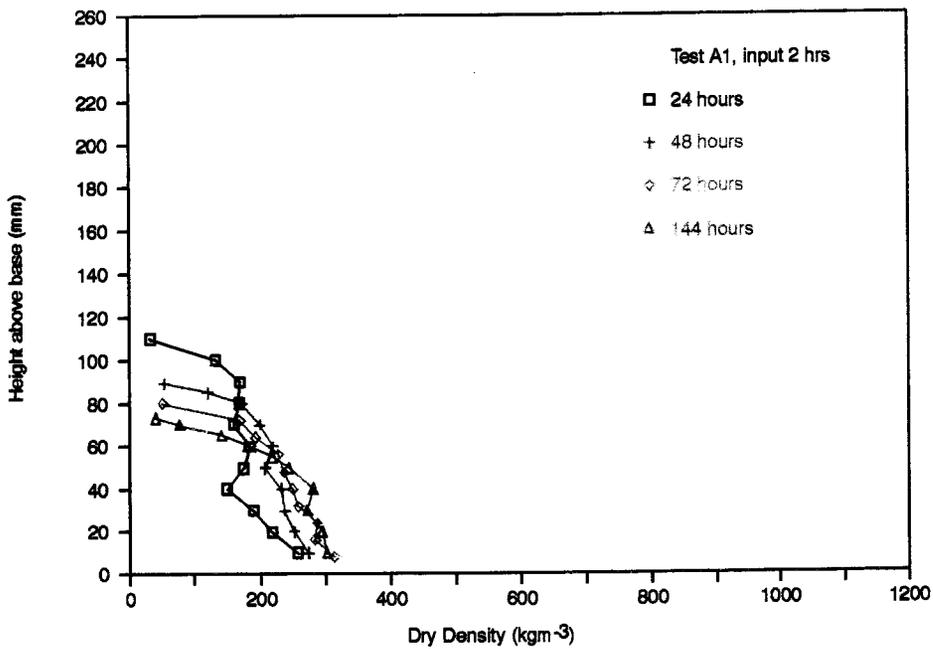


Fig 4 Comparison of consolidation rates for test A1 (0%) and E1 (47% sand) for an input of 2 hours

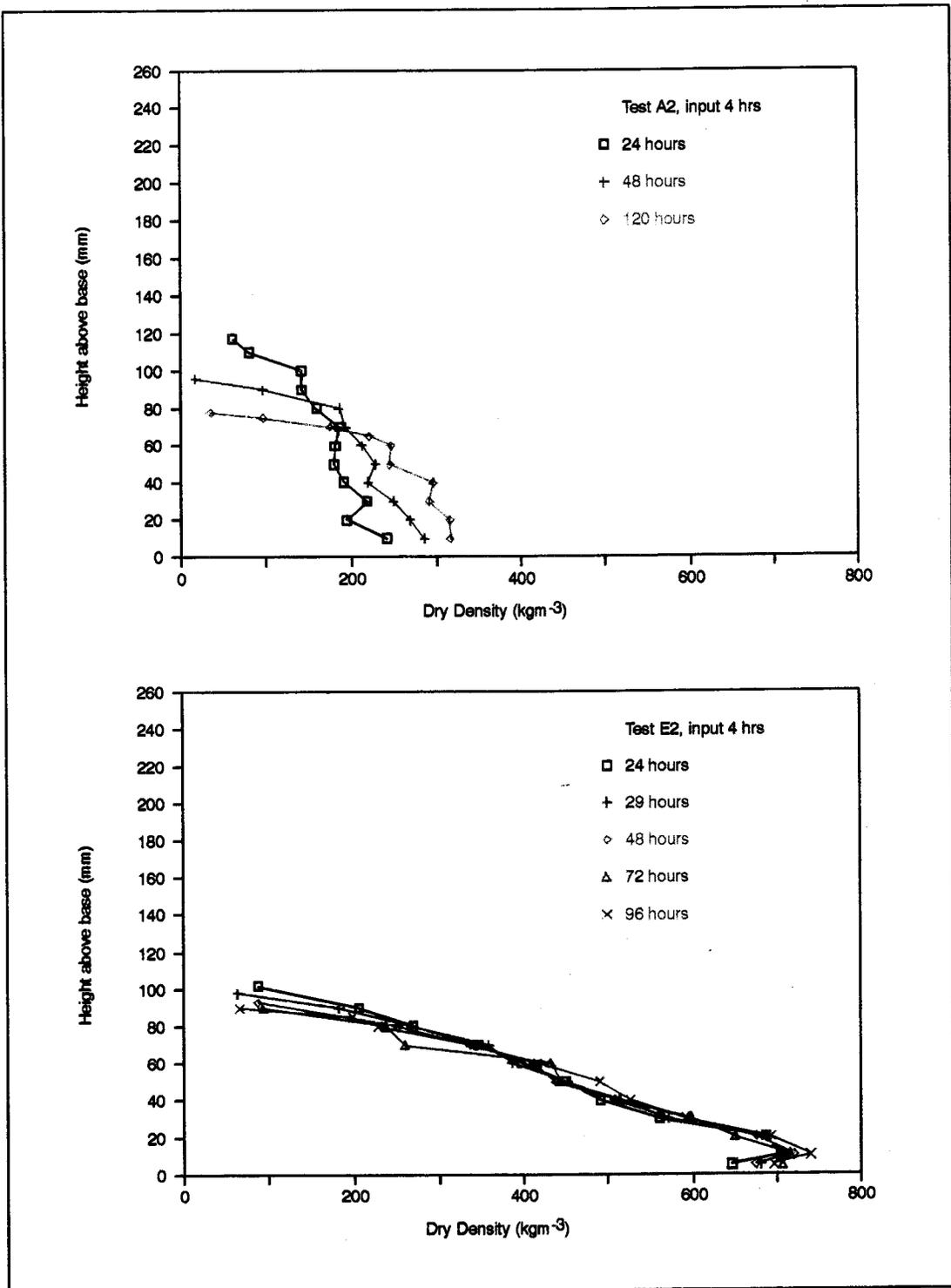


Fig 5 Comparison of consolidation rates for test A2 (0%) and E2 (45% sand) for an input of 4 hours

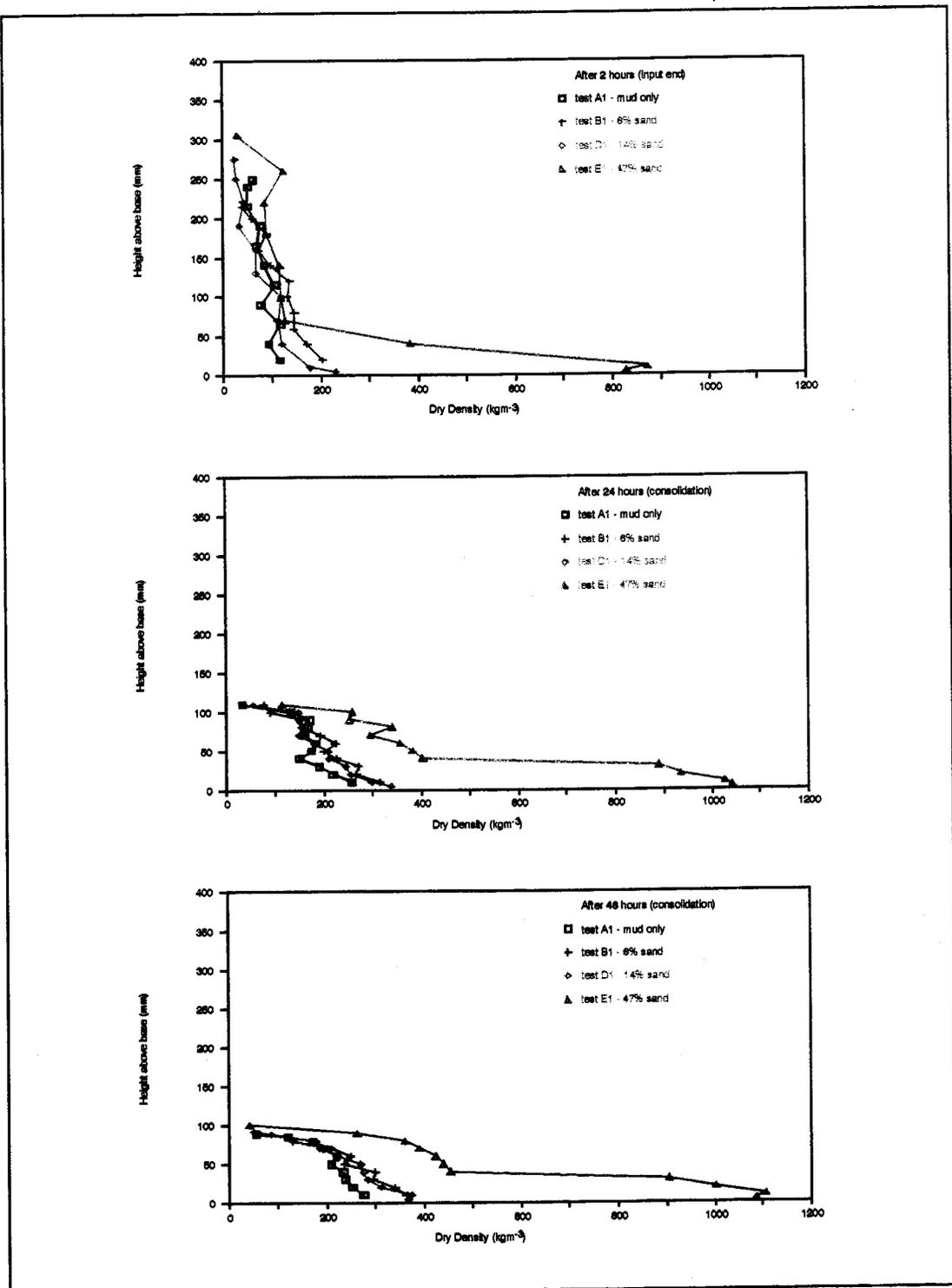


Fig 6 Density profile structure development with varying sand content for a 2 hour input period

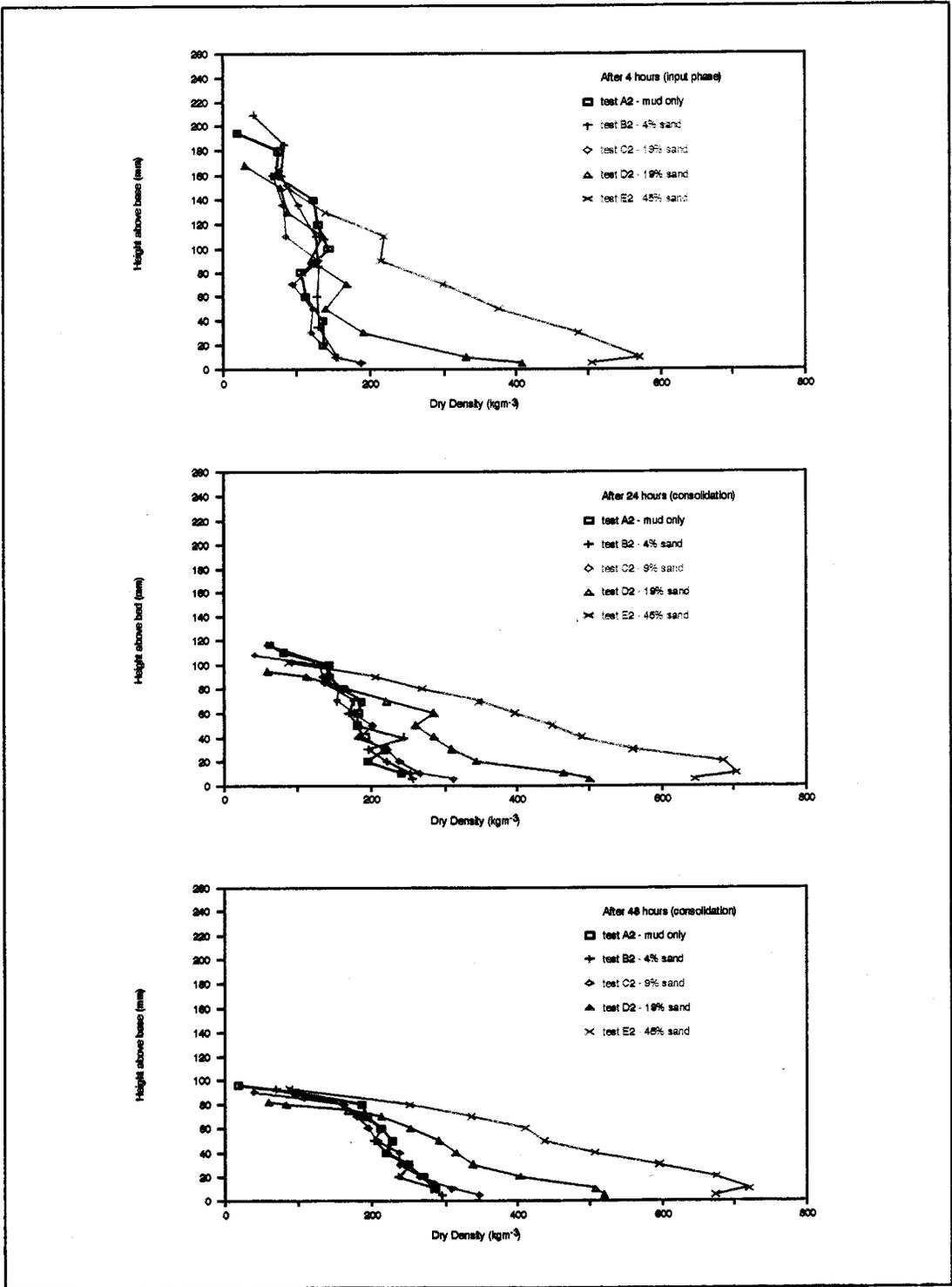


Fig 7 Density profile structure development with varying sand content for a 4 hour input period

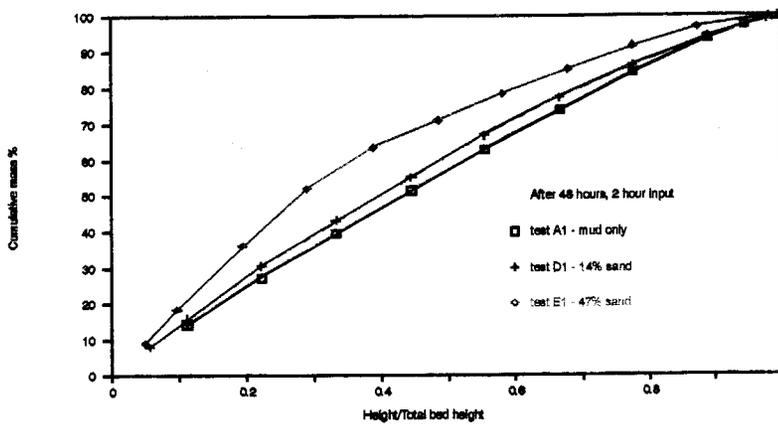
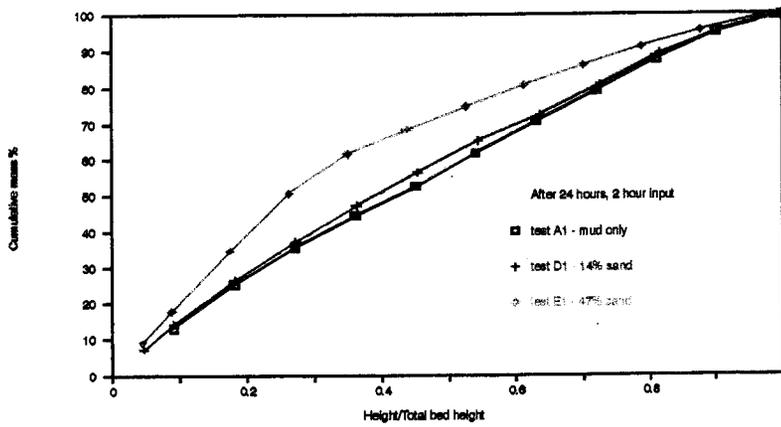
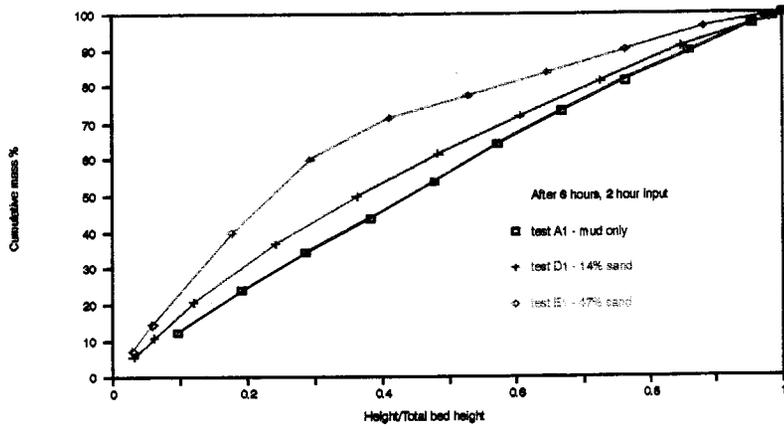


