Hydraulics Research
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SLUDGE DISPOSAL TO SEA:
SETTLING, CONSOLIDATION AND EROSION CHARACTERISTICS OF SEWAGE SLUDGE

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CONTRACT

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ABSTRACT

Hydraulics Research has been involved for many years in studying the behaviour of sewage sludge discharged into the marine environment. Approximately 25% of the sewage sludge produced in the UK is disposed of at sea at licensed dumping grounds such as that in Liverpool Bay. This report describes recent laboratory investigations into the effects of turbidity in the water column on the settling velocity, consolidation and eventual resuspension of sewage sludge obtained from Davyhulme Sewage Treatment Works.

Settling tube tests were set up to investigate the effect of mud on the settling velocity of a sludge/mud slurry. These tests revealed a linear increase in median settling velocity (W_{50}) with the proportion of mud in the slurry.

Further settling tests were carried out to identify a relationship between settling velocity and slurry concentration. Sludge, mud and a 50:50 mixture by weight of the two were tested independently, each material at 8 different concentrations. In general terms the equal mixture of sludge and mud had the highest settling velocities for a given concentration with the mud having the lowest. Both, however, tended to increase with concentration. The sludge showed no clear relationship between settling velocity and concentration of slurry.

Consolidation tests on the sludge revealed that the sludge bed was very slow to consolidate and after 2 days had only reached a mean density of 20g/l with a very small density gradient from the surface to the bottom of the bed. The density profile of the settled mud bed after 2 days exhibited a uniform 'S' shape, a characteristic of mud beds. The bed had consolidated to a thin layer with a mean density of 385g/l and a large density gradient between the surface and the bottom of the bed, which would provide more resistance to erosion. The density profile of the 50:50 mix after 2 days lies between the two extremes of the poorly consolidated sludge bed and the dense mud bed. The general form is very similar to that of the mud bed, indicating the importance of the mud fraction in the consolidation of the bed.

The resistance of a sludge bed to re-erosion was measured; as a sludge bed, as a sludge layer on top of a mud bed and as a combination of sludge and mud. Sludge alone and sludge settled on a mud bed had a very similar resistance to erosion. The critical shear stress for erosion was less than $0.02N/m^2$. The sludge/mud combination consisted of a stratification of mud, sludge and mud, and mud rather than a homogeneous bed. The critical shear stress for the top layer of mud was approximately $0.1N/m^3$. Once the protecting mud layer had been removed the exposed sludge layer was subjected to rapid erosion.

The tests indicate that the presence of mud in the water column through which a sewage sludge is settling has a significant effect on the behavioural characteristics of the sludge. The results suggest that settling velocity will be increased and consolidation will be faster than for sludge alone. This will result in a bed with more resistance to erosion. The extent of the effect is likely to be proportional to the ratio of sludge to mud.

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1 INTRODUCTION

Hydraulics Research (HR) was commissioned by the Department of the Environment (DoE) to carry out a programme of research investigating the hydraulic aspects of sewage sludge disposal to sea. Approximately 10 million tonnes bulk weight of sewage sludge per year are currently released into British coastal waters at 15 sites. One at these sites, Liverpool Bay, has been the subject of much investigation by various research bodies, including HR, on behalf of DoE (Department of the Environment, 1972).

The programme of work at Hydraulics Research consisted of:

(i) Laboratory studies to examine the depositional and erosional characteristics of sludge on a rippled sand bed, simulating conditions that are known to occur at the sea bed in Liverpool Bay (Burt and Turner, 1983).

(ii) Field exercises to observe and measure the near-bed flow velocities and associated sand bed movement in Liverpool Bay (Hydraulics Research, 1986).

(iii) Development of a new mathematical model designed to simulate tidal flow, circulations and transport of heavy metals associated with sewage sludge and marine effluent in Liverpool Bay (Hydraulics Research, 1985).

In addition, HR has carried out a series of tests for the Water Research Centre (WRC) to study the settling and dispersive properties of both 'ordinary' and thickened sewage sludges (Hydraulics Research, 1983a,b and Hydraulics Research, 1984). For more cost-effective transport, the dumping of thickened sewage sludge may be a viable alternative to present practices.

The experiments described in this report were set up to investigate the effect of turbidity on the settling velocity, consolidation and subsequent erosion of sewage sludge dumped in turbid waters (as occurs in the natural environment).

2 SETTLING OF SEWAGE SLUDGE

Two series of settling tests were carried out by Hydraulics Research in 1984 (Series I) and 1986 (Series II). The aim of the first series of tests was to investigate the effect of settling a sludge slurry through a muddy suspension. The second series of tests was a natural progression from the first and these were set up to identify the relationship between the settling velocity and the slurry concentration of various sludge and mud combinations.

The tests were performed in the HR Sedimentation Laboratory, using apparatus which had been specifically designed for an earlier study investigating the settling of thickened sewage sludge (Hydraulics Research, 1983a,b).

In order to reduce the number of variables encountered during each series of tests, similar sub-samples of mud were used from a bulk sample obtained from Liverpool Docks (River Mersey) in 1984. A size grading of the material is shown in Figure 1, illustrating that it comprises 97% silt (< 63μm).

For each series of tests a sample of sewage sludge was obtained from Davyhulme Sewage Treatment Works in Manchester. The material was typically 40% digested and 60% undigested, although this was subject to fluctuation. The sludge sample used in the Series I tests had a dry density of 82g/l, and that used in the Series II tests a density of 30g/l. The difference in the measured concentrations was not considered to be important as each of the tests was carried out by dry weight rather than volume.

2.1 Settling tests - Series I

This series of settling tests was designed to investigate the effect of mud on the settling velocity of a sludge slurry.

2.1.1 Procedure

In order to control the variables finely, each settling test used the same dry weight of material. Eleven tests were carried out ranging from 100% of mud by dry weight to 100% of sludge by weight. By varying the ratio of sludge/mud contained within the slurry it was possible to establish the effect of progressively combining the two materials. The composition of the sludge/mud mixture for each test is shown in Table 1.

The following procedure was used for each test. A predetermined amount of the material combination was thoroughly mixed with salt water (28 ppt) to produce a slurry volume of 500ml. A 0.05m diameter, 1.6m high perspex settling tube was filled with 2.5 litres of salt water (28 ppt). Using a specially designed injection system the prepared slurry was introduced at the top of the tube so that it had no initial downward velocity. This was considered to be the start of the test. At predetermined time intervals after this, 330ml samples of the liquor were drawn from the bottom of the tube and subsequently analysed for sludge/mud content. By this method the settling velocities were calculated.

2.1.2 Observations

The test observations are summarised below:

(i) On injection of the 500ml slurry a dark cloud formed at the top of the water column. This feature occurred at the start of all the tests with the exception of the high mud to sludge ratios (> 80% mud).

(ii) A few particles immediately began to settle to the bottom of the tube.

(iii) After 2 minutes, flocculation was taking place at the interface between the darker cloud and the water beneath it.

(iv) After 5-10 minutes (depending on the sludge/mud ratio) flocculation was well advanced and settlement was more rapid.

(v) Settlement was complete after 3 hours at which time the cloud could still be seen at the top of the water column.

2.1.3 Results

For each test a graph of settling velocity against percentage below stated velocity was obtained. Examples of these graphs are shown in Figure 2, comparing the settling velocities results from tests 1, 6 and 11. The graph indicates that as the proportion of sludge in the mixture was increased, the percentage of material settling at less than some fixed settling velocity also increased.

The median settling velocity (W_{50}) is defined as the settling velocity which is not exceeded by 50% of the material. Similarly, 10% of the material has a settling velocity less than W_{10}. The settling velocities W_{10} to W_{90} for each of the eleven tests are shown in Table 2.

The median settling velocity for each test is plotted against its respective sludge/mud composition in Figure 3. A least squares regression line was fitted to the data and is also shown on the graph, demonstrating that a linear relationship existed between median settling velocity (W_{50}) and the ratio of sludge to mud for a slurry of constant dry weight. The graphs shows that the median settling velocity increases with the proportion of mud in the slurry.

2.2 Settling tests - Series II

The aim of this series of settling tests was to identify the relationship between settling velocity and concentration for slurries of sewage sludge, mud and a combination of the two components.

2.2.1 Procedure

The procedure adopted in this series of tests was identical to that adopted in the first series of tests, using the same laboratory apparatus. The three compositions, tested independently, were Davyhulme sludge, Mersey mud and a mixture of the two (50:50 by dry weight).

Eight tests were carried out on each mixture. In each case, 500ml of slurry was made up with between 0.050g and 0.500g total dry weight of material thus giving eight different concentrations for each mixture. (This is compared with the Series I tests where the mixture was made up with a fixed total dry weight of 0.410g). As in the Series I tests the water and slurry salinities were held constant at 28ppt.

2.2.2 Observations

The Series II tests observations are summarised below:

(i) In all the settling tube tests the 500ml slurry took on the appearance of a dark layer overlaying the clearer saline water. During both the sludge and mud tests the depth of the layer remained constant (0.3m) throughout the 3 hour period, visibly reducing in density as material settled and dispersed from the layer into the water below.

(ii) During the tests on the sludge/mud mixture the layer expanded to 80% of the tube length within 10 minutes; this expansion did not appear to be concentration dependent.

(iii) The material was observed to settle faster in the sludge tests than in the mud tests.

(iv) The material in the mixture tests settled faster than either of the two constituents.

(v) During all of the tests the lower concentrations resulted in more swirling of the flocs as they settled. The swirling observed in the mud and the sludge/mud mixture tests was greater than that observed in the sludge tests.

2.2.3 Results

For each settling test a graph of settling velocity against percentage below stated velocity was obtained. Examples are shown in Figure 4, comparing the settling velocity of sludge, of mud and of a 50/50 sludge/mud mixture by dry weight. In each test shown in Figure 4 the 500ml slurry contained approximately 0.280g dry weight of solids.

Table 3 summarises each of the 24 settling tests in terms of settling velocity with respect to percentage of total sample weight. Figure 5 is a summary graph of total dry weight against median settling velocity (W_{50}) for each of the tests. The results show that for most slurry concentrations up to 1.0g/l the equal mixture of sludge and mud had the highest settling velocities. These settling velocities increase approximately in proportion to the slurry concentration starting at 0.12mm/s (0.1g/l) and rising to 0.77mm/s (1.0g/l). The Mersey mud generally had the lowest settling velocities. However, the settling velocity still increased with slurry concentration up to a concentration of 0.55g/l whereafter it remained reasonably constant at 0.35mm/s. The Davyhulme sludge gave no clear pattern of variation of settling velocity with slurry concentration. At a concentration of 0.3g/l the settling velocity reached a peak of 0.4mm/s but then showed a sharp decline in settling velocity as the concentration was increased. After a concentration of 0.5g/l the sludge again exhibited an increase in settling velocity with concentration and had a settling velocity of 0.62mm/s at 1.0g/l.

3 CONSOLIDATION OF A SLUDGE BED

Initially, three consolidation tests were carried out with the aim of investigating the effect of mud on the consolidation characteristics of a sludge slurry, using material collected from the Davyhulme Sewage Works. The three tests examined a bed of sludge, a bed of mud and a 50/50 combination by dry weight of the two materials respectively. Two further tests were carried out - the results from these were required in the analysis of the erosion tests (Section 4).

All the consolidation tests were carried out in a perspex settling column with internal diameter 0.092m and height 10m. Once a sediment bed had formed in the bottom of the column its density-depth profile could be measured at any time. Measurements were made using a Harwell radioactive transmission probe mounted on a purpose-built frame which allowed it to be moved up and down the column. The instrument was calibrated using salt solutions of known concentration in the column. In the analysis of the data, allowance was made for the deterioration in the strength of the source after calibration, according to its known half-life.

3.1 Sludge test

The settling column was filled to 5.6m with salt water (32ppt). A slurry was then prepared by mixing 150g dry weight of sludge with 15 litres of salt water (32ppt). The slurry was then poured into the top of the column giving a total depth of 7.85m.

The sludge-water interface took about 45 minutes to reach the base of the column, although it was preceded by larger particles which had broken away from the dispersing mass. Considerable flocculation was observed in the falling slurry; the flocs were small and densely packed. After about 60 minutes a 0.05m frothy layer had formed at the top of the column and remained throughout the rest of the test.

After all the sludge (except that remaining in the frothy layer) had settled onto the bed (about 9 hours) it consolidated rapidly for 4 hours after which time the consolidation rate gradually decreased towards the end of the test (7 days). After 2 days consolidation the bed had reached a thickness of 0.485m and was profiled using the radioactive probe. The measured density-depth profile is reproduced in Figure 6, showing a natural scatter in the results for a bed of very low density (mean density 20g/l).

3.2 Mud test

The same procedure was adopted as for the sludge test. Approximately 150g dry weight of River Mersey mud was made up to a volume of 15 litres using salt water (32 ppt). The prepared slurry was poured into the top of the column resulting in total depth of 7.85m. After about 4 minutes the mud had fully dispersed throughout the entire depth of the column. The bed reached its maximum thickness after 2 hours and then rapidly consolidated over the next 8 hours after which the rate of consolidation decreased towards the end of the test.

As with the sludge bed, the mud bed was profiled after 2 days consolidation. The measured density-depth profile is shown in Figure 6, illustrating that the bed had consolidated to a thickness of 0.051m, (one-tenth the thickness of the sludge bed consolidated for the same period). The mean density of the bed was 385g/l.

3.3 Sludge/mud test

As the results from this test were to be compared with those of the first two tests it was decided to use the same amount of each material: 150g sludge and 150g mud were made up into a 15 litre slurry. Salt was added to the slurry until a salinity of 32 ppt was reached. Again the column was filled to a depth of 5.6m with water of the same salinity. The prepared slurry was poured into the top of the column resulting in a total depth of 7.85m. After 28 minutes the slurry interface had reached the bottom of the column. The flocs within the slurry were observed to be small and densely packed.

After the resulting bed had been allowed to consolidate for 2 days, the density profile was measured using the radioactive probe. The thickness of the bed at this stage was 0.56m, with a mean bed density of 65g/l. The density-depth profile is shown in Figure 7, along with profiles of the bed after 7 and 33 days. It can be seen that the density profile is smoothed out as the bed consolidates with time.

3.4 Results

Mud beds which have been settled out of suspension and consolidated commonly demonstrate a density profile which increases from zero at the surface of the bed to a maximum at the bottom, with a characteristic 'S' shape. This is shown by the Grangemouth mud in Figure 8. The potential for resuspension by erosion of a bed depends on the surface density of the bed and how quickly the density of the bed increases with depth.

Comparing the 2 day density-depth profiles for each test shows that the sludge bed has a very small change in density between the surface and the bottom of the bed (which has a maximum density of about 40g/l) and will therefore have less resistance to resuspension by erosion than the mud bed, which has a very large change in density over a comparable depth.

The bed settled from the sludge/mud mixture (Figure 7) shows a profile between the sludge bed profile and the mud bed profile, with an increase in density with depth, particularly at the bottom of the bed. This indicates that the mud fraction makes a significant contribution to the consolidation of the bed, which increases its resistance to erosion.

4 EROSION OF A SLUDGE BED

4.1 Introduction

Three erosion tests were carried out to investigate the erodibility of a bed of sewage sludge and to identify a possible relationship between bed configuration and resistance to erosion. Each test used a different bed preparation procedure as follows:

1. A sludge bed was settled through salt water and allowed to consolidate for 7 days before testing;

2. A bed of mud was first settled into the erosion flume and left to consolidate for 7 days. A sludge bed was then settled on top of the mud and allowed to consolidate for 2 days before testing;

3. A mud bed was settled out of suspension. After 2½ hours consolidation, a small amount of mud still remained in suspension, at which time a sludge slurry was added to the erosion flume. This resulted in a bed of sludge sandwiched between layers of mud. The test was carried out after a further 24 hours consolidation.

As for all the studies carried out for the Department of the Environment the sludge used in these tests came from Davyhulme Sewage Treatment Works in Manchester.

Ideally, mud from the River Mersey (as in the settling and consolidation tests) would have been used as a base material in the second and third tests. However, in order to reduce the number of variables encountered it was decided to use Grangemouth mud, a mud with properties more thoroughly understood by Hydraulics Research. Mud obtained from Grangemouth Docks, located on the south bank of the Forth Estuary, has been intensively studied by HR (Hydraulics Research, 1977) and its erosional properties well established.

Comparison of the density structures of beds of Mersey, Grangemouth and Junin (Peru) muds consolidated over a similar period of time (Fig 8) indicate that the bed structures of Mersey and Grangemouth muds are not radically different.