Fig 8 Cumulative mass distribution of mud/sand beds for a 2 hour input period

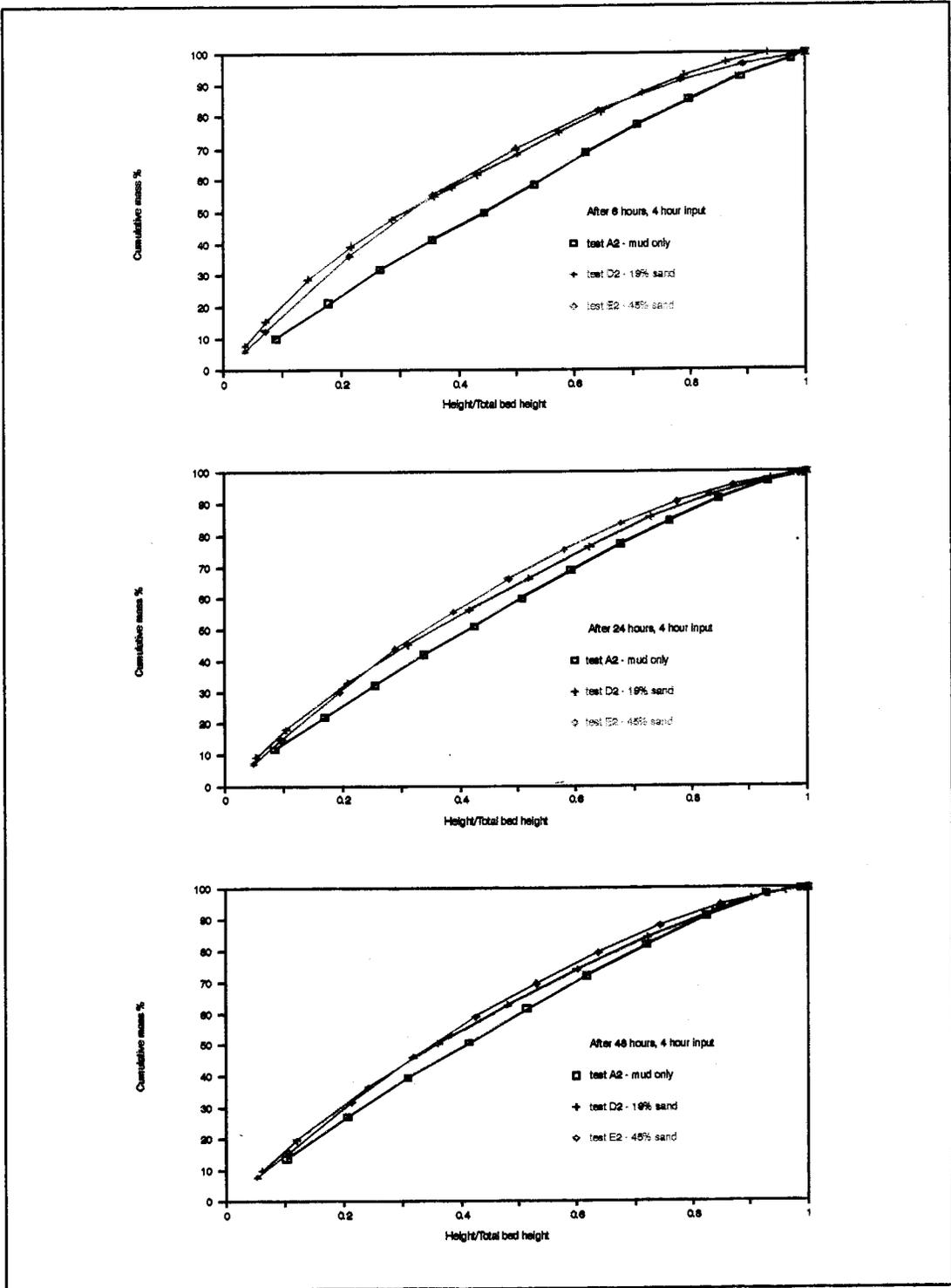
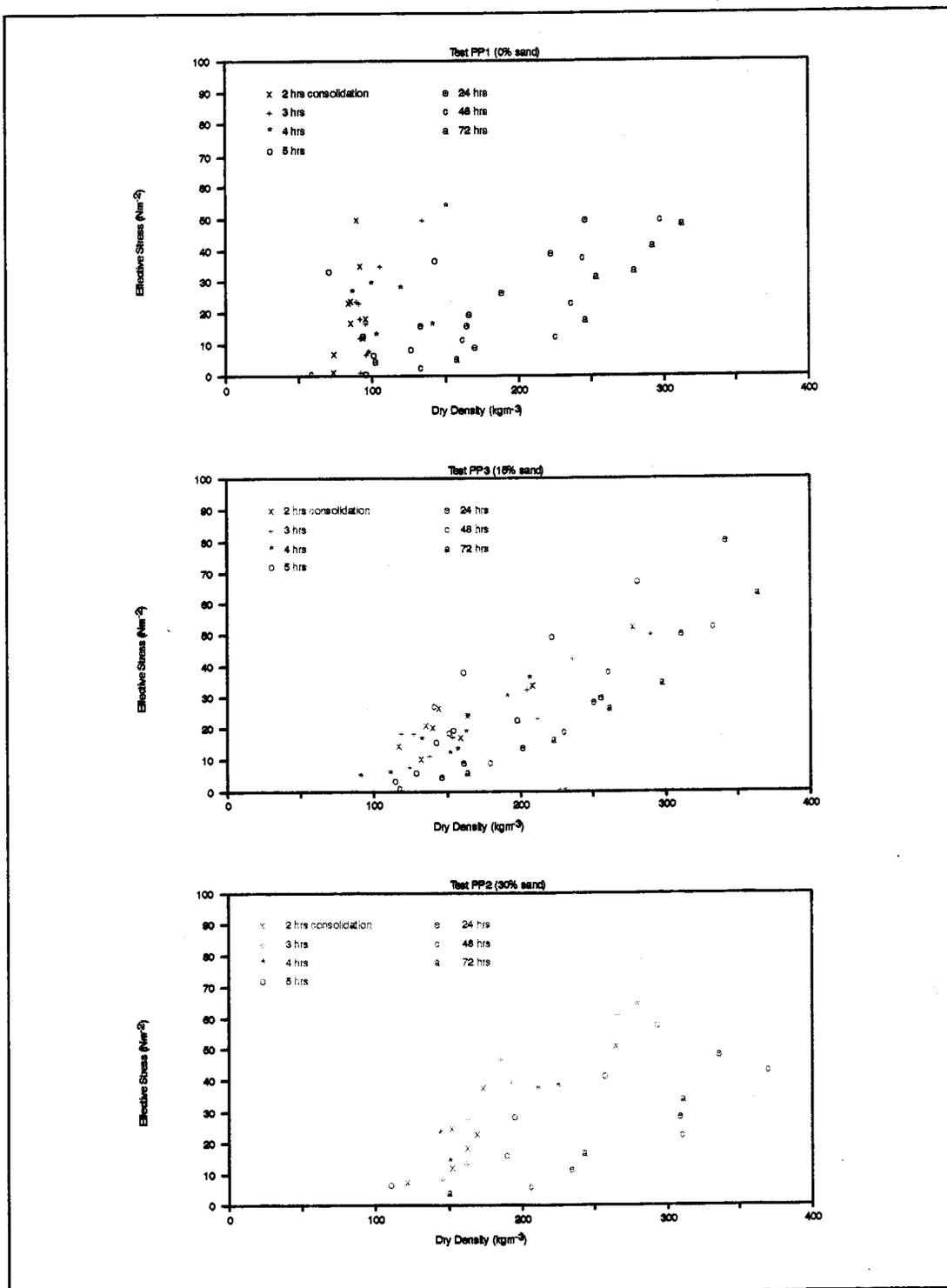


Fig 9 Cumulative mass distribution of mud/sand beds for a 4 hour input period



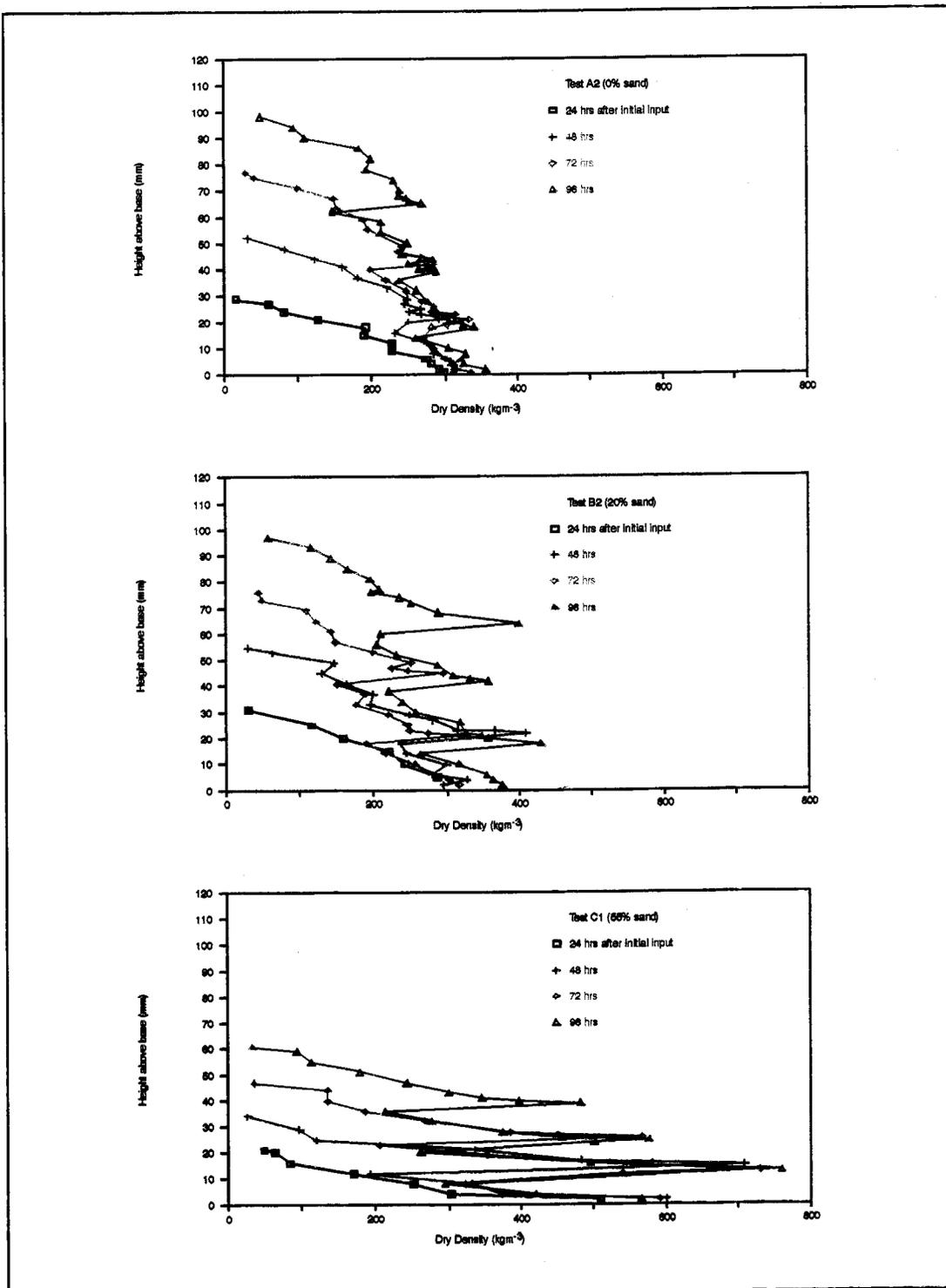


Fig 11 Density profile development with time for layered beds of varying sand content

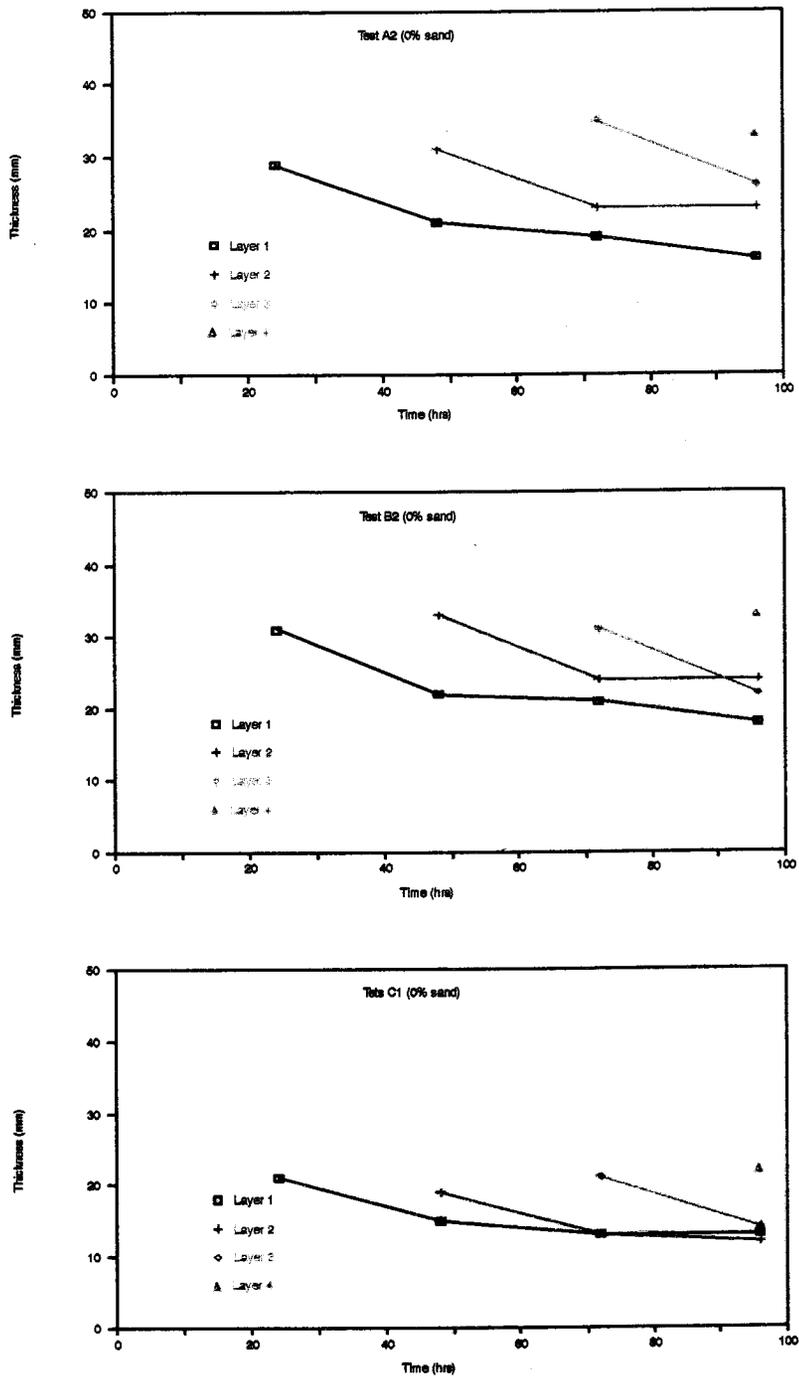
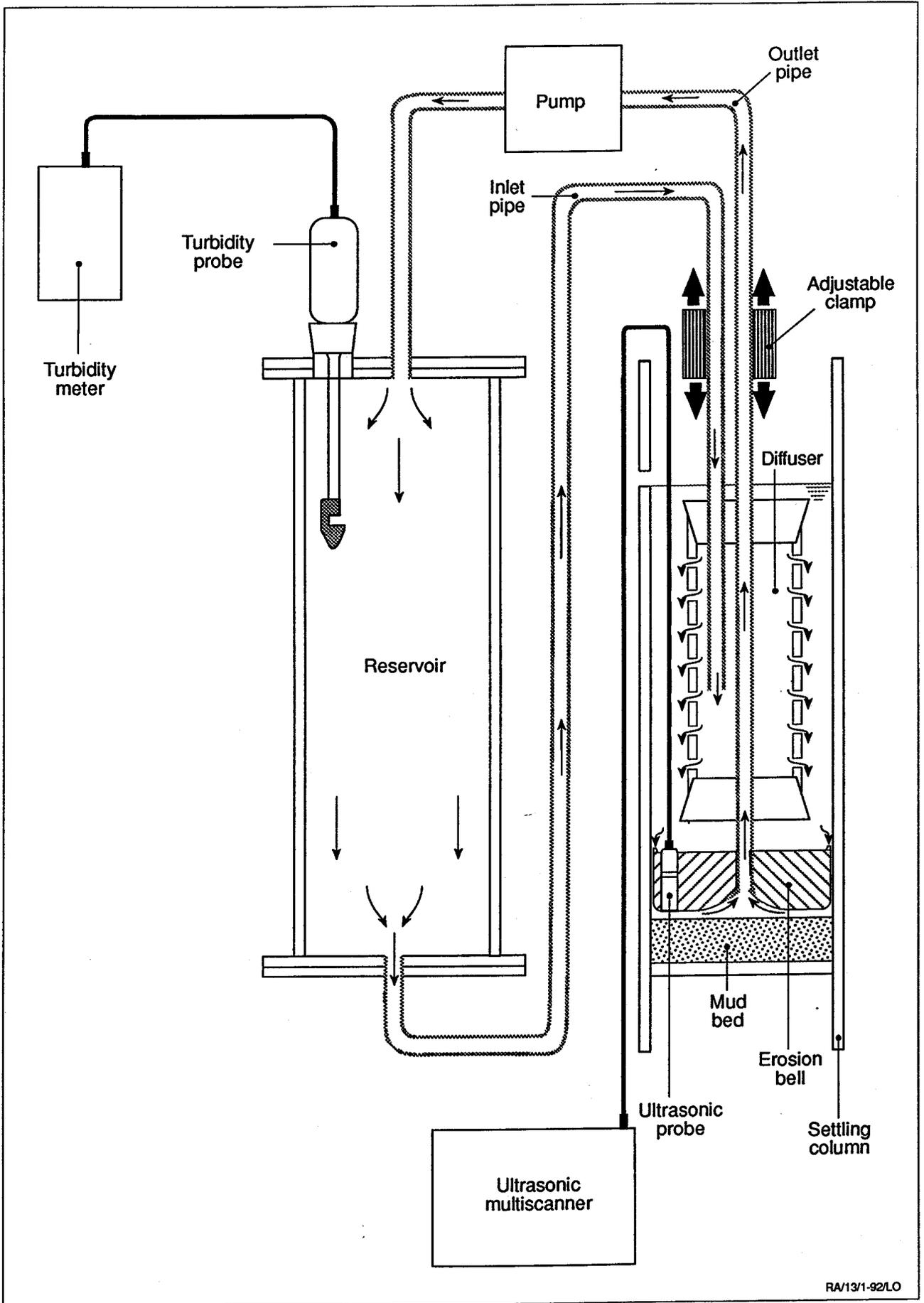


Fig 12 Variation of layer thickness for tests on layered beds of varying sand content



RA/13/1-92/LO

Fig 13 Diagram of erosion bell apparatus

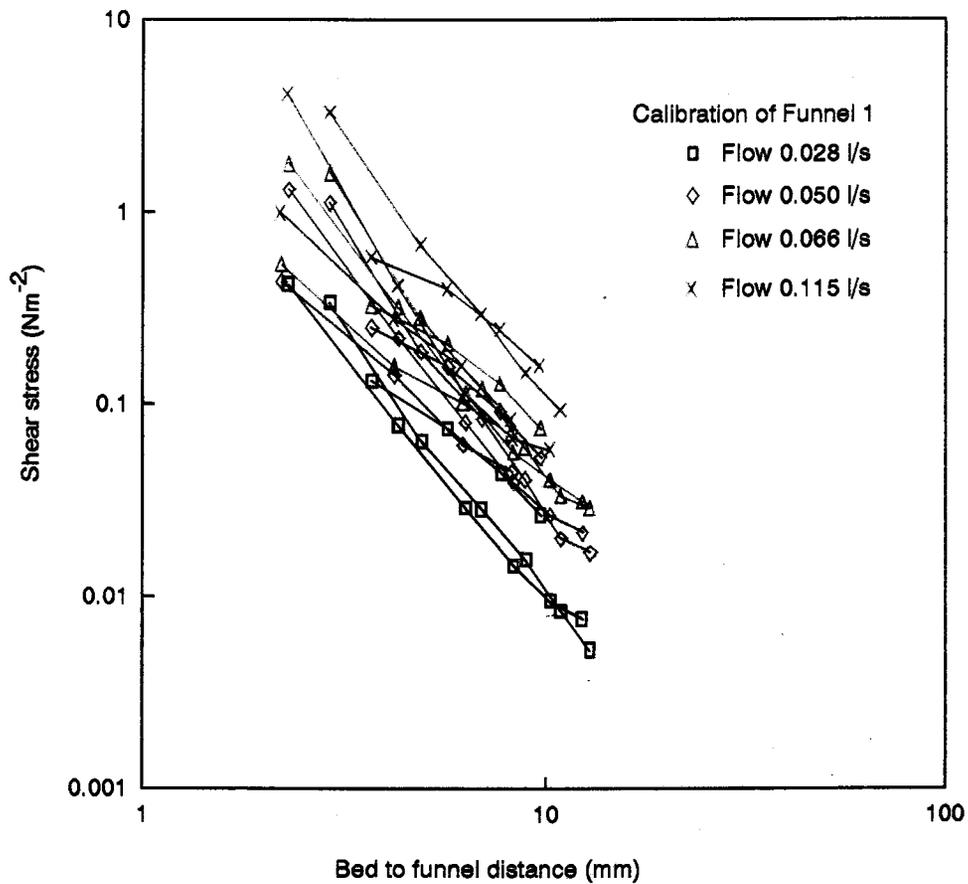


Fig 14 Erosion bell calibration tests showing the shear stress and bed funnel distance relationship

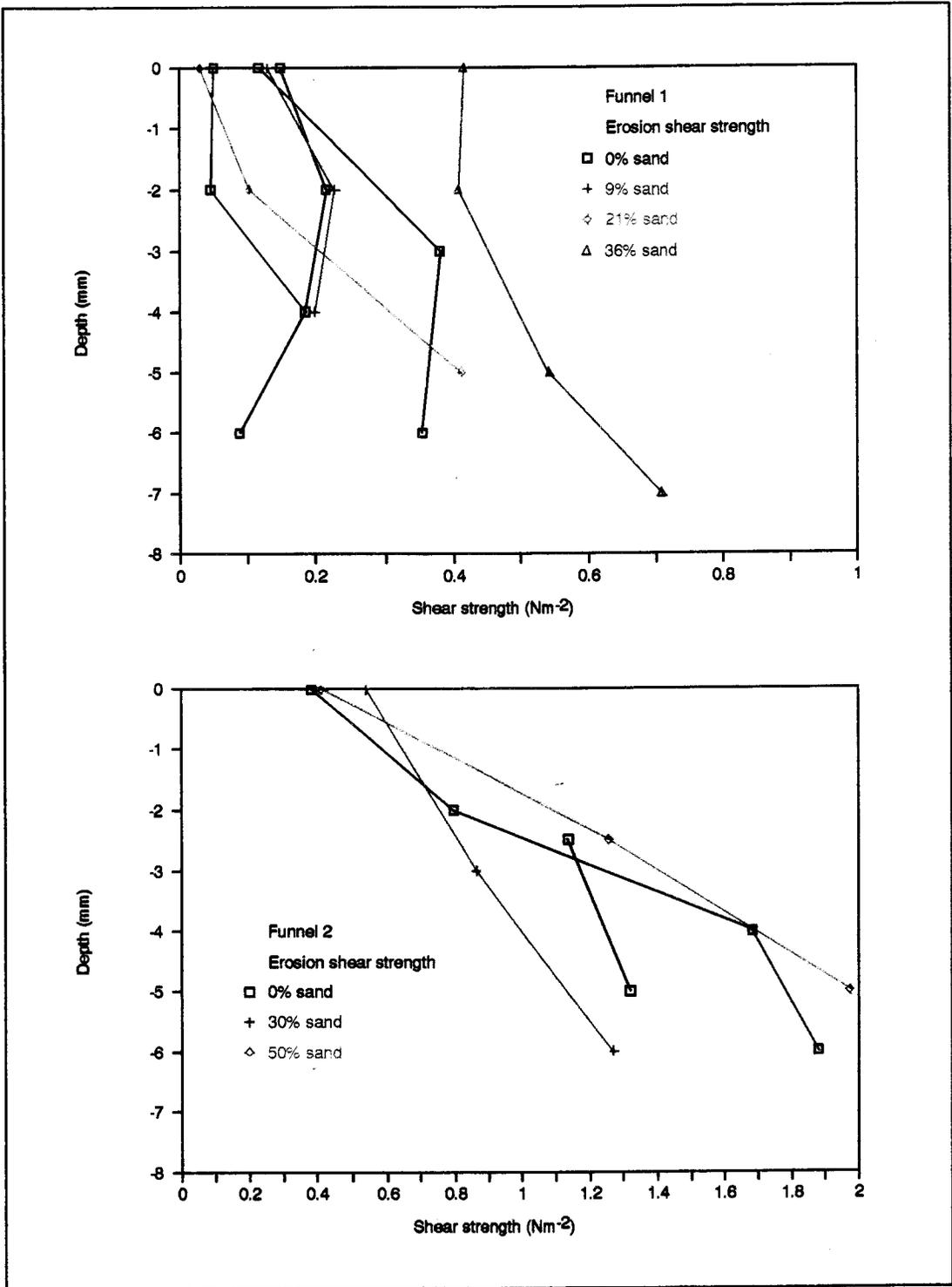


Fig 15 Shear strength profiles obtained by the erosion of varying sand content beds using the erosion bell