4.2 Erosion Tests

4.2.1 Erosion Flume Facility

The erosion flume has a rectangular cross-section 0.3m wide and 0.2m deep. This channel consists of an entry section (8.5m long), a working section (7.3m) and an exit section (1.8m). Regularly spaced glass windows in both sides of the entry and working sections allow observations of the settled bed to be made during a test. The roof of the working section can be entirely removed and replaced with an open-bottomed tank, thus converting it into a 2m deep, 0.3m wide and 7.3m long settling tank. This is used to hold the slurry suspension from which a bed is deposited on to the floor of the working section. A variable speed axial-flow pump located in the return pipe provides flow through the closed-loop system.

During an erosion test measurements of water discharge, suspended solids concentration and temperature are regularly made. The shear stress on the bed due to the flow is calculated from the pressure gradient along the working section, which is measured at seven positions along the length of the bed.

The facility is described in more detail in a previous report (Hydraulics Research, 1977).

4.2.2 Erosion Test 1

A bed of Davyhulme sludge was settled in the working section of the flume and allowed to consolidate for a period of 7 days after which it had attained a thickness of 0.055m. The settling tank was then removed from above the working section of the flume and the roof section bolted back into place.

Before the start of an erosion test the axial flow pump was run for 30 minutes at its minimum discharge (mean flow velocity = 0.12m/s) in order to clear any air trapped in the system and to pick up any material in places other than the working section. Just before the start of the test, samples were removed from the flow and averaged to determine the background concentration for the test. For Test 1 the background was approximately 0.022g/l.

The test was a run in a number of discrete phases with the water discharge Q, (and hence mean flow velocity), being increased in discrete steps by increasing the speed of the axial-flow pump. After each increase the discharge was generally held constant until the concentration of the withdrawn samples became constant. This was termed the equilibrium condition and signalled the end of a phase, after which the discharge was increased to the next desired value.

Figure 9 shows the concentration, mean flow velocity and applied shear stress against time for Test 1. It can be seen that by the end of the first phase (mean flow velocity 0.14m/s), the concentration of the flow had reached an equilibrium at approximately 0.230g/l. This suggested that the critical shear stress for the start of erosion of the sludge bed had been exceeded. The shear stress applied to the bed at this discharge was calculated to be less than $0.02 N/m^2$.

During the second phase (mean flow velocity 0.21m/s), the concentration increased by a factor of four, indicating mass erosion of the bed. By the end of the third phase (mean flow velocity 0.25m/s) more than half the original bed had been eroded. The test was stopped at this stage as it was suspected that the bed along the centre of the flume had eroded down to the flume floor due to the severe scouring action observed.

4.2.3 Erosion Test 2

A bed of Grangemouth mud was settled into the working section of the flume. After 7 days consolidation the bed had a thickness of 0.048m. A slurry of sewage sludge was then pumped into the top of the settling tank and allowed to settle on top of the existing mud bed. After a further two days the sludge layer had attained a thickness of 0.010m (i.e. a total thickness of about 0.058m).

To give an indication of the likely density profile of the bed a consolidation test was conducted by settling a sludge bed on top of a mud bed. A bed of Grangemouth mud was settled on to the base of a settling column and allowed to consolidate for 24 hours after which a sludge slurry was poured into the clear water overlying the mud bed. After a further 1 and 6 days, the resulting bed was profiled using the Harwell radioactive transmission probe. The density profile of the bed after 7 days consolidation is shown in Figure 10, illustrating the layer of low density sludge at the top of the bed, above the higher density mud layer.

As the critical shear stress for the start of erosion of the sludge bed was exceeded in Test 1, it was decided to increase the discharge in smaller increments so that the critical velocity for erosion could be determined more accurately. The axial flow pump was run at its minimum speed (mean flow velocity = 0.12m/s) during the first phase. Even at this flow velocity the sludge bed was observed to be undergoing erosion. This indicated that the critical velocity for erosion of the sludge is less than 0.12m/s. Figure 11 illustrates that the bed shear stress associated with this flow velocity was approximately $0.01N/m^2$.

During the next three phases sludge continued to be eroded from the bed surface until by the end of the fourth phase (mean flow velocity 0.21m/s) all of the sludge had been resuspended, leaving the mud bed exposed. The erosion test was continued until mass erosion occurred at a bed shear stress of approximately 0.68N/m^2.

4.2.4 Erosion Test 3

The aim of the third erosion test was to reproduce the sea bed conditions which may occur in turbid water. For this purpose a mud slurry was introduced into the settling tank and allowed to settle out of suspension for 2½ hours. A slurry of sludge was then also pumped into the tank. The two slurry suspensions were allowed to settle and consolidate for a further 24 hours after which time a layered bed had formed. This consisted of a mud bed 0.051m thick covered by a sludge/mud bed 0.008m thick which in turn was covered by a further thin layer of mud about 0.003m thick. This stratification of the bed existed because the sludge had a faster settling velocity than the fine mud fraction.

During the first phase (mean flow velocity 0.12m/s), erosion did not take place. At the second and third discharges (bed shear stress approximately 0.1N/m^2) the surface mud layer was resuspended (see Fig 12) leaving the sludge bed exposed. The large increase in suspended solids concentration observed during the fourth phase (mean flow velocity 0.20m/s) was due to erosion of the sludge. The bed shear stress associated with this flow velocity was about 0.12N/m^2. The sludge continued to be resuspended during the fifth and sixth phases, bed shear stresses of up to 0.34N/m^2 being recorded. At the start of the seventh phase all the sludge had been eroded, leaving the mud bed exposed. Mass erosion of the mud bed took place during the seventh and eighth phases.

5 CONCLUSIONS

1. A series of laboratory tests was constructed to examine the behavioural characteristics of sewage sludge during different phases of its disposal to sea, i.e. settling, consolidation and erosion. Tests were carried out in the HR laboratory using samples of Davyhulme sewage sludge. Mersey mud was used in the settling tests and Grangemouth mud in the erosion tests.

2. Settling tube tests were set up to investigate the effect of mud on the settling velocity of a sludge/mud slurry. These tests revealed a linear increase in median settling velocity (W_{50}) with the proportion of mud in the slurry (Fig 3).

3. Further settling tests were carried out to identify a relationship between settling velocity and slurry concentration. Sludge, mud and a 50:50 mixture by weight of the two were tested independently, each material at 8 different concentrations. In general terms the equal mixture of sludge and mud had the highest settling velocities for a given concentration with the mud having the lowest. Both, however, tended to increase with concentration. The sludge showed no clear relationship between settling velocity and concentration of slurry (Fig 5).

4. Consolidation tests on the sludge revealed that the sludge bed was very slow to consolidate and after 2 days had only reached a mean density of 20g/l with a very small density gradient from the surface to the bottom of the bed (Fig 6). The density profile of the settled mud bed after 2

days exhibited a uniform 'S' shape, a characteristic of mud beds (Fig 6). The bed had consolidated to a thin layer with a mean density of 385g/l and a large density gradient between the surface and the bottom of the bed, which would provide more resistance to erosion. The density profile of the 50:50 mix after 2 days (Fig 7), lies between the two extremes of the poorly consolidated sludge bed and the dense mud bed. The general form is very similar to that of the mud bed, indicating the importance of the mud fraction in the consolidation of the bed.

5. The resistance of a sludge bed to re-erosion was measured; as a sludge bed, as a sludge layer on top of a mud bed and as a combination of sludge and mud. Sludge alone and sludge settled on a mud bed had a very similar resistance to erosion. The critical shear stress for erosion was less than $0.02N/m^2$. The sludge/mud combination consisted of a stratification of mud, sludge and mud, and mud rather than a homogeneous bed. The critical shear stress for the top layer of mud was approximately $0.1N/m^3$. Once the protecting mud layer had been removed the exposed sludge layer was subjected to rapid erosion.

6. The tests indicate that the presence of mud in the water column through which a sewage sludge is settling has a significant effect on the behavioural characteristics of the sludge. The results suggest that settling velocity will be increased and consolidation will be faster than for sludge alone. This will result in a bed with more resistance to erosion. The extent of the effect is likely to be proportional to the ratio of sludge to mud.

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TABLES.

TABLE 1: **Composition of sludge/mud mixtures for Series I tests**

Test No	Sludge fraction (ml)	Sludge fraction (%)	Mud fraction (g)	Mud fraction (%)
1	5.0	100	0.000	0
2	4.5	90	0.041	10
3	4.0	80	0.082	20
4	3.5	70	0.123	30
5	3.0	60	0.164	40
6	2.5	50	0.205	50
7	2.0	40	0.246	60
8	1.5	30	0.287	70
9	1.0	20	0.328	80
10	0.5	10	0.369	90
11	0.0	0	0.410	100

NB 5ml of sludge ≡ 0.410g dry weight of solids.