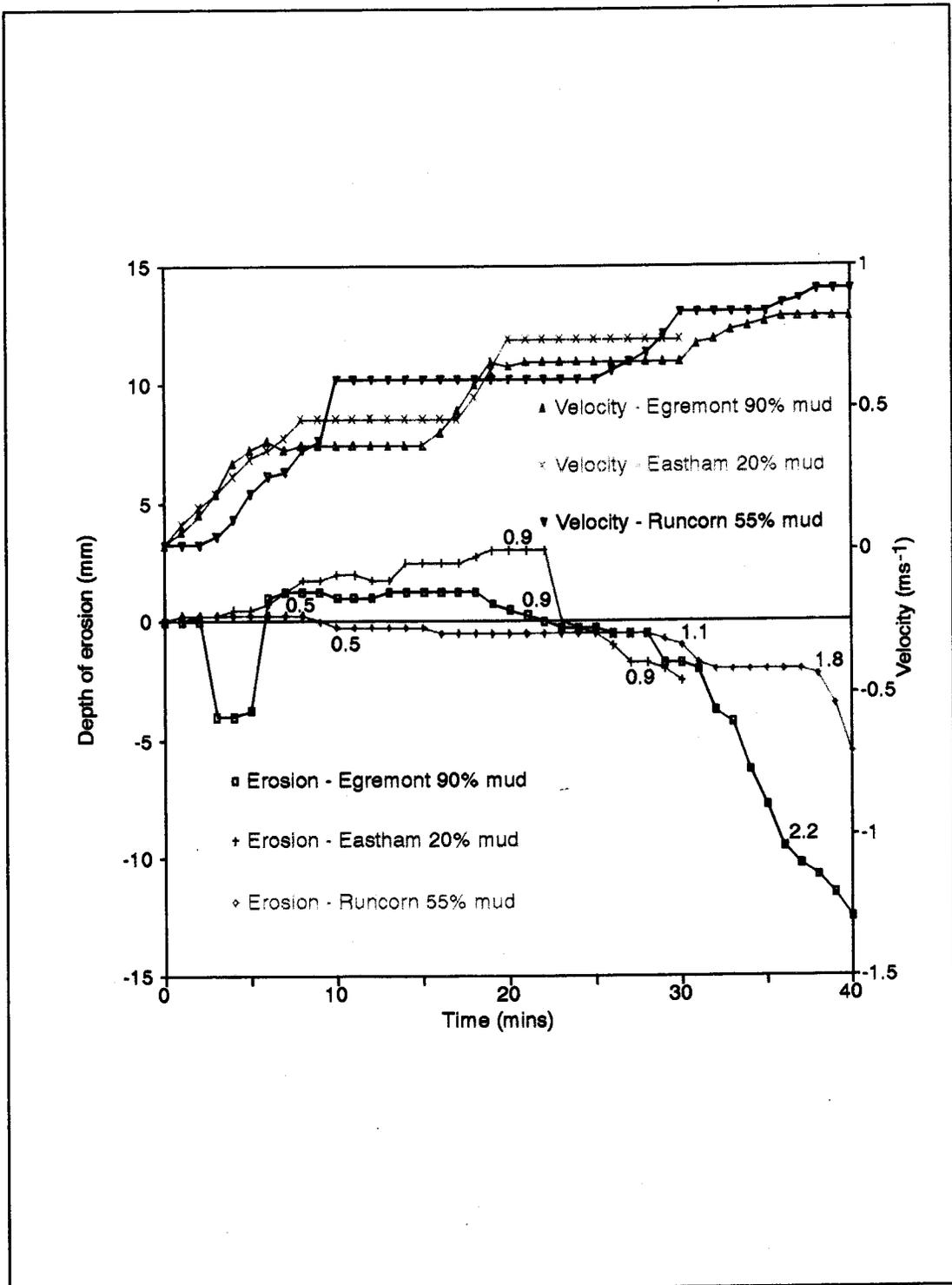


Fig 16 Uni-directional erosion tests for Mersey mud

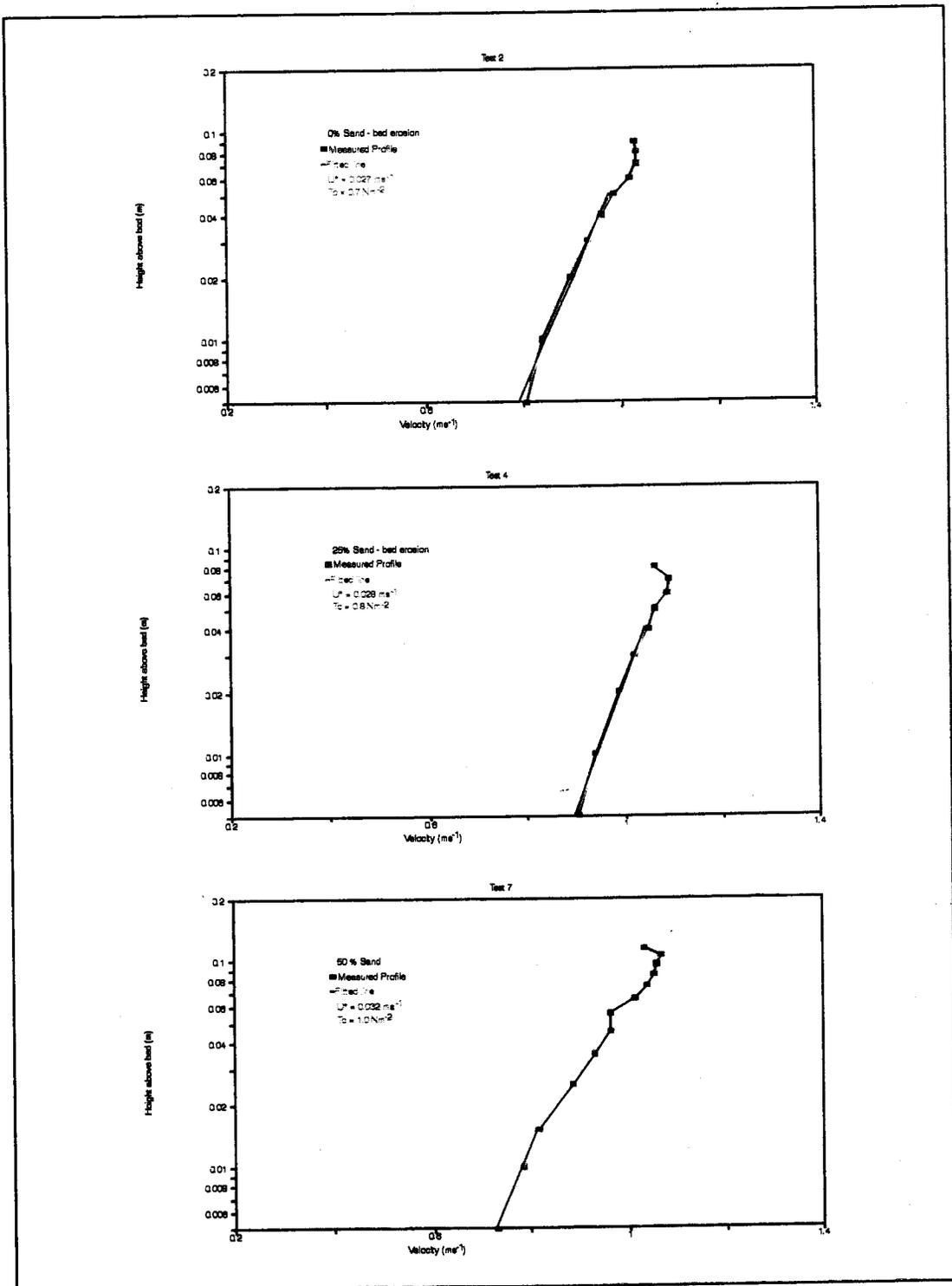


Fig 17 Velocity profiles for erosion of blended mud and sand beds by uni-directional currents

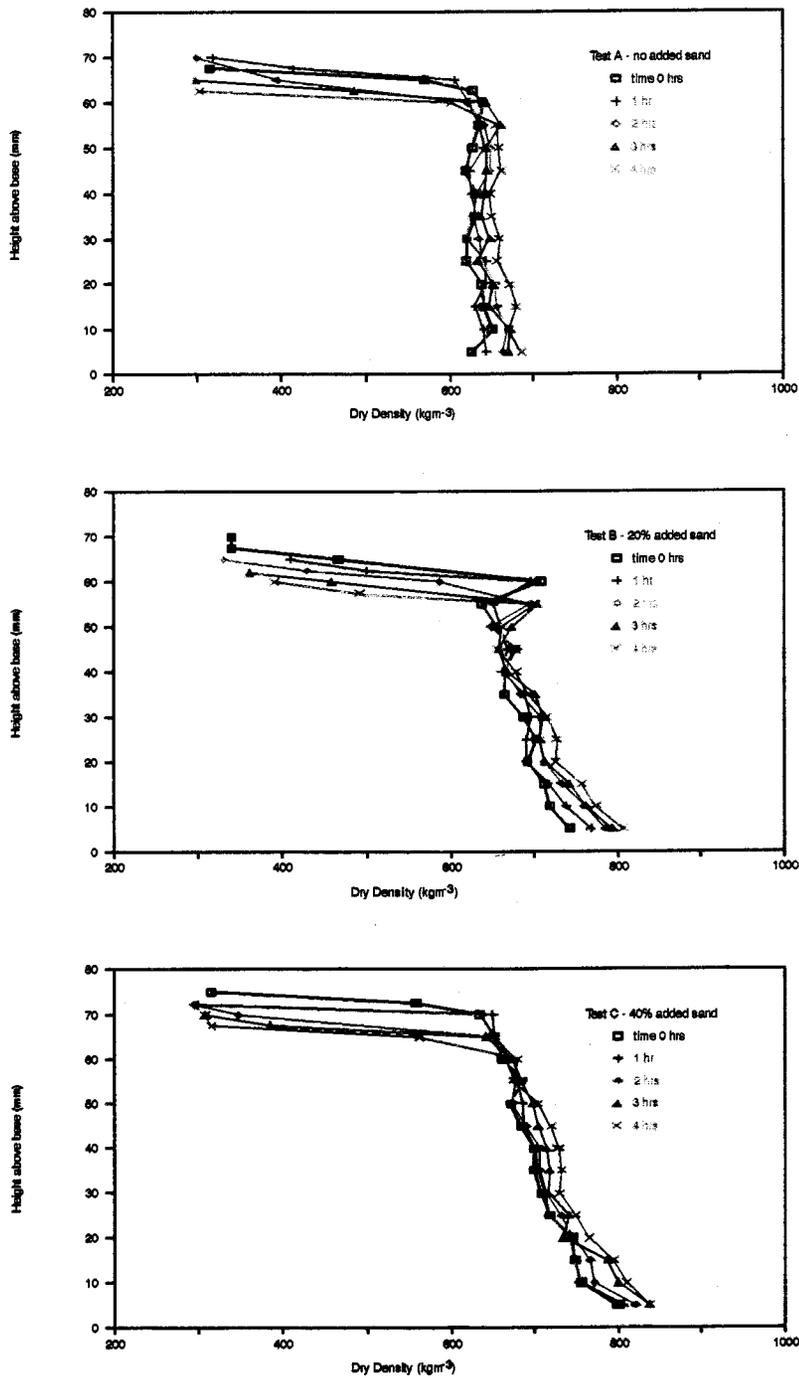


Fig 18 Density profiles of Harwich mud slurry with varying sand content

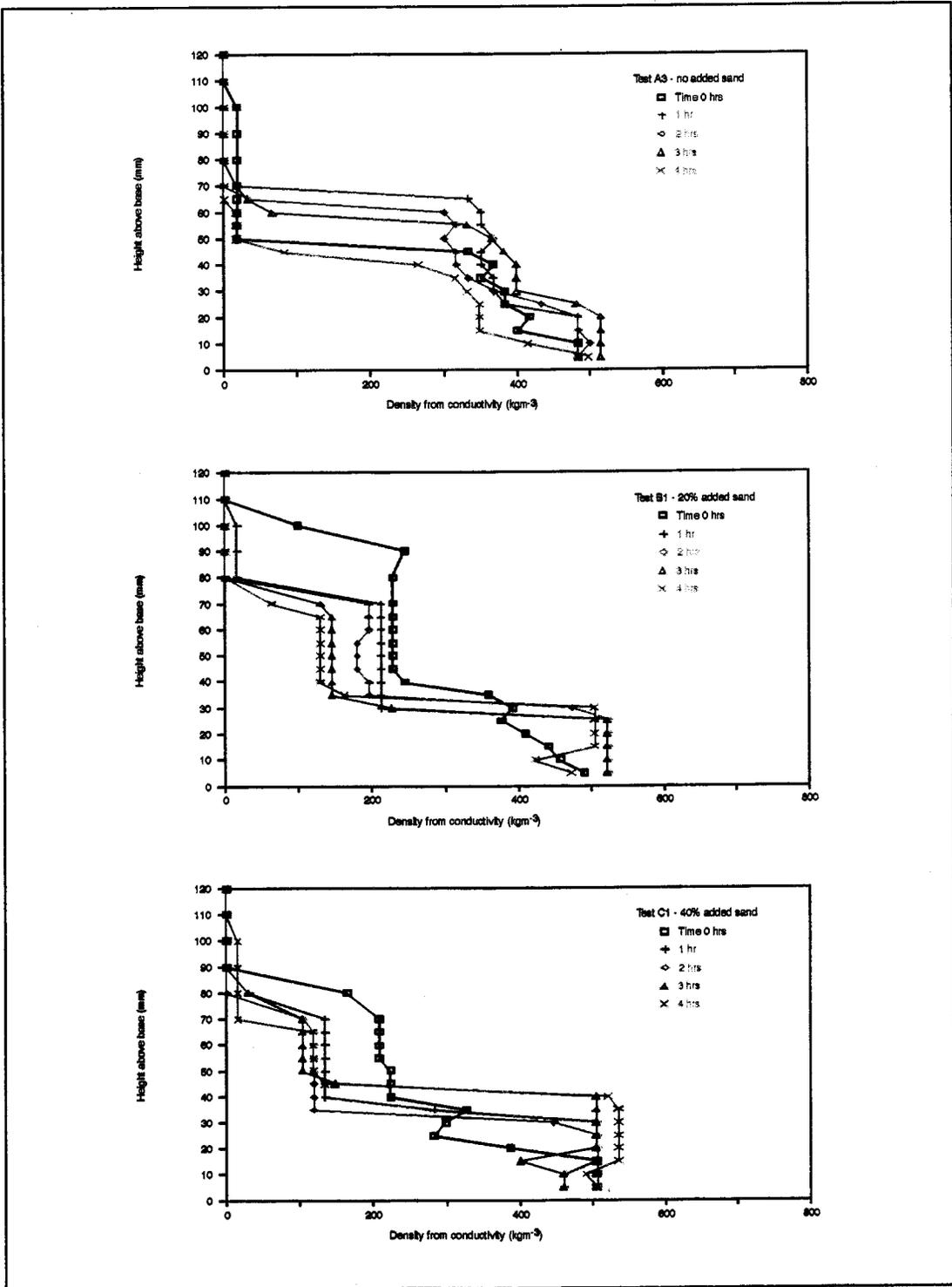


Fig 19 Density profiles during wave erosion tests for Harwich mud slurry with varying sand contents

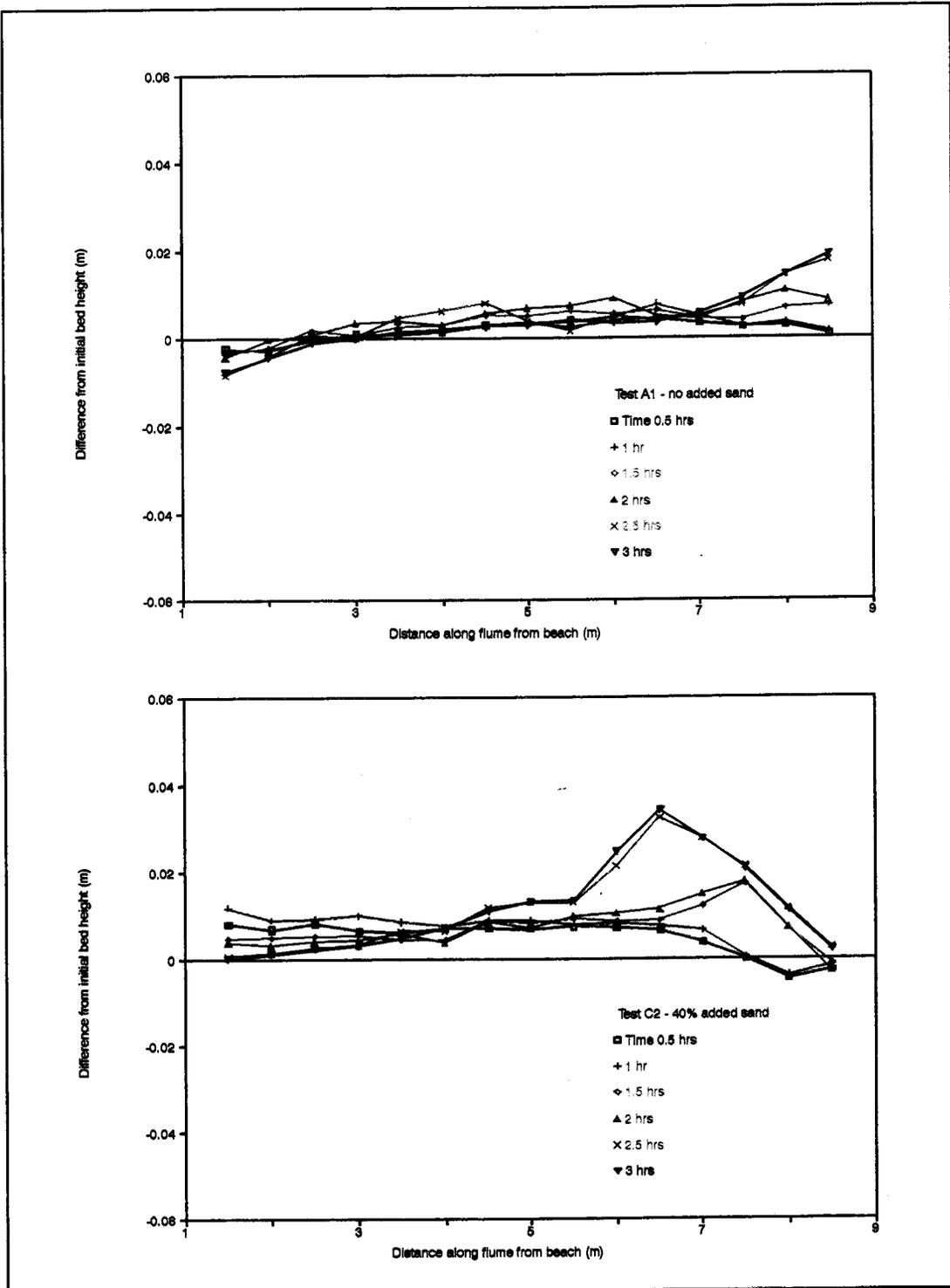


Fig 20 Bed level changes during wave erosion tests for varying sand contents

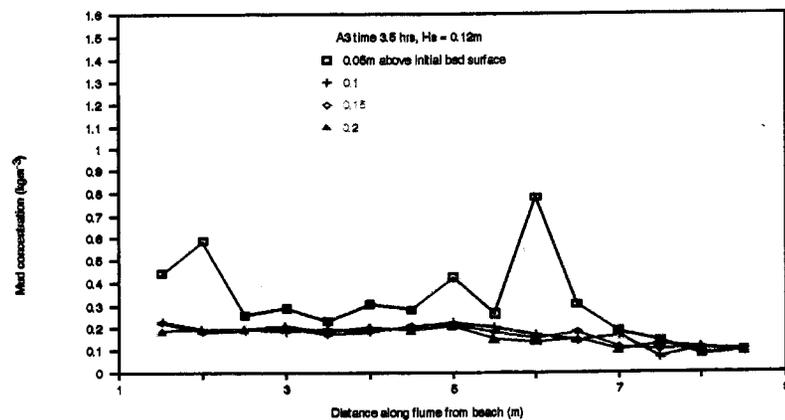
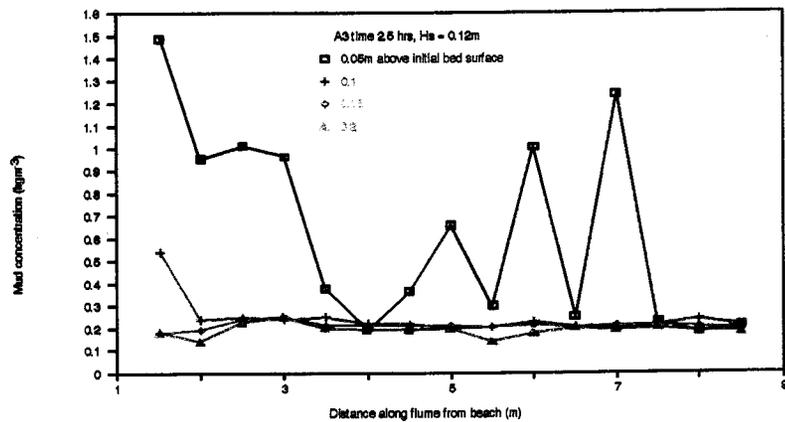
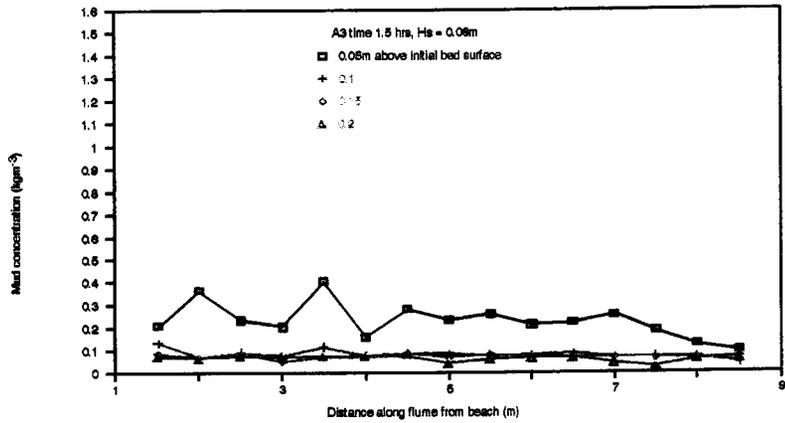


Fig 21 Development of mud concentration in suspension with time for test A3, with no added sand

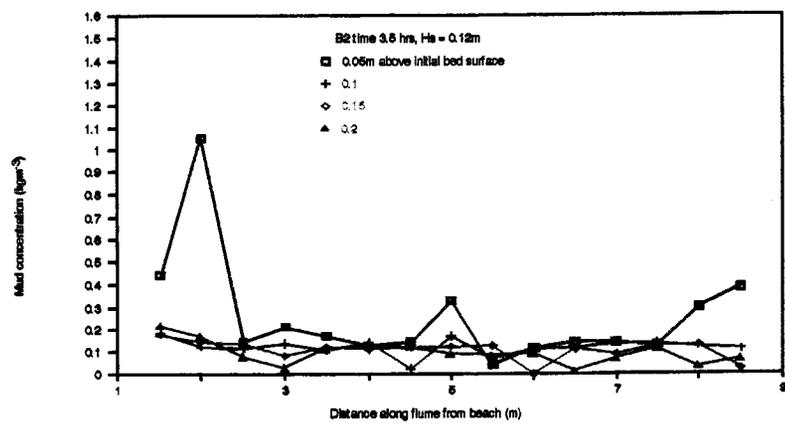
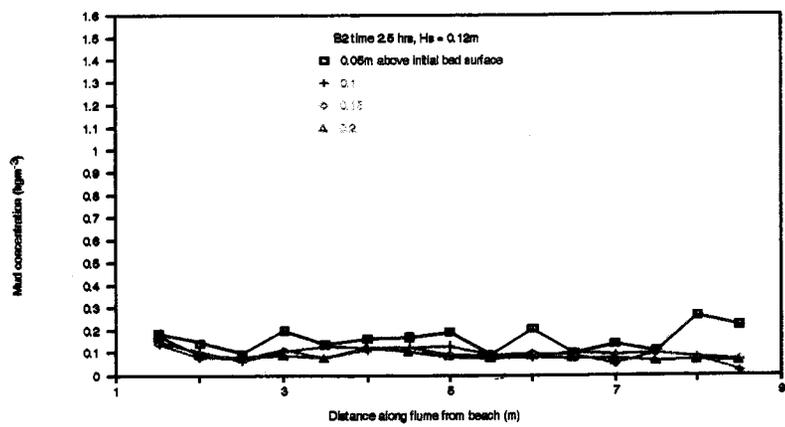
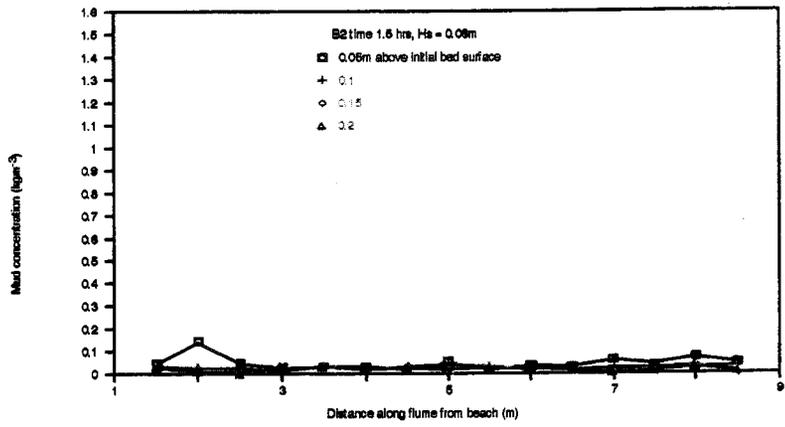


Fig 22 Development of mud concentration in suspension with time for test B2, with 20% added sand

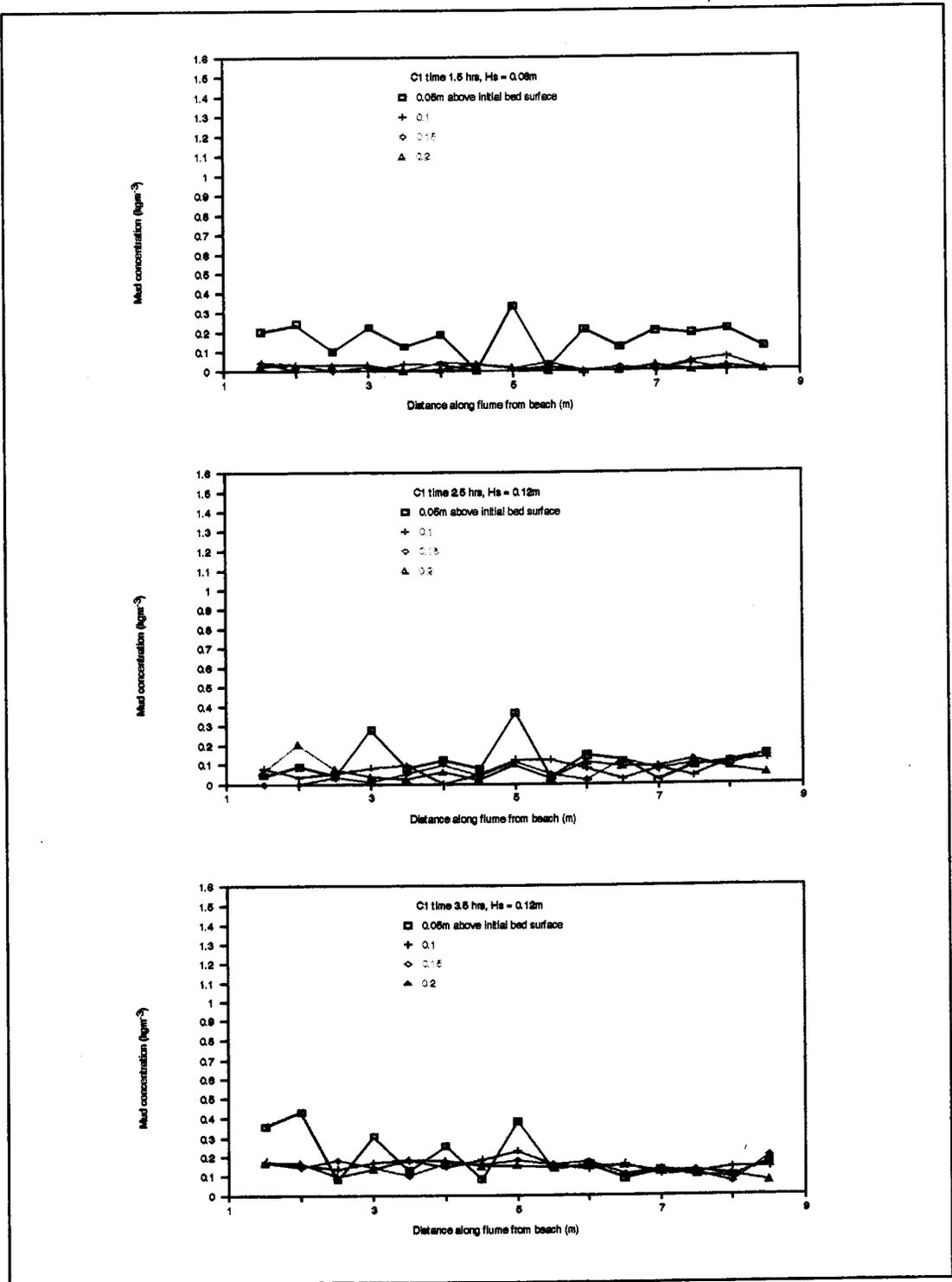


Fig 23 Development of mud concentration in suspension with time for test C1, with 40% added sand

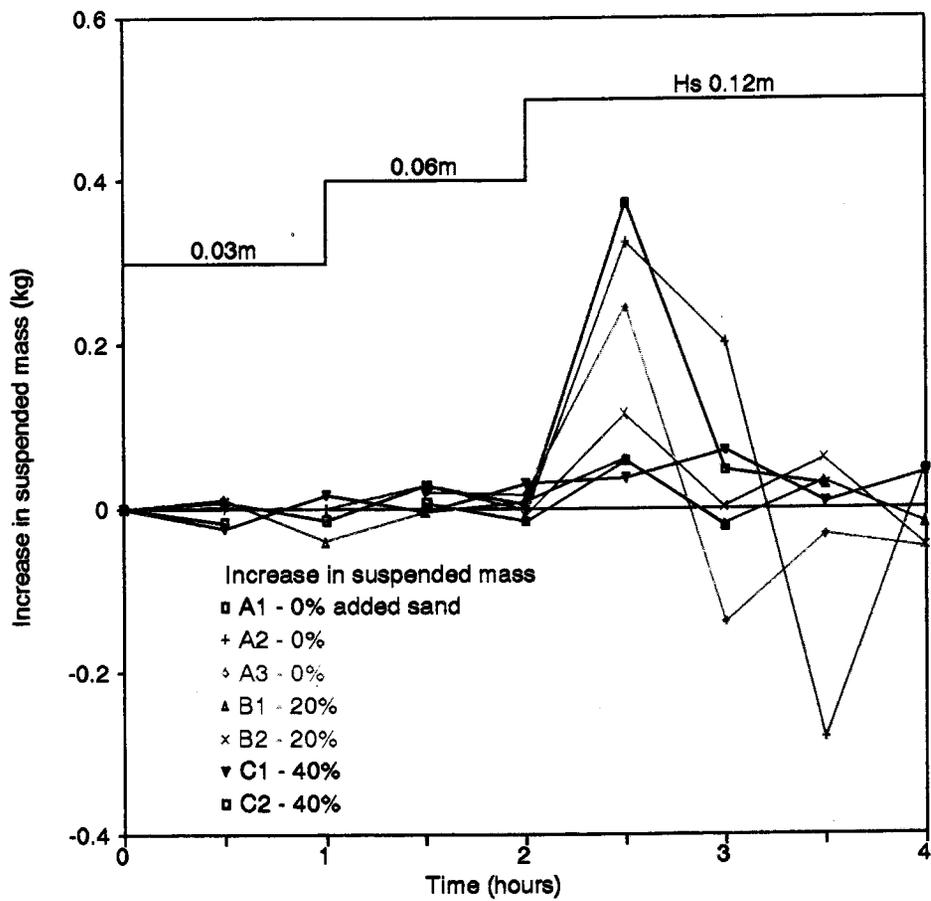


Fig 24 Increase in suspended mass with time for wave erosion tests with varying added sand contents

PLATE

mm



140

120

100

80

60

40

20

0

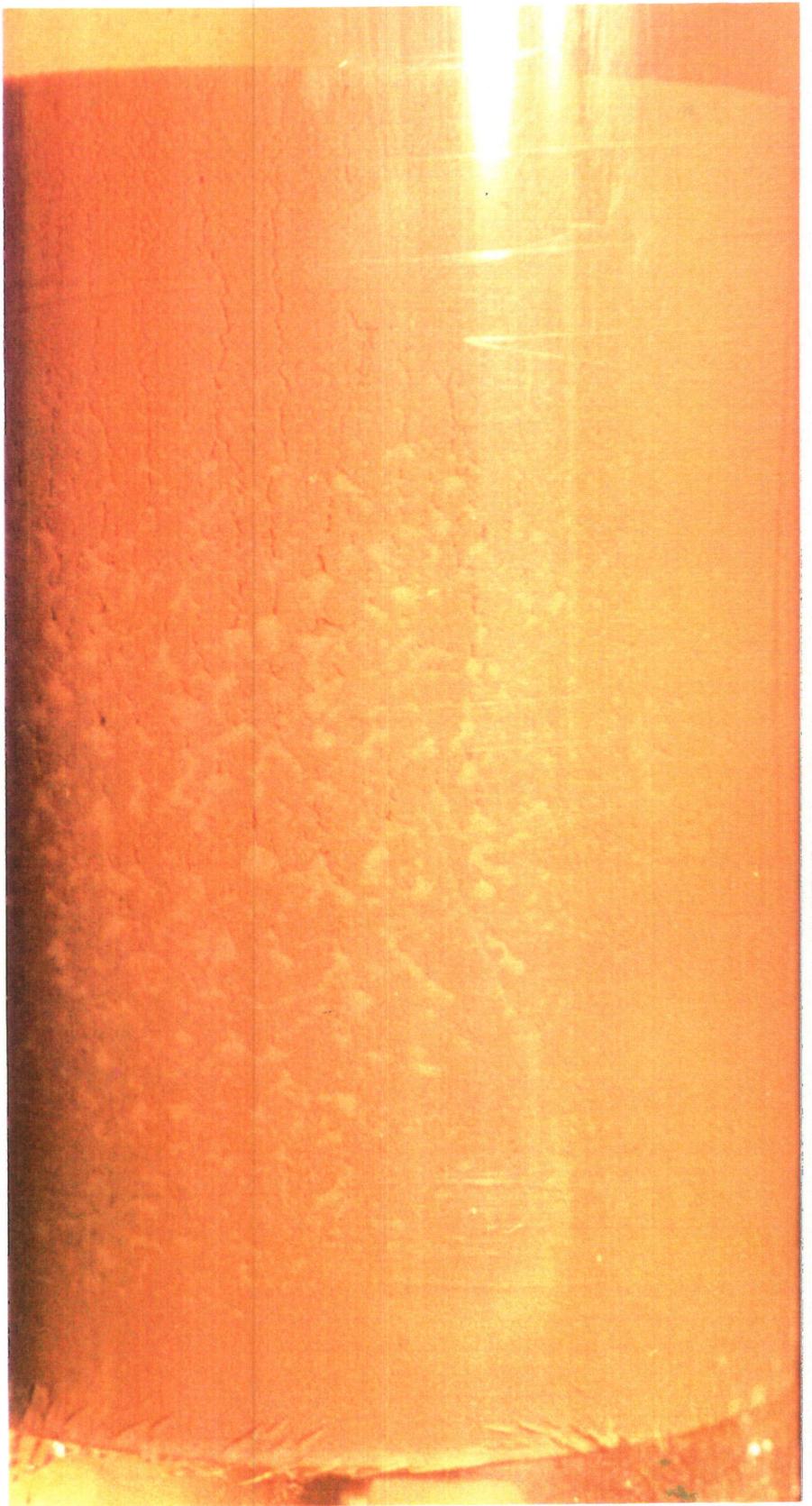


Plate 1

Photograph of bed E2 (49% sand) 2 hours after input

APPENDICES

APPENDIX 1

CONSOLIDATION TESTS : TEST PROCEDURE AND ANALYSIS

Description of apparatus

The tests are carried out in a 2 metre settling column of 0.092m internal diameter, constructed of perspex (Fig A1.1). At a height of 0.5m above the base of the column there is a sampling port for extracting small volumes of the suspension for concentration and salinity analysis. At the same height a steady stream of a mixed suspension is injected into the column, which is initially full of saline water. An outlet at 1.75m above the base of the column is used to extract the excess clear water above the settling bed. The suspension to be injected is kept constantly mixed by a recirculating pump. It is then extracted from the bottom of the mixing tank by a variable speed peristaltic pump and injected into the column.