TABLE 2: Settling Velocity Analysis, Series I Tests

Settling Tube No	Sludge/ Mud Ratio	Settling Velocity (mm/s)								
		W_{10}	W_{20}	W_{30}	W_{40}	W_{50}	W_{60}	W_{70}	W_{80}	W_{90}
1	100/0	0.014	0.033	0.065	0.122	0.228	0.384	0.570	0.775	1.320
2	90/10	0.018	0.061	0.160	0.250	0.345	0.600	0.900	1.320	2.000
3	80/20	0.019	0.054	0.124	0.240	0.375	0.550	0.800	1.180	1.820
4	70/30	0.030	0.081	0.170	0.330	0.570	0.790	1.100	1.750	-
5	60/40	0.049	0.155	0.295	0.455	0.660	0.920	1.300	1.900	-
6	50/50	0.031	0.105	0.240	0.415	0.590	0.860	1.330	2.300	-
7	40/60	0.043	0.155	0.320	0.500	0.700	0.980	1.420	2.100	-
8	30/70	0.057	0.178	0.340	0.580	0.850	1.230	1.850	-	-
9	20/80	0.055	0.200	0.370	0.600	0.840	1.130	1.640	-	-
10	10/90	0.076	0.227	0.410	0.640	0.880	1.160	1.700	-	-
11	0/100	0.042	0.430	0.710	1.110	1.700	-	-	-	-

TABLE 3: Settling Velocity Analysis, Series II Tests

Settling Tube No	Dry weight in 500ml(g)	Settling Velocity (mm/s)								
		W_{10}	W_{20}	W_{30}	W_{40}	W_{50}	W_{60}	W_{70}	W_{80}	W_{90}
SLUDGE										
1	0.499	0.037	0.098	0.210	0.410	0.620	0.875	1.165	1.545	2.455
2	0.470	0.016	0.037	0.120	0.245	0.395	0.616	0.900	1.300	2.200
3	0.272	0.006	0.011	0.036	0.074	0.170	0.347	0.638	1.030	1.550
4	0.247	0.009	0.013	0.024	0.064	0.143	0.300	0.440	0.655	1.055
5	0.204	0.027	0.056	0.090	0.142	0.217	0.315	0.445	0.660	1.210
6	0.151	0.029	0.072	0.144	0.259	0.415	0.588	0.860	1.100	1.700
7	0.110	0.024	0.054	0.098	0.166	0.278	0.467	0.730	1.100	1.825
8	0.048	0.007	0.008	0.012	0.017	0.025	0.041	0.075	0.314	1.190
MUD										
9	0.547	0.025	0.073	0.145	0.220	0.305	0.395	0.482	0.547	0.642
10	0.374	0.016	0.062	0.146	0.264	0.344	0.421	0.515	0.637	0.820
11	0.287	0.025	0.088	0.174	0.268	0.359	0.454	0.553	0.660	0.780
12	0.215	0.012	0.027	0.049	0.080	0.124	0.180	0.235	0.315	0.470
13	0.213	0.014	0.034	0.071	0.122	0.175	0.234	0.300	0.388	0.585
14	0.178	0.010	0.037	0.055	0.084	0.123	0.179	0.252	0.347	0.600
15	0.129	0.012	0.023	0.039	0.061	0.090	0.132	0.201	0.340	0.750
16	0.090	0.008	0.014	0.024	0.043	0.072	0.118	0.198	0.380	1.900
50/50 MIX										
17	0.520	0.021	0.094	0.248	0.475	0.780	1.090	1.320	1.615	2.350
18	0.434	0.007	0.052	0.165	0.334	0.590	0.904	1.250	1.500	1.930
19	0.2t4	0.024	0.092	0.187	0.308	0.448	0.608	0.780	0.957	1.220
20	0.243	0.008	0.040	0.131	0.291	0.495	0.685	0.839	1.000	1.350
21	0.204	0.009	0.029	0.074	0.181	0.338	0.501	0.690	0.910	1.300
22	0.169	0.011	0.028	0.063	0.125	0.215	0.330	0.492	0.680	0.990
23	0.099	0.027	0.058	0.098	0.153	0.225	0.309	0.410	0.593	1.000
24	0.041	0.013	0.031	0.050	0.081	0.135	0.226	0.388	0.715	1.052

FIGURES.

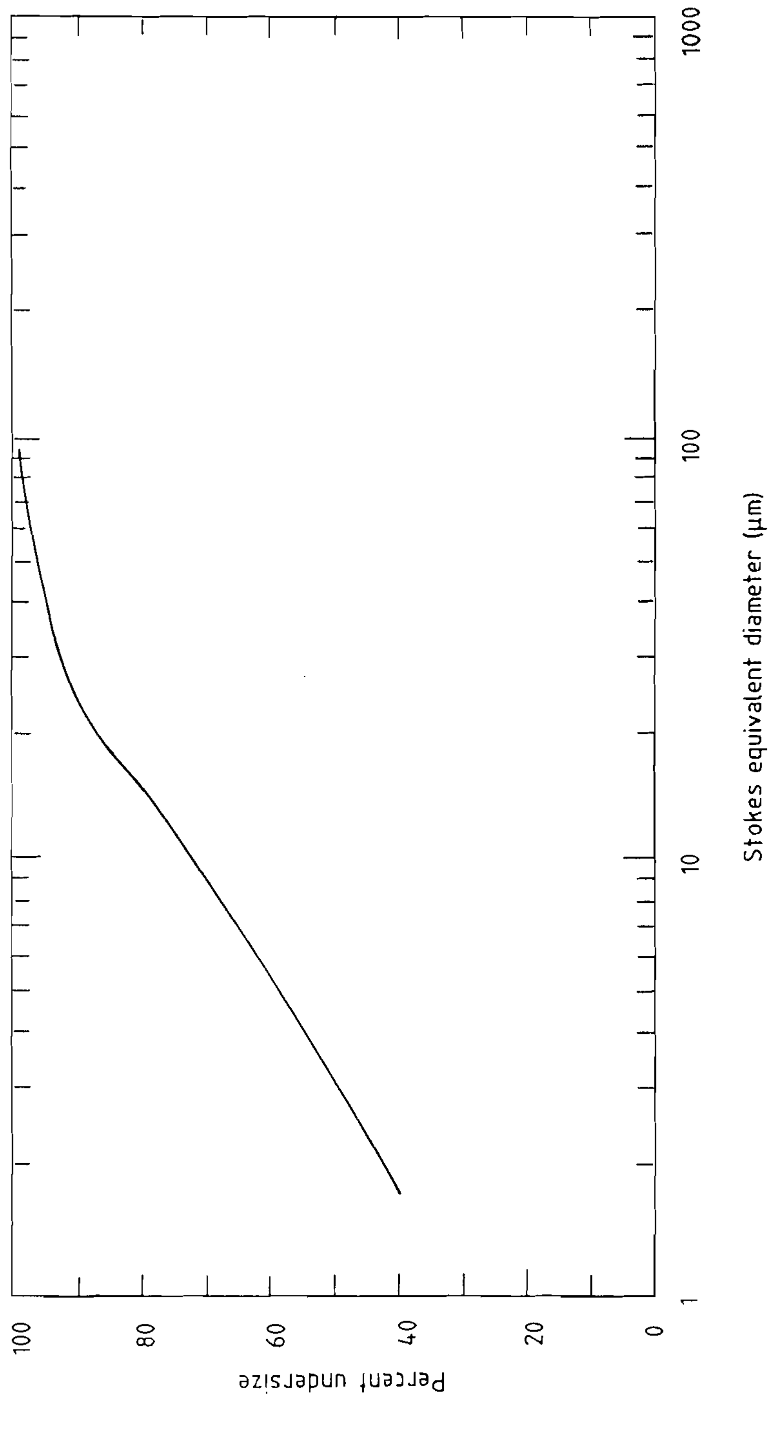

Fig 1 Particle size analysis of Mersey mud

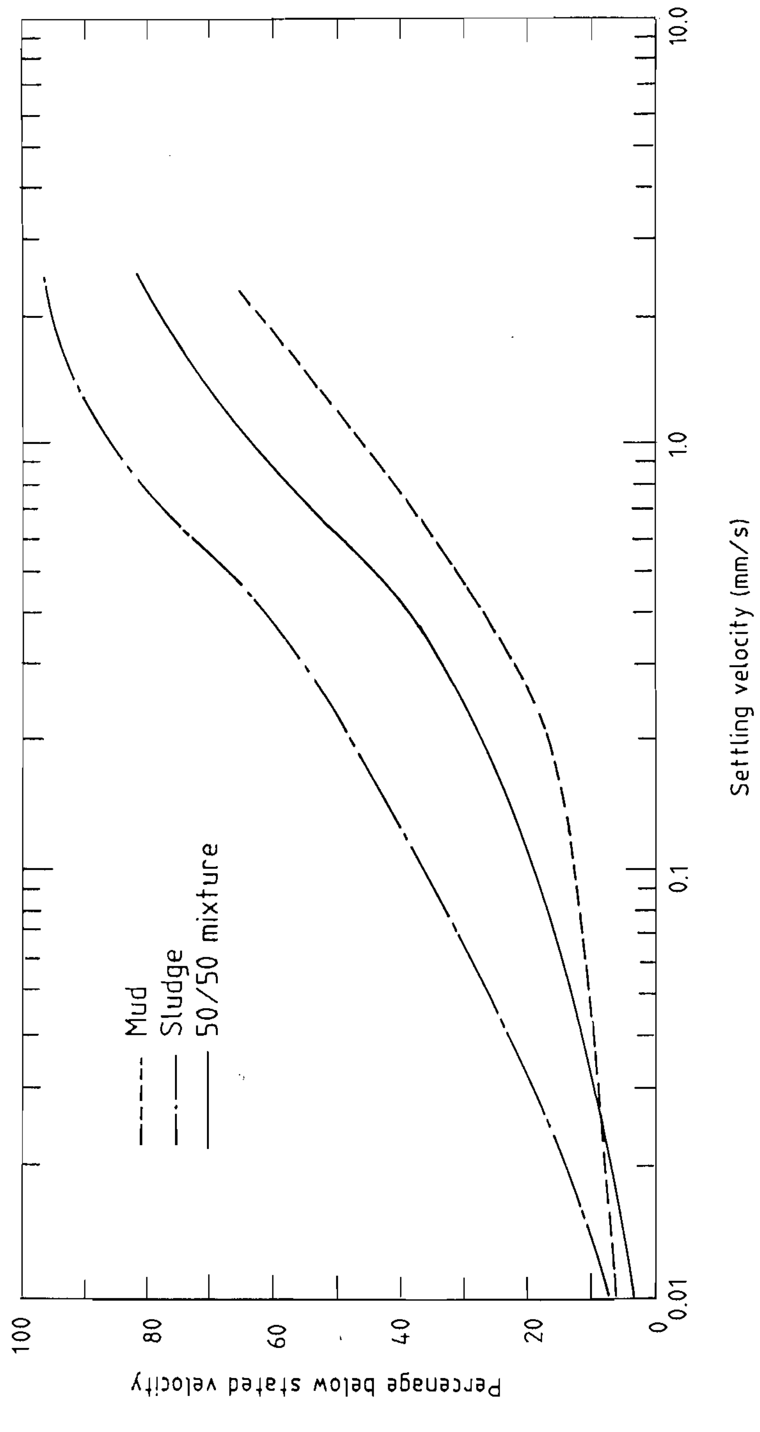

Fig 2 Settling velocity summary (Series I)