Density profiles are obtained for the bed in the settling column by measuring the transmission of emissions from a Ba^{133} source (having a 7.5 year half life) over a 30 second time period. This is measured at 3mm, 5mm or 10mm vertical intervals throughout the depth of the bed. The interval used is dependent on the thickness of the bed and is chosen to give approximately 10 readings for each bed.

It is assumed that there is no significant change in density over the time period taken to read the complete profile. The standard deviation of a reading was found in a previous investigation to be approximately $\pm 1\%$, which results in a dry density with an accuracy of approximately $\pm 10\text{kgm}^{-3}$. The vertical height of the transmission probe can be

read to the nearest 0.5mm. The transmission probe is calibrated regularly by measuring the count rate in saline solutions of known density. The calibration indicates a linear relationship over the density range applicable in the tests of the form

$$\rho_d = K_1 r + K_2 \quad (A1.1)$$

where

ρ_d = dry density (kgm^{-3})

r = count rate per minute

K_1, K_2 = constants

Excess pore pressures are determined at the same time as the density profiles. These pressures are measured at set distances above the column base, giving measurements throughout the settled bed and overlying fluid throughout the test.

Test procedure

The input conditions for the column are chosen to be representative of conditions at the site of interest. Different final bed thicknesses and resulting densities are obtained by changes in the input rate and duration of input. A constant rate of input over a set period of time is chosen for each test.

At the start of the test the peristaltic pump is switched on to allow the suspension into the column. The speed of the pump is chosen according to the thickness of bed required and is left running for 2 or 4 hours. To prevent the suspension from mixing upwards in the column the inlet is angled towards the column base, thereby allowing clearer fluid to be drawn off at the overflow outlet.

Samples of the suspension being injected by the peristaltic pump are taken at regular intervals during the input phase. These are analysed for suspended sediment concentration.

The total quantity of sediment put into the column during each test is estimated from the input variables, so integration of the density profiles indicates the distribution of mass through the column and checks the total mass in the column.

Density profiles, excess pore pressures and bed thicknesses are recorded regularly during the first day of the test. Subsequent readings are made at approximately 24 hour intervals until the excess pore pressures have dissipated and the decrease in bed thickness has stabilised.

Analysis

The results of each test are entered into a spreadsheet in the form of density profiles with time and pore pressures at several fixed heights above the base with time. Analysis of the data is as follows:

1. For each density profile, calculate the cumulative mass from the top of the bed.
2. For each set of pore pressure readings, use linear interpolation of the corresponding density profile to calculate the cumulative mass above and the density at each point of pore pressure measurement.
3. For each time profiles were taken, calculate the effective stress at each pore pressure measurement point from

$$\sigma' = \sigma - u$$

where

σ' = effective stress

σ = total stress

u = excess pore pressure

Total stress is calculated from the cumulative mass above that point. Plot effective stress against density at that point.

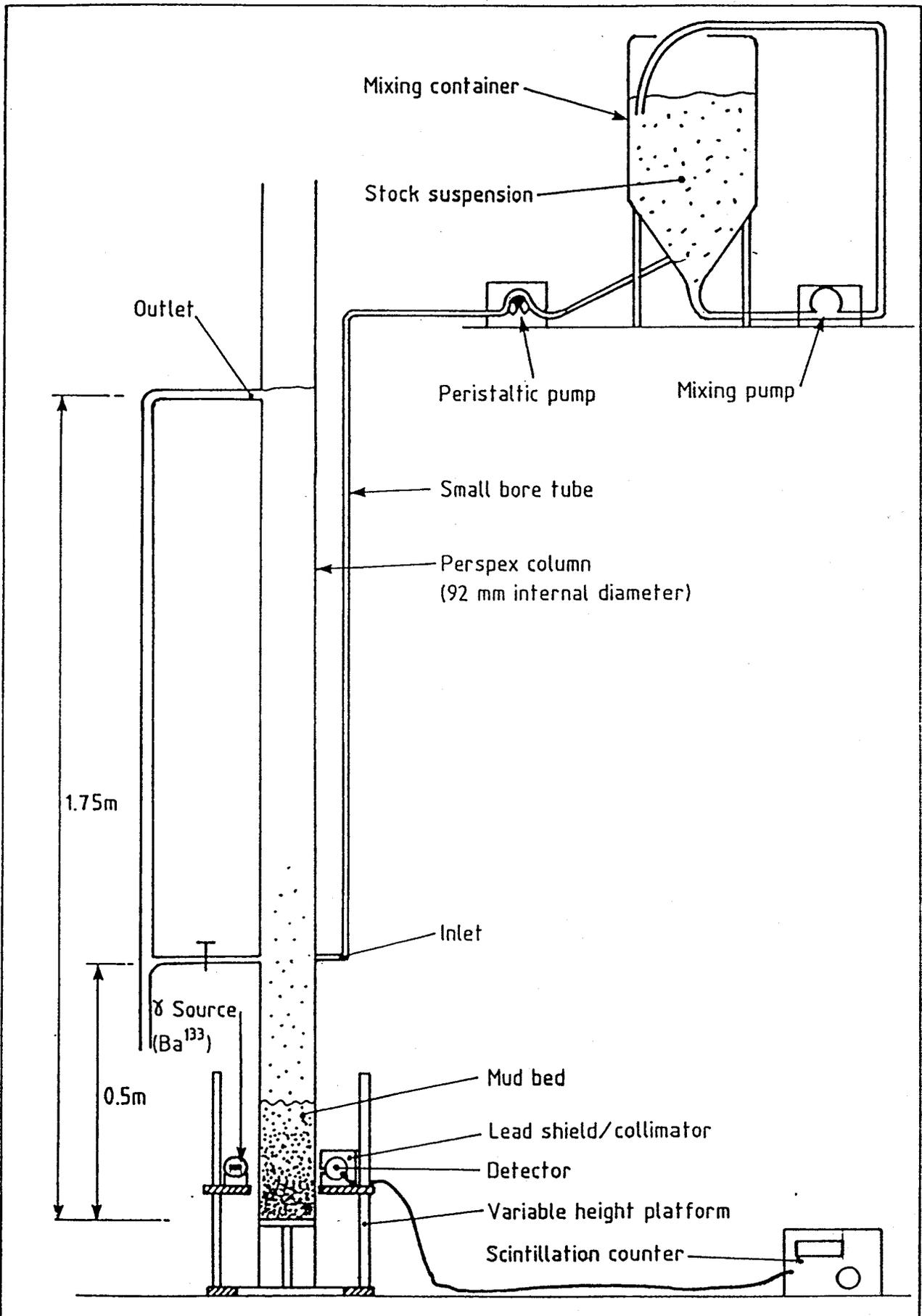


Fig A1.1 Settling column apparatus

APPENDIX 2

EROSION BY UNI-DIRECTIONAL CURRENTS : TEST PROCEDURE AND ANALYSIS

The objectives of the uni-directional current erosion tests are to determine the shear strength of a mud as a function of its dry density, and to determine the rate of erosion with applied shear stress.

Description of apparatus

Uni-directional current erosion tests are conducted in the HR Carousel. The carousel flume (Fig A2.1) is an annular flume, with an outer diameter of 6m, a channel width of 0.4m and depth of 0.35m, and has a detachable roof 0.09m thick. The flume stands approximately 1.1m off the ground, supported by 12 brick pillars. The channel and the roof are constructed of fibre glass, with a 0.12m long perspex section in the channel for viewing. The roof fits into the channel, and floats on the fluid. Fluid motion in the carousel flume is induced and continued by the drag between the roof and the fluid surface as the roof rotates.

The driving mechanism for the roof consists of a DC Torque motor with a drive wheel, which turns a horizontal plate around the central spindle. The drive arm is attached to this horizontal plate at one end and to the roof at the other end.

A strain gauge is used to measure the force applied to the roof of the carousel flume as it rotates. It consists of a spring and displacement transducer arrangement attached to the driving arm at the point of contact with the roof (Fig A2.1). The magnitude of the applied force is determined by the

displacement transducer deflection, which is displayed on a chart recorder. The strain gauge is calibrated by applying known forces via a pulley system.

The speed of the motor, and hence roof speed, is controlled by a micro computer. The motor speed can be set to an accuracy of 0.1% of the maximum speed. This produces a mean water velocity range in the flume from zero to approximately 0.7ms^{-1} , with a corresponding applied shear stress range from zero to approximately 0.7Nm^{-2} .

In the carousel flume the sampling system consists of two port holes, one on each wall of the flume, 80mm above the floor. Through each of these port holes protrudes an 'L' shaped stainless steel sampling tube, which has an internal diameter of 2mm. The outer wall sampling tube has its entrance facing upstream and its elevation can be altered by rotating the outer portion of this tube across a scale corresponding to 0-100mm above the flume floor.

During bed erosion tests fluid is continuously extracted from the carousel flume by a peristaltic pump and passed through a constant temperature water bath and a densiometer before being returned to the carousel flume. The densiometer works on the principle of determining the frequency of a thin vibrating glass tube through which the fluid is pumped and comparing this to the frequency of clean water pumped through a second densiometer. The readings obtained are analysed and displayed on a chart recorder. Bottle samples of the fluid are taken from time to time and analysed gravimetrically to maintain an accurate calibration. In this manner the suspended sediment concentration of the fluid in the carousel flume is measured

continuously to within a few percent. Previous measurements by Burt and Game (Ref A2.1) have shown that the mean suspended solids concentration of the fluid in the carousel flume is very close to the suspended solids concentration at the centre of flow, certainly less than 5% difference.

The thickness of the bed in the carousel flume is measured from beneath the flume at the perspex viewing section by an ultrasonic transducer. This instrument displays a peak in a signal which indicates the interface between the mud bed and the overlying fluid and enables the thickness of the bed to be determined to within 0.1mm. The transducer is calibrated through a fluid with a salinity similar to that in the mud bed. A movable mounting device holds the transducer in contact with the underside of the perspex section and is used to position the transducer at any point across the 0.4m width of the flume. In this way it is possible to obtain profiles of the bed and determine the depth of erosion at any time during the test.

Bed shear stress measurement

The average shear stress exerted by the fluid on the bed has been measured and calculated in several previous studies (Ref A2.2). Both different roof rotational speeds and different flow depths have been investigated.

The first method was simple and involved direct measurement of the energy input to the roof through the calibrated strain gauge for a number of different speeds of rotation of the roof.

The second and more complex way of determining the bed shear stress was by measurement of the near bed velocity profiles in the flume using laser doppler

anemometry. The operation of the laser is explained in detail in reference A2.2. The friction velocity at the bed was determined from a log-linear plot of height above bed and tangential velocity.

Velocities were determined at three sections across the width of the flume for different speeds of rotation of the roof. The bed shear stresses were then computed from the logarithmic portion of the velocity-depth profiles. An average bed shear stress across the whole width of the flume was calculated for different speeds of roof rotation. However, it must be appreciated that the eroding fluid in an erosion test may have a high concentration of suspended solids and will not exhibit the same hydrodynamic behaviour as the clean water used in the calibration. Nevertheless, for the concentrations of suspended solids present in the carousel flume during an erosion test ($\leq 4\text{kgm}^{-3}$), it is believed that this factor would not significantly affect the calculation of the erosion properties of the mud.

Thirdly, flush mounted shear stress probes were deployed to measure the shear stress along the base and side walls of the flume. The probes used the constant temperature hot wire anemometry technique. Each probe consisted of two thin electrically connected metallic strips mounted side by side on a perspex base. The strips were heated to approximately 30°C by an electrical current; the relative deflection of the connecting wire under stress produced a variation in output voltage, which was calibrated to shear stress.

In addition, the shear stress distribution along the bed was predicted by a numerical model which was developed by Polytechnic South West to predict the hydrodynamics in the carousel (Refs A2.3 and A2.4).

Figure A2.2 shows the bed shear stress against rotational roof speed as measured by these various methods for a flow depth of 100mm. This shows the shear stress on the wetted perimeter as given by the power input measured through the strain gauge, the average bed shear stress across the width of the flume measured by the laser velocity, the average bed shear stress across the width of the flume measured by the shear stress probes, and the average shear stresses predicted by the numerical model. All methods show an increase in bed shear stress with increasing speed of rotation of the roof, with the shear stress probes and the numerical model showing higher stresses at the higher roof speeds than the other two methods.

For the purpose of estimating the bed shear stress during an erosion test the curve representing the average shear stress as calculated from the numerical model is used. For a flow depth of 100mm in the carousel this curve is described approximately by the relationship

$$\tau_{av} = 0.06(\text{rpm})^{1.77} \quad (\text{A2.1})$$

where

τ_{av} = average shear stress across the width of the flume (Nm^{-2})

rpm = rotational speed of carousel roof

Test procedure

To prepare a mud bed in the carousel flume, the mud is first mixed homogeneously in a mixing tank with a recirculating pump. The suspension is then pumped into the flume from the tank until the required depth of suspension in the flume is reached. The roof is lowered onto the suspension surface and the mud in suspension is allowed to deposit and

consolidate. The period of consolidation is usually in the range of 2-10 days and the resulting bed has a thickness of 10-25mm. The depth of fluid above the bed is adjusted to be close to 100mm which corresponds to the depth of flow for which the bed shear stress measurements were made.

An erosion test in the carousel flume comprises a number of discrete runs during which the speed of rotation of the roof (and hence the bed shear stress) is held constant. In a test there may be between 2-5 runs each lasting 60-200 minutes. The speed of the carousel flume is systematically increased for each successive run.

A run commences when the concentration of suspended solids is constant in the previous run. The speed of rotation of the roof is increased over a period of about 30 seconds to its new value. The concentration of suspended solids as measured continuously by the densiometer will at first increase rapidly (indicating a strong erosion), then more smoothly (modest erosion) and finally the concentration will remain nearly constant (no erosion). This pattern is reflected by the readings from the ultrasonic transducer which is mounted on the underside of the flume mid-way across its width. The change in the readings is directly proportional to the depth of erosion.

At the end of a run when erosion has stopped the actual depths of erosion at 20mm intervals across the width of the flume are determined using the ultrasonic transducer. The typical depth of erosion which is normally attained at the end of the test is about 5mm. If more mud is eroded then the high concentrations of suspended sediment begin to prevent the densiometer and ultrasonic depth transducer from functioning correctly. Furthermore,

at the higher speeds of rotation the effects of secondary currents are greater and the differential depths of erosion across the flume become more pronounced.

Analysis

The basic data obtained from a test are the suspended solids concentration with time, the depth of erosion at the mid-section of the flume with time and the depths of erosion across the flume at the equilibrium point in each run.