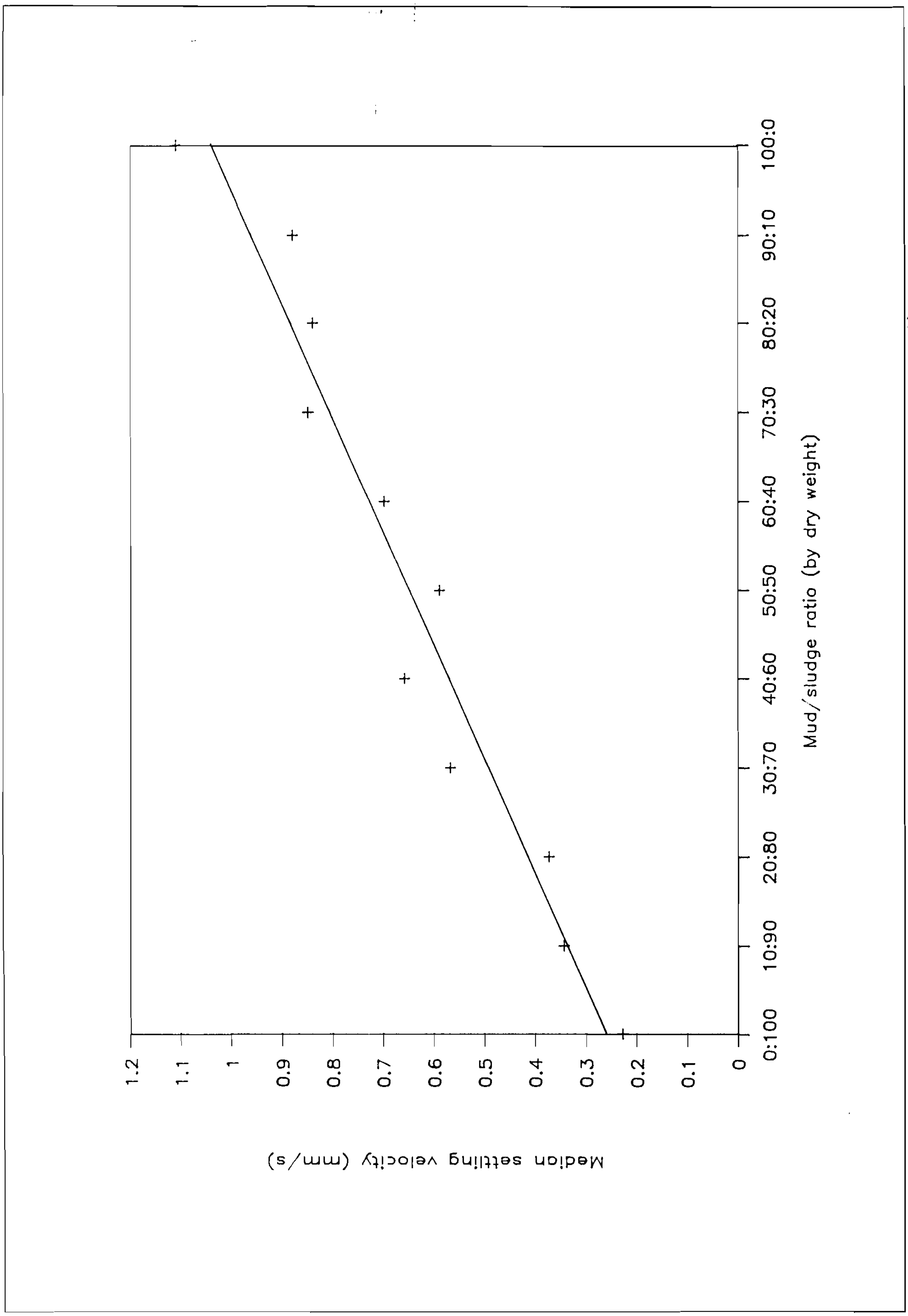

Fig 3 Median settling velocity against slurry composition

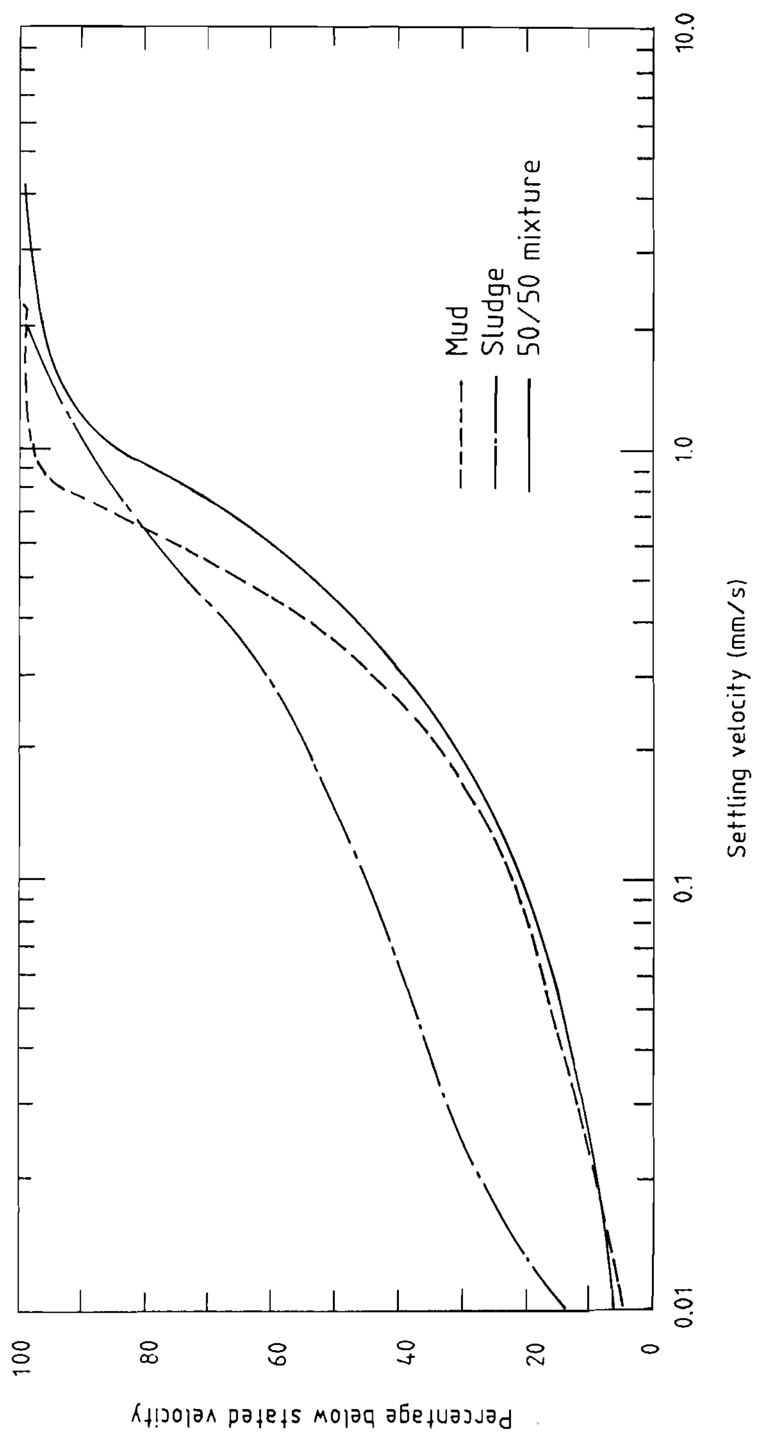

Fig 4 Settling velocity summary (Series II)

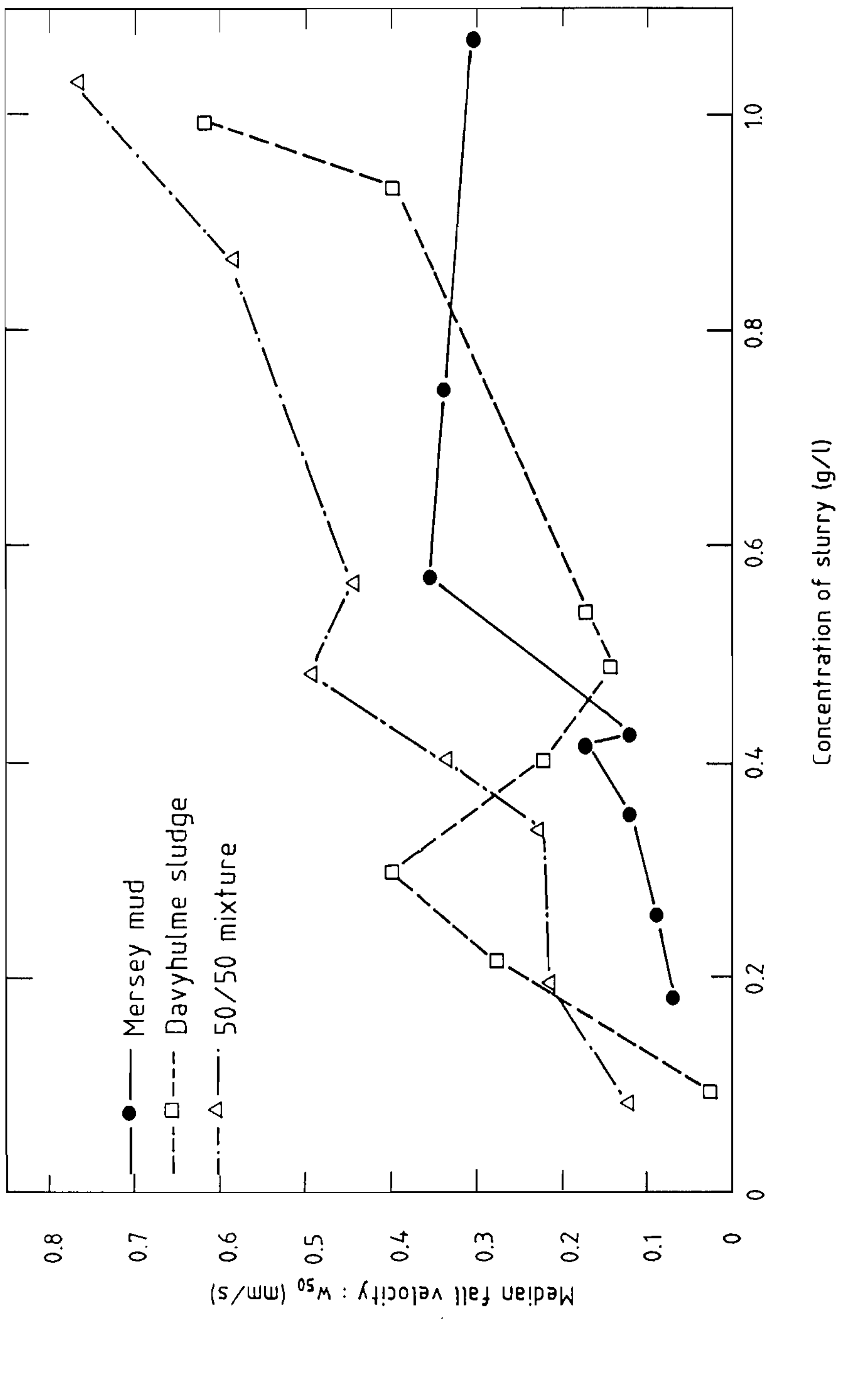

Fig 5 Dry weight of material in slurry against median settling velocity

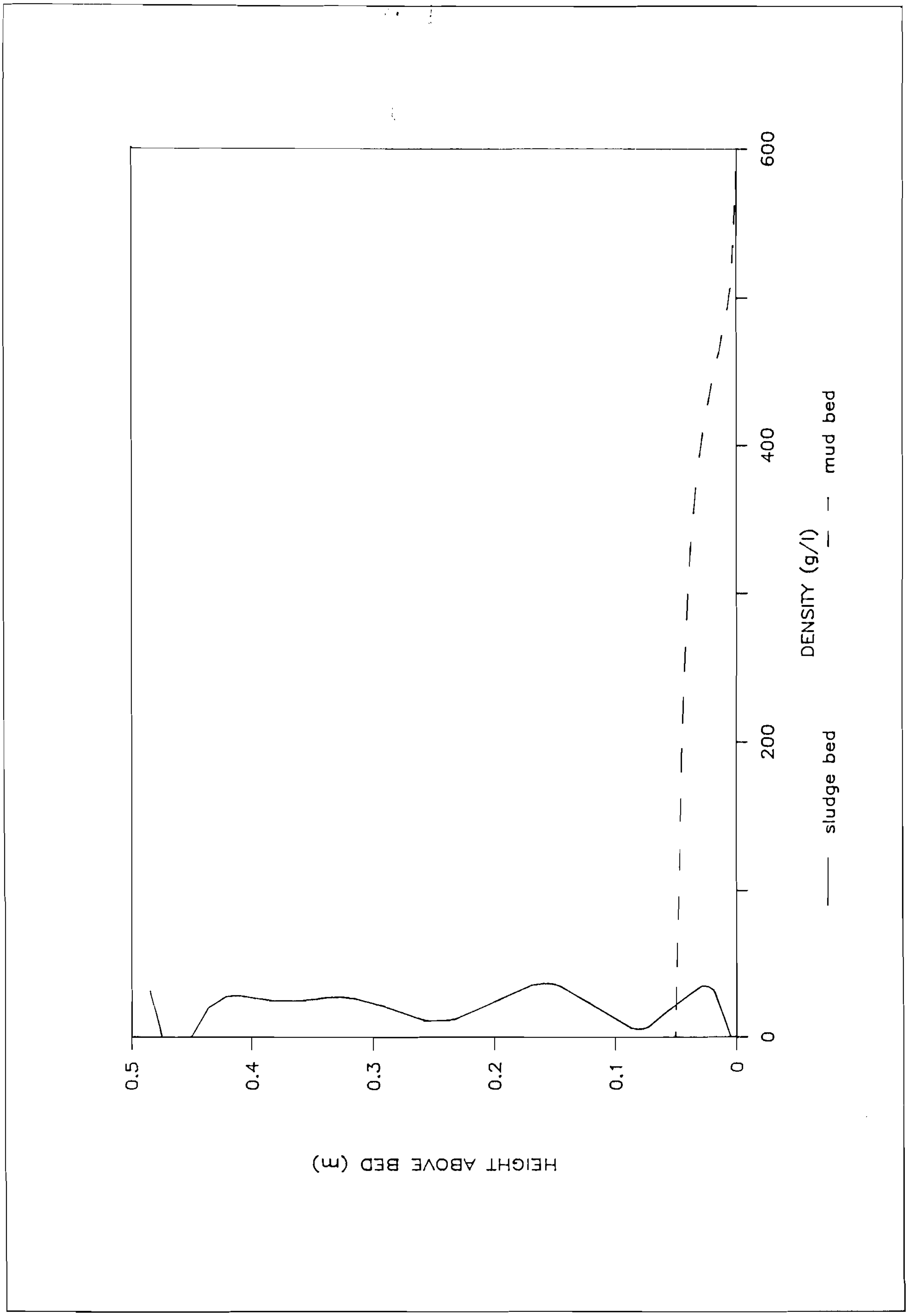

Fig 6 Density-depth profiles of sludge bed and mud bed after 2 days consolidation

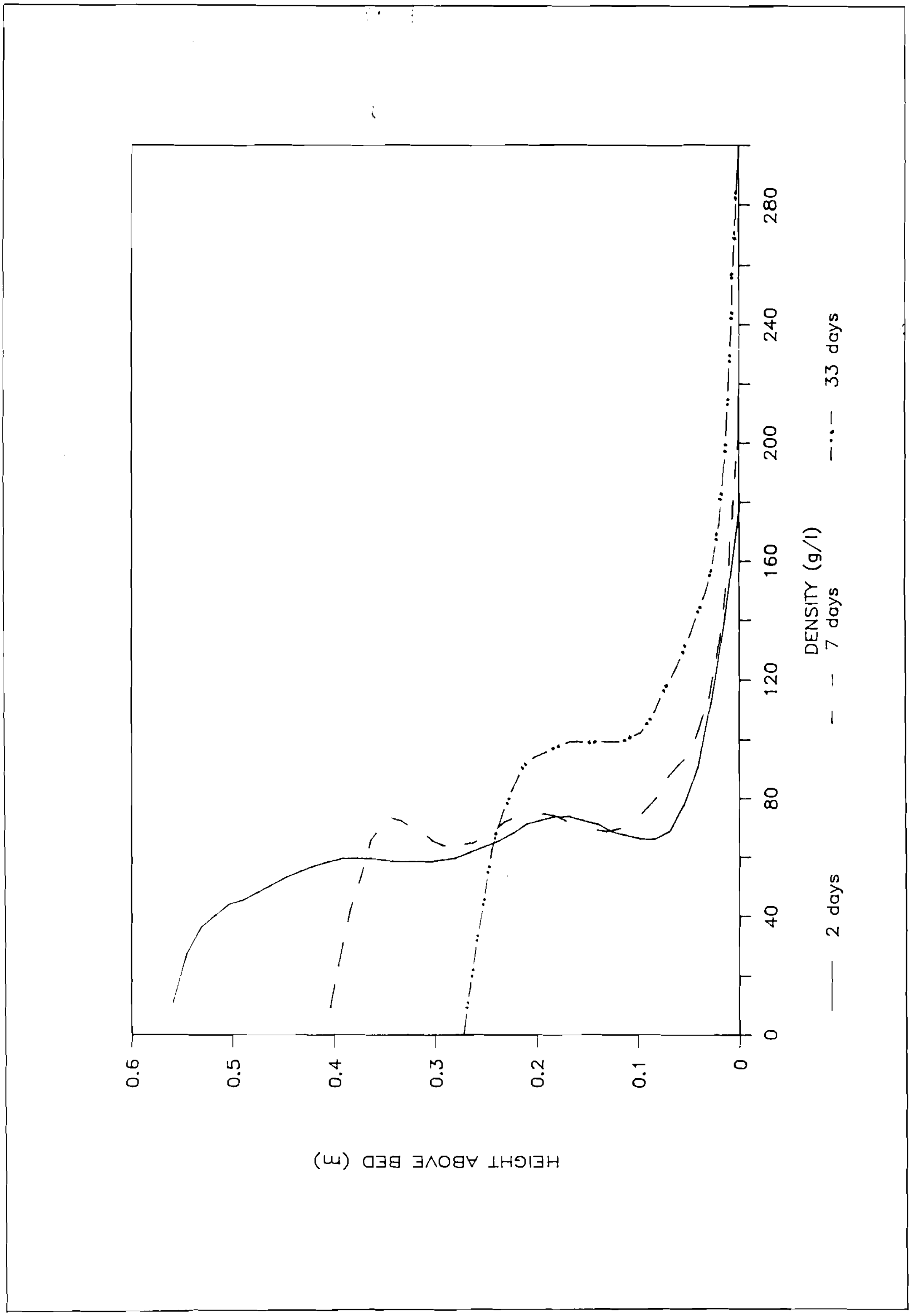

Fig 7 Density-depth profiles of 50/50 mixture bed after 2, 7 and 33 days consolidation