The shear strength with density relationship is described by the discrete values, at the equilibrium point in each run, of the speed of rotation of the roof, the suspended solids concentration of the fluid and the average depth of erosion across the flume. Using the results presented in figure A2.2 the average bed shear stress is then estimated for the prescribed speed of rotation of each run. At equilibrium in each run, the shear strength of the exposed surface of the bed is equal to the applied shear stress. Therefore, the shear strength against depth relationship of the eroded portion of the bed can be described by these points and expressed in a functional form

$$\tau_e = f_1(h) \quad (A2.2)$$

where

τ_e = erosion shear strength of bed (Nm^{-2})

h = average depth of erosion below original surface (m)

f_1 = function

It is also necessary to calculate the variation in density of the mud bed with depth. The density may be expressed as

$$\rho_h = (dm/dh)A^{-1} \quad (\text{A2.3})$$

where

ρ_h = dry density of mud at a depth h (kgm^{-3})

m = mass of solids in suspension (kg)

A = area of erosion (m^2)

Expressing the mass of suspended solids eroded from the bed in terms of the concentration of suspended solids, equation (A2.3) can be rewritten as:

$$\rho_h = (dc/dh)(V/A) \quad (\text{A2.4})$$

where

c = concentration of suspended solids (kgm^{-3})

V = volume of suspension (m^3)

The ratio of V/A in equation (A2.4) will be nearly constant during a test and is the depth of flow, d . By plotting the concentration of suspended solids against the average depth of erosion, a quadratic function (f_2) may be approximated, giving

$$c = f_2(h) \quad (\text{A2.5})$$

Differentiating equation (A2.5) and substituting into equation (A2.4) leads to the relationship

$$\rho_h = K_3 + K_4 h \quad (\text{A2.6})$$

Combining equations (A2.2) and (A2.6) leads to an expression which relates the erosion shear strength to the density of the exposed mud, and which can be approximated to the form

$$\tau_e = K_5 \rho_h^{K_6} \quad (\text{A2.7})$$

Intuitively, one would expect erosion to start when the stress exerted by the flow exceeded the shear strength of the exposed bed and the erosion rate to depend on the excess shear. If the erosive power of the stream is low not much erosion would be expected to take place. There will be times when a burst of turbulence slightly higher than average hits a slightly weaker part of the bed causing untypical erosion, but for practical purposes this can be ignored and it may be assumed that there is a cut off for erosion. The most common representation of erosion is

$$\begin{aligned} dm/dt &= Am_e(\tau - \tau_e) \quad , \quad \text{for } \tau \geq \tau_e & (A2.8) \\ dm/dt &= 0 \quad , \quad \text{for } \tau < \tau_e \end{aligned}$$

where

m_e = erosion constant ($\text{kgN}^{-1}\text{s}^{-1}$)

τ = applied shear stress (Nm^{-2})

This means that erosion is gradual which is not necessarily the case for certain types of newly formed slack water deposits. Although there is no physical reason for assuming erosion rate to be directly proportional to the excess shear, Delo and Burt (Ref A2.5) showed that this is a better variable for describing mud erosion than others. In any event it is not critically important in tidal conditions to know the erosion rate precisely because the erosion process is self correcting in the sense that if the erosion constant (m_e) is too high then too much erosion occurs in the early stages, but this exposes stronger bed material and erosion slows down accordingly. The opposite happens if m_e is under-valued. The ultimate result in any case would be erosion down to the bed level, where the strength of the exposed material corresponds to the maximum bed stress of the tidal

cycle or of the spring-neap cycle, if longer periods are being considered.

A useful analysis of the erosion constant can be made by assuming that the shear strength of the bed during any discharge run is proportional to the eroded mass (Ref A2.6). The constant of proportionality for a run is given by

$$\alpha = (\tau_b - \tau_o) / (c_e - c_o) \quad (A2.9)$$

where

τ_b is applied bed stress for the run

τ_o is shear strength of bed at start = equilibrium from previous run

c_e is equilibrium concentration at the end of run

c_o is initial concentration = equilibrium concentration at end of previous run

This does not assume that there is a linear relation between strength of bed and overlying weight for the complete bed. This overall structure is fixed by the equilibrium conditions at the end of each run. It is merely assumed that there is a linear variation from one equilibrium state to the next and α can vary for each run.

If it is further assumed that the erosion rate for the exposed mud surface area is given by equation (A2.8) , then using (A2.9) and replacing m by cV gives

$$dc/dt = Am_e\alpha(c_e - c_o)/V \quad (A2.10)$$

where V is the volume of fluid in the flume and A is the area of erosion. This can be integrated as

$$(c_e - c) = (c_e - c_o) \exp (-Am_e\alpha t/V) \quad (A2.11)$$

This solution exhibits the expected behaviour of concentrations, tending to equilibrium values for large times. Based on the analytic form of this theoretical solution, the carousel erosion flume results for a test can be normalised and plotted using linear (αt) (m^2s^{-1}) and logarithmic $[(c_e - c_0)/(c_e - c)]$ axes to give a representative erosion constant for the test.

References

- A2.1. Burt T N, Game A C. "The carousel: commissioning of a circular flume for sediment transport research", Hydraulics Research, Wallingford, England. Report SR 33, January 1985.
- A2.2. Besley P, Delo E A. "The hydrodynamics of the carousel", Hydraulics Research, Wallingford, England. Report SR 223, January 1990.
- A2.3. Graham D I. "Numerical modelling of turbulent water flow in the Hydraulics Research carousel flume". Polytechnic South West. Research Report MSOR-89-04.
- A2.4. Graham D I. "Numerical evaluation of wall shear stresses in the Hydraulics Research Carousel flume for various depths of flume". Polytechnic South West. Research Report MSOR-89-09.
- A2.5. Delo E A and Burt T N. "The hydraulic engineering characteristics of estuarine muds". Hydraulics Research, Wallingford, England. Report SR 77, December 1986.
- A2.6. Miles G V. "Numerical simulations of the erosion of marine mud", Hydraulics Research, Wallingford, England. Report SR 31, February 1985.

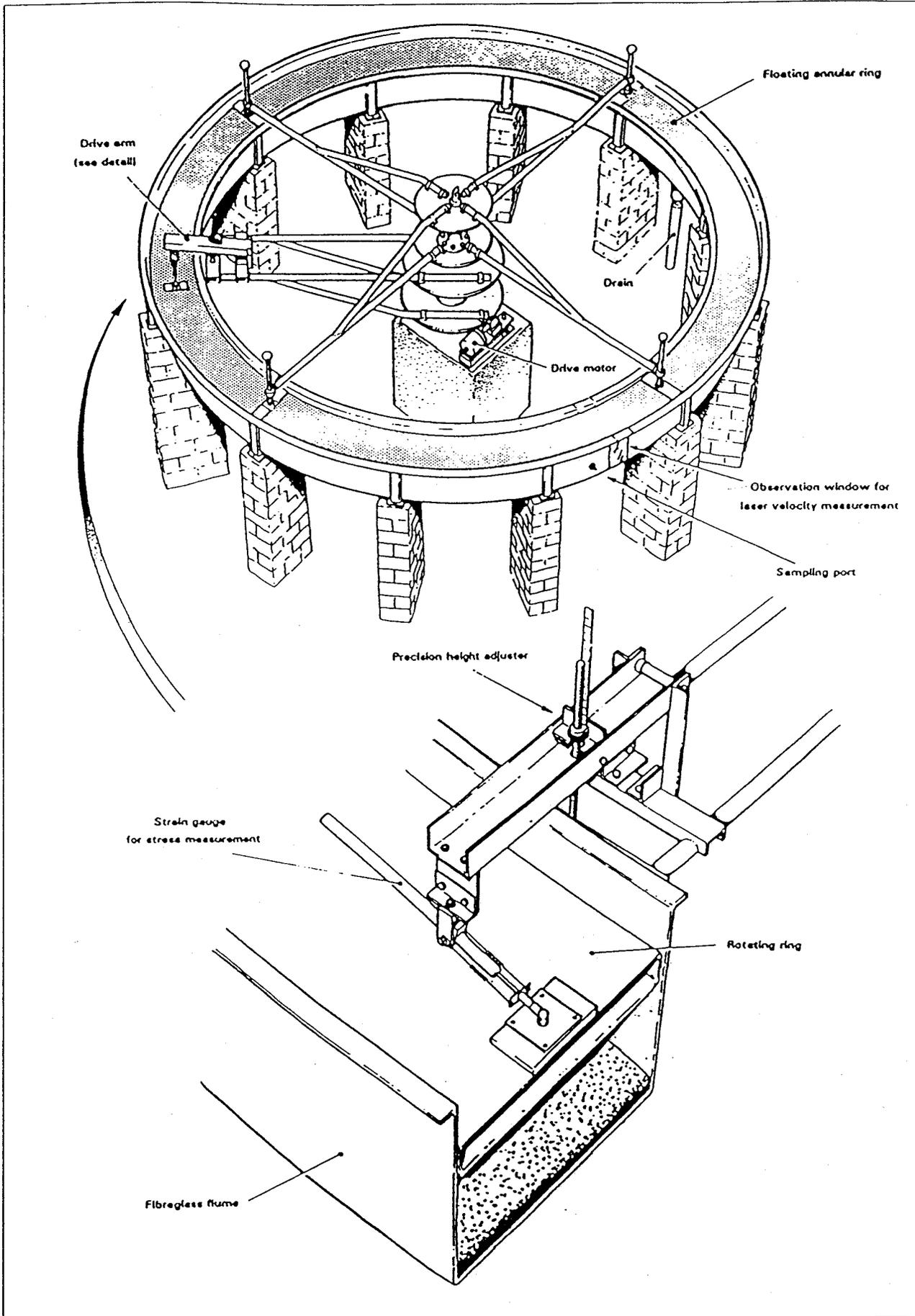


Fig A2.1 The carousel

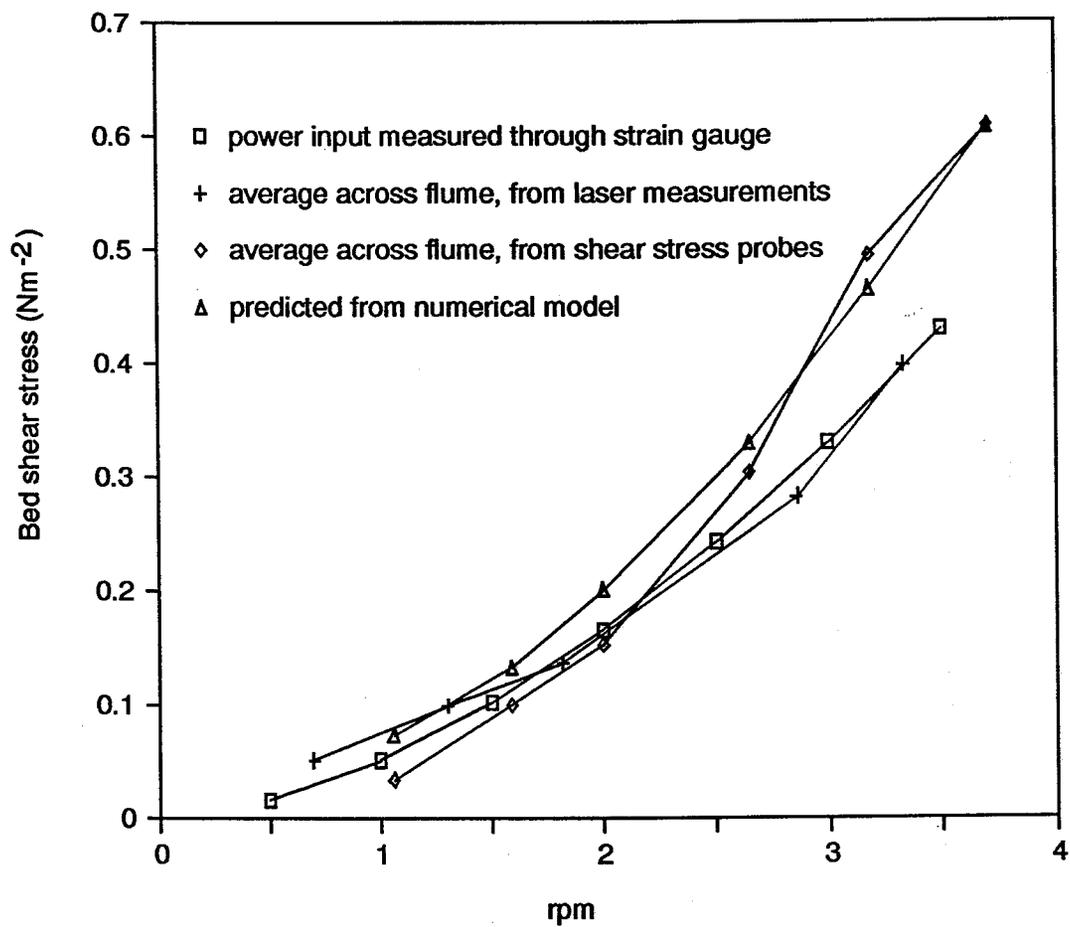


Fig A2.2 Average bed shear stress against roof speed

APPENDIX 3

WAVE EROSION TESTS : TEST PROCEDURE AND ANALYSIS

The objective of the wave erosion tests is to determine a threshold bed shear stress for erosion of mud of a known density and to calculate erosion rates above this critical shear stress. The relationship between density and critical peak bed shear stress is also of interest. This will assist in estimating the amount of mud eroded by waves in the field.

Description of apparatus

The tests are carried out in a wave flume 23m long and 0.3m wide, with a maximum water depth of 0.55m. There is a trough in the floor of the flume to hold the test bed, starting 9.5m from the end of the flume with the wave paddle. The trough is 8m long, 0.3m wide and 0.1m deep. At each end of the test bed section there is a raised lip to prevent mud escaping from the bed as bed load transport. There are available concrete blocks of 0.03 and 0.07m thickness to provide a false bottom to the trough and fill the trough for calibration purposes. A diagram of the wave flume apparatus is shown in Figure A3.1.

At one end of the flume are two wave generators, which can be set for monochromatic and random waves. For monochromatic waves, the user controls the wave frequency and wave height manually, by altering the stroke length and frequency on the generator. The random wave generator is controlled by a micro-computer. For random waves, the user inputs a zero crossing period and a significant wave height; the program generates a random wave spectrum which satisfies these input conditions. The wave spectrum

generated in this case is the JONSWAP spectrum. At the other end of the flume there is a shingle spending beach to absorb the wave energy and hence minimise wave reflections back into the flume.

An ultrasonic probe mounted above the bed on a computer controlled robot is used to monitor the surface level of the mud bed at intervals along the length of the bed. At positions throughout the test section water pressure transducers are mounted below the water surface and the signals logged onto a computer. The wave spectrum is determined by analysis of the water pressure signals.

A conductivity probe is used to determine the vertical bed density profile in situ. It is assumed that the conductivity of the pore water in the mud bed is constant and, hence, the overall conductivity of the mud is a function of its pore volume ie. its density. The instrument is calibrated using samples of known dry density of the mud under investigation and with saline solutions of known density. The calibration samples have dry densities typically in the range 50kgm^{-3} to 500kgm^{-3} .

A turbidity sensor is used to measure suspended sediment concentrations at various depths and positions along the flume, at time intervals throughout each test. The instrument used is an Analite Nephelometer, which operates on the principle of backscatter of infra red light. The degree of backscatter is proportional to the reflection coefficient and concentration of suspended sediment.

Test procedure

A uniform slurry is made up from the collected mud sample by dilution with saline water. This slurry

usually has a dry density in the range 300kgm^{-3} - 500kgm^{-3} . This is then poured into the test section of the flume.

The mud is then subjected to a pattern of waves, either monochromatic or random waves. The wave generating equipment is capable of generating higher peak bed shear stresses with monochromatic waves. The wave period is fixed for the duration of the test. The input parameter of wave height (significant wave height for random waves) is changed up to four times during a test; each wave height is imposed for one hour, then it is changed so that the resulting peak bed shear stress is increased.

The vertical density profile of the bed is determined with the conductivity probe before the start of a test and at half-hourly intervals during a test. This monitors changes in bed density caused by consolidation or wave action.

The bed levels at 0.5m intervals along the test section are measured at the start of the test and at half-hourly intervals with the ultrasonic probe.

The concentration of suspended sediment is measured every 30 minutes. Turbidity readings are taken at several heights in the water column at positions along the entire length of the flume.