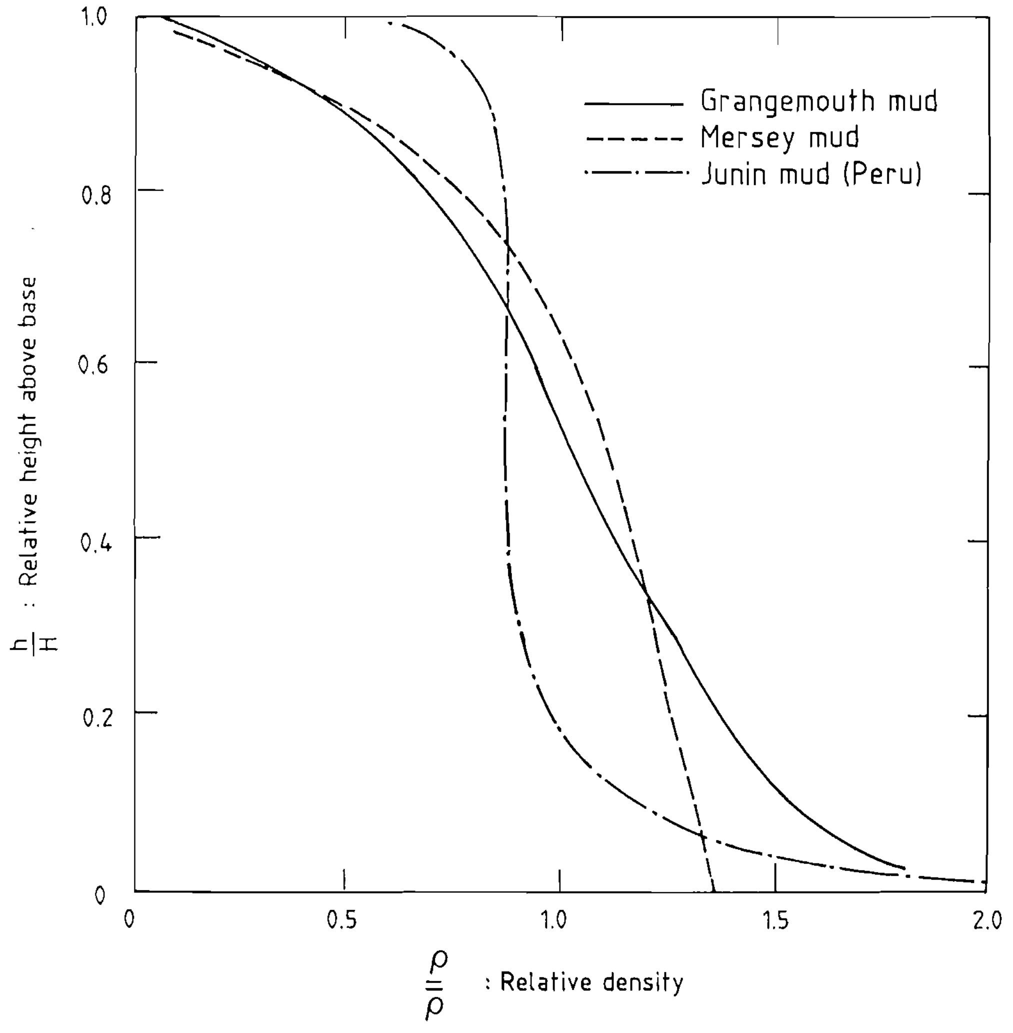

Fig 8 Density structure comparison of Grangemouth, Mersey and Junin (Peru) muds

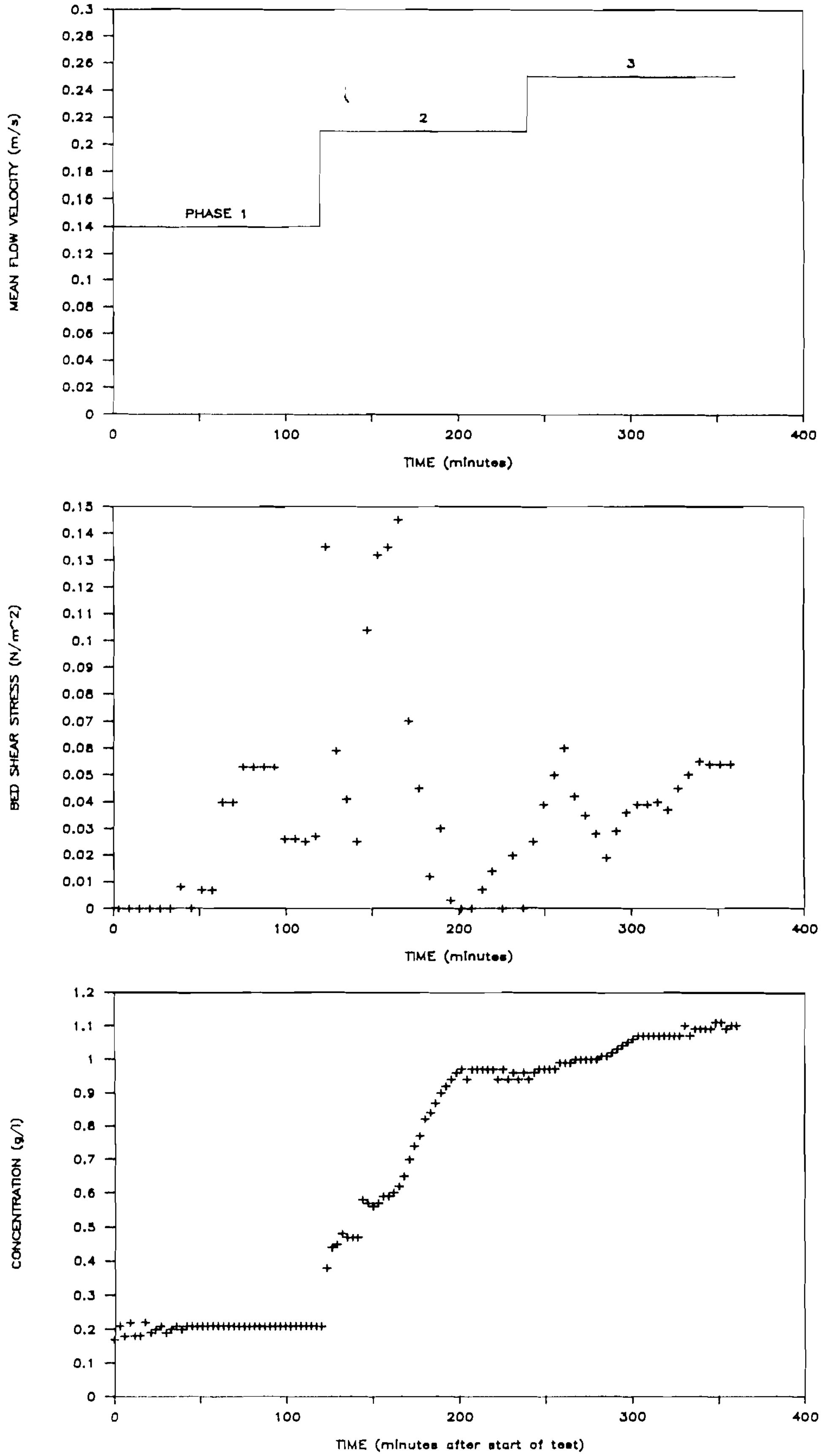

Fig 9 Concentration, mean flow velocity and bed shear stress with time-Erosion Test 1

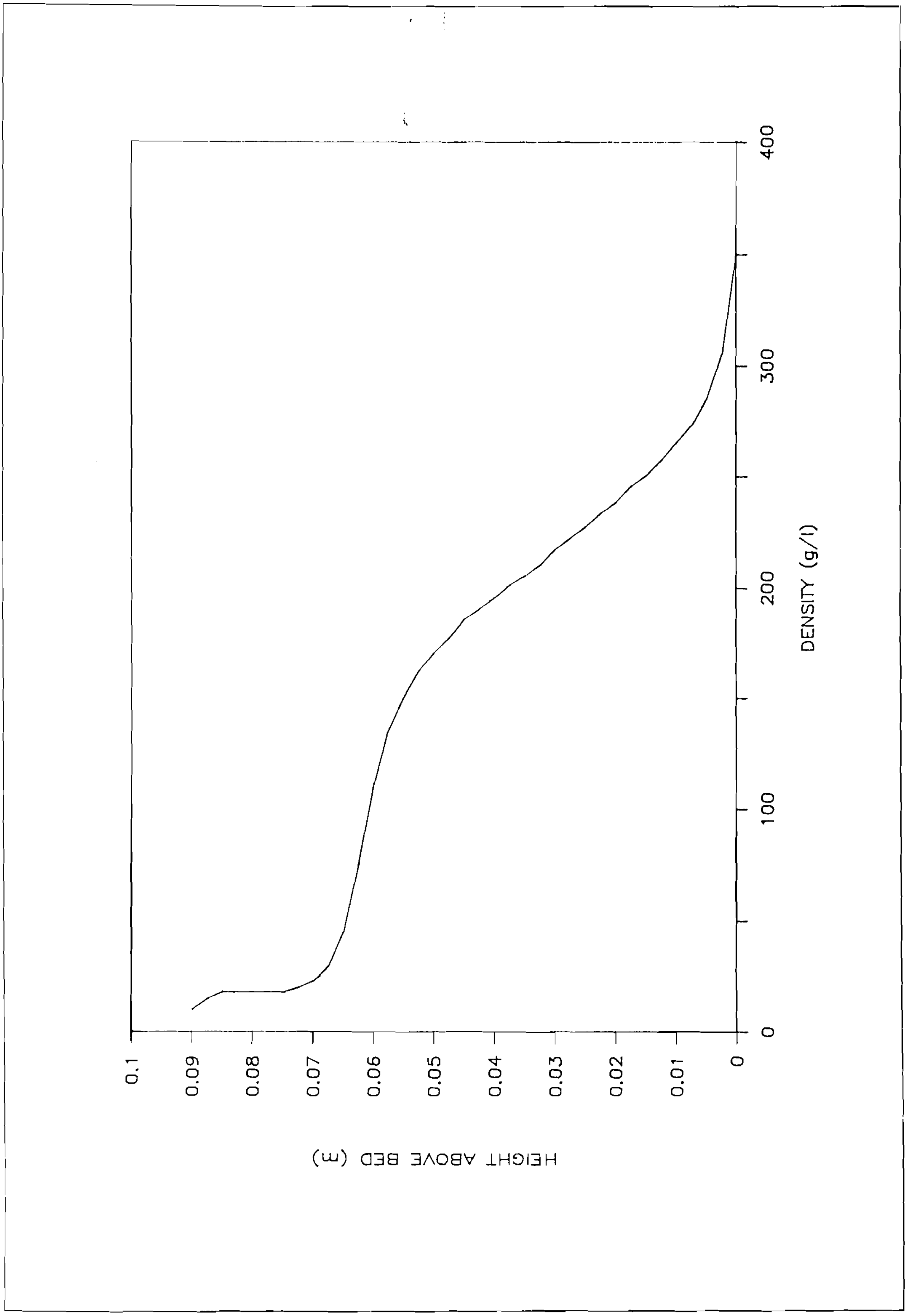

Fig 10   Density-depth profile of bed for Erosion Test