Analysis

The objective of the tests is to determine the critical bed shear stress at which erosion of the bed commenced. For monochromatic waves, the peak bed shear stress can be calculated from the water depth and wave characteristics using first order linear wave theory (Ref A3.1) such that:

$$U_m = \frac{\pi H}{T \sinh(2\pi d/L)} \quad (A3.1)$$

where

U_m = maximum bottom orbital velocity (ms^{-1})

H = wave height (m)

T = wave period (s)

L = wave length (m)

d = water depth (m)

The magnitude of the wave length is determined iteratively from:

$$\omega^2 = gk \tanh(kd) \quad (A3.2)$$

where

$\omega = 2\pi/T$ (s^{-1})

g = acceleration due to gravity (ms^{-2})

$k = 2\pi/L$ (m^{-1})

The peak bed shear stress is estimated using the following relationship :

$$\tau_m = 0.5 \rho_w f_w U_m^2 \quad (A3.3)$$

where

τ_m = peak bed shear stress (Nm^{-2})

ρ_w = fluid density (kgm^{-3})

f_w = wave friction factor

U_m = maximum bottom orbital velocity (ms^{-1})

The wave friction factor is dependent upon the wave reynolds number and the relative roughness (Ref A3.2).

For random waves, the surface elevation spectrum generated is the JONSWAP spectrum:

$$S(f) = 4.732 \cdot 10^{-4} \exp(-1.25 f_m^4 f^{-4}) f^{-5} 3.3^x \quad (A3.4)$$

with

$$x = \exp(-(f f_m^{-1} - 1)^2 y^{-1})$$

$$y = 0.0162 \text{ if } f > f_m$$

$$= 0.0098 \text{ if } f \leq f_m$$

where

f = frequency of ordinate

f_m = frequency at which spectral peak occurs

$$= 0.87T_z^{-1} \quad \text{or} \quad = 0.217H_s^{-0.5}$$

T_z = mean zero crossing period (seconds)

H_s = significant wave height (m)

$S(f)$ = value of spectral ordinate at frequency f

Where both T_z and H_s are input, T_z is used as the defining value and the spectrum magnitude is defined with an implied gain. The near-bottom velocity cannot now be described by a single U_m , and is usually described by the standard deviation, U_{rms} , of the time-series of instantaneous velocities. U_{rms} can be approximated as a function of H_s and T_z (Ref A3.1):

$$U_{rms} T_n / H_s = 0.25 / (1 + At^2)^3 \quad (\text{A3.5})$$

where

$$A = (6500 + (0.56 + 15.54t)^6)^{1/6}$$

$$t = T_n / T_z$$

$$T_n = (d/g)^{0.5} \quad \text{scaling period}$$

d = water depth

g = acceleration due to gravity

This fits the JONSWAP curve to an accuracy of better than 1% in the range $0 < t < 0.55$. For equivalent monochromatic waves and random waves with the same variance of bottom orbital velocities

$$U_m = \sqrt{2} U_{rms} \quad (\text{A3.6})$$

The bed shear stress can therefore be calculated according to equation A3.3, using $\sqrt{2} U_{rms}$ in place of U_m , yielding a representative bed shear stress for the wave spectrum. The equations used to calculate a representative bed shear stress from the bottom orbital velocity are given in Table A3.1.

The total mass of mud eroded per unit area of bed is calculated by two methods for each half hour time interval. Firstly, the difference in bed levels at successive time intervals is calculated, giving a depth of erosion. An allowance is made for consolidation, if this has occurred. Multiplying the depth of erosion by the bed density gives the mass eroded per unit area of bed surface. Secondly, the suspended concentrations at intervals throughout the flume are integrated to give the total mass in suspension for each set of readings. The total mass in suspension is normalised to give mass eroded per unit area of bed surface.

An erosion constant may be found from a relationship between the excess bed shear stress and the rate of entrainment, which is given by:

$$dm/dt = m_{ew} (\tau_{bm} - \tau_{be}) \quad (A3.7)$$

where

dm/dt = rate of erosion ($kgm^{-2}s^{-1}$)

m_{ew} = erosion constant under waves ($kgN^{-1}s^{-1}$)

τ_{bm} = bed shear stress (Nm^{-2})

τ_{be} = critical bed shear stress (Nm^{-2})

References

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A3.2. Delo E A. "Estuarine muds manual" Hydraulics
Research, Wallingford, England. Report No SR 164,
February 1988.

TABLE A3.1 Equations used in calculation of bed shear stress from bottom orbital velocity

Input parameters

U_{rms}	Root-mean-square bed orbital velocity for random waves (ms^{-1})
T_z	Mean zero crossing period (s)
ν	Viscosity of fluid (m^2s^{-1})
ρ	Density of fluid (kgm^{-3})
k_s	Nikuradse equivalent grain roughness (m)

Calculated parameters

U_m	Orbital velocity for equivalent monochromatic wave (ms^{-1})
A	Semi-orbital excursion length (m)
R_w	Wave Reynolds number
r	Relative roughness (a/k_s)
F_s	Smooth friction factor
F_r	Rough friction factor
F_w	Wave friction factor
τ	Representative bed shear stress for random wave spectrum (Nm^{-2})

Equations used

$$U_m = \sqrt{2} U_{rms}$$

$$\tau = 0.5 \rho F_w U_m^2$$

$$A = U_m T_z / 2\pi$$

$$R_w = U_m A / \nu$$

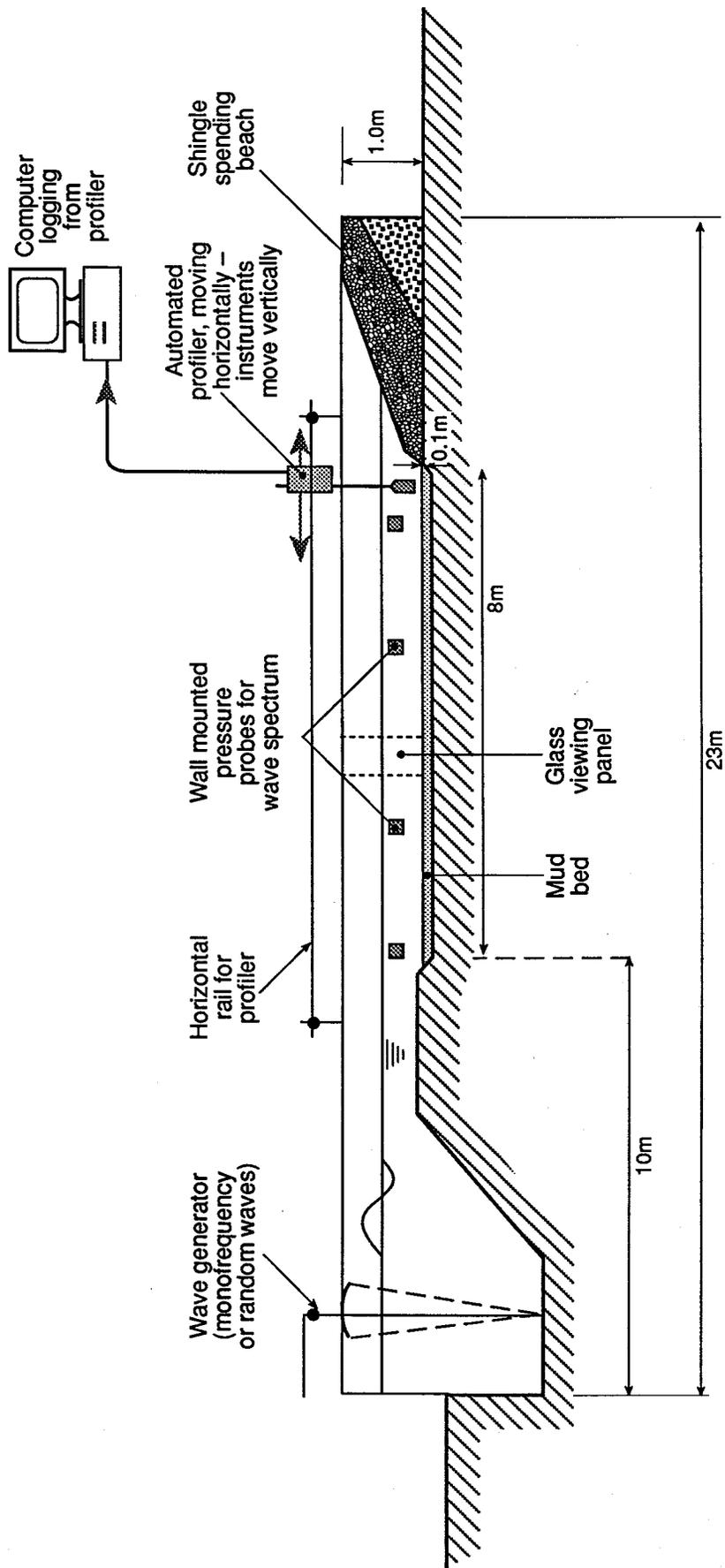
$$F_s = 2 R_w^{-0.5} \quad \text{if } R_w < 5 \cdot 10^5 \quad \text{Laminar}$$

$$F_s = 0.0521 R_w^{-0.187} \quad \text{if } R_w > 5 \cdot 10^5 \quad \text{Smooth turbulent}$$

$$F_r = 0.3 \quad \text{if } r < 1.57 \quad \text{Rough turbulent}$$

$$F_r = 0.00251 \exp(5.21 r^{-0.19}) \quad \text{if } r > 1.57 \quad \text{Rough turbulent}$$

$$F_w = \max(F_s, F_r)$$



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Fig A3.1 The wave flume

APPENDIX 4

INVESTIGATION INTO THE VARIATION IN BED SHEAR STRENGTH WITH DIFFERENT OVERLYING WATER TYPES.

Background

In some laboratory equipment it is necessary or desirable to use fresh water as the eroding medium. As this does not simulate the natural situation, a short investigation was carried out to investigate the effect of the eroding medium on the shear strength of the mud sample.

Test Procedure

Three different water mediums were used in the carousel to deposit and erode beds, starting from the same sample of mud.

A description of the carousel apparatus, test procedure and calculation of shear stress are given in Appendix 2.

The three water types used were original seawater, collected from the same site as the mud (15.5kgm^{-3} salt), artificial seawater made from NaCl(s) and tap water (26.0kgm^{-3} salt), and freshwater (3.7kgm^{-3} salt). The freshwater contained some saline pore water from the mud. In each test the initial depth of the mud suspension was 110mm, and the beds were allowed to settle for a period of 2.7 days prior to erosion. After this period of settling, the carousel roof speed was rotated, increasing the rotation speed in steps, and therefore applying an increasing shear stress on the surface of the deposited bed. The same steps of shear stress were applied in each test.

The shear stress was held constant at each step until no further erosion was observed. At this time, the shear strength of the bed was assumed to be equal to the shear stress applied by the overlying flow. The suspended solids concentration, measured at a point in the middle of the carousel channel, was continuously recorded on a chart recorder.

The applied shear stress at the onset of erosion was calculated from a numerical model of shear stresses in the carousel, recently developed at the Polytechnic South West (Ref A4.1). This indicated that the shear stress in the carousel can be related to the roof rotational speed (rpm) as a power law. This law varied for different depths of flow and for the position across the width of the flume.

The mean densities of the layers of eroded mud were calculated from the ultrasonic probe measurements of bed thickness and the increase in suspended solids concentration after each increase in applied shear stress. The densities were calculated from the volume of material lost from the bed and the mass of material which caused an increase in the overlying water concentration. For each overlying water type, values of erosional shear strength of bed and dry density were calculated for each applied shear stress.

Results

The erosion shear strength of the bed has been plotted against dry density for each of the different eroding fluids (Fig A4.1). The figure shows error bars for the measurements of density and erosional shear strength ($\pm 20\%$ for density and $\pm 10\%$ for the shear strength). It can be seen that

the variation in erosion shear strength with density lies within the error bars. On comparison with other experiments performed on muds from the same site and with identical water mediums, the variation in these results is not significant. The results of these tests suggest that the erosional shear strength with density relationship is not affected by the water medium of the overlying suspension.

This investigation is limited to beds which were mixed with water and deposited from suspension. Therefore, the pore water in the bed was the same as the overlying water. This would not necessarily be the case where an undisturbed sample is brought into the laboratory to be tested. However, these results suggest that the effect would be within the natural variability expected from the erosion tests.

Reference

- A4.1 Graham D I, 1989, "Numerical evaluation of wall shear stresses in the Hydraulics Research Carousel flume for various depths of flume". Polytechnic South West, Research Report MSOR-89-09.

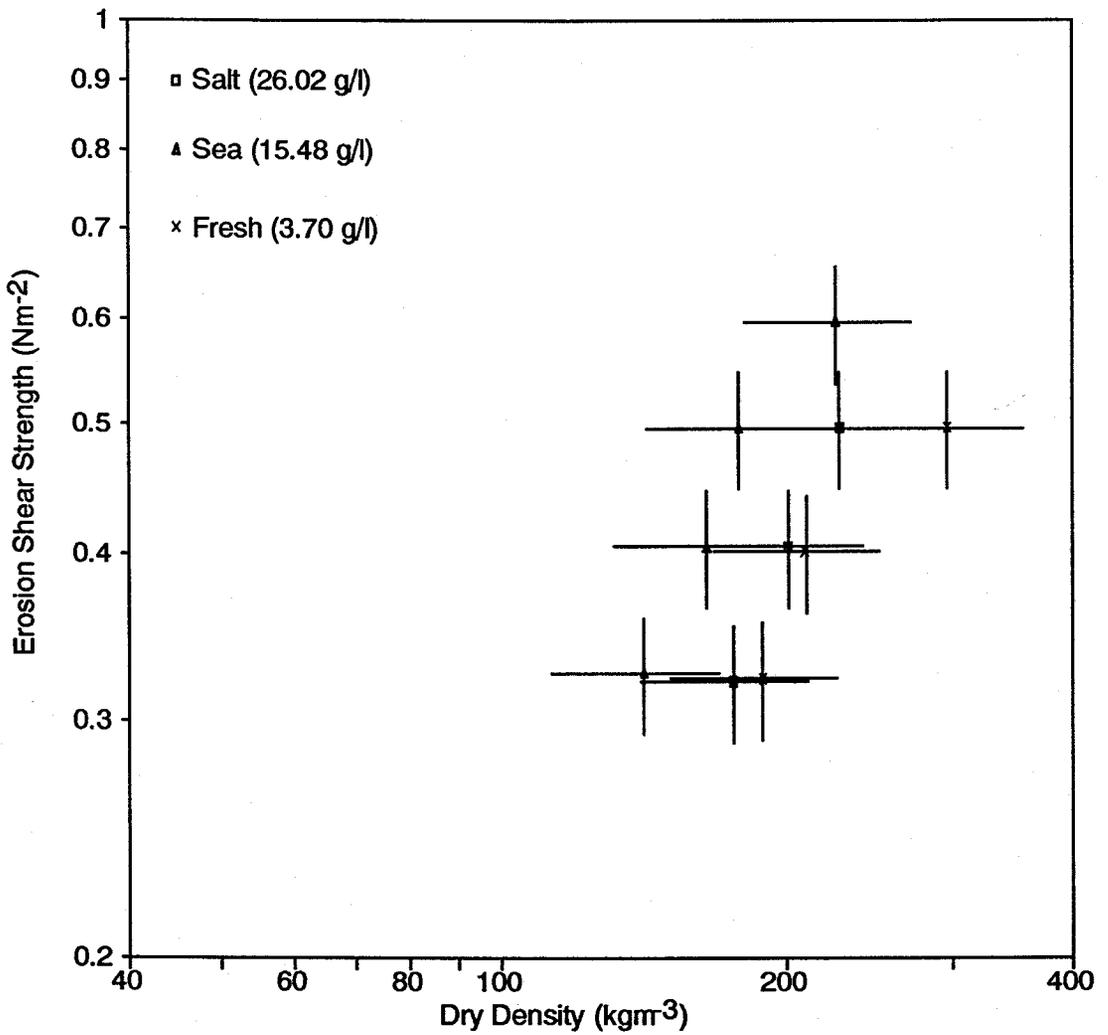


Fig A4.1 Bed shear strength with density for different overlying water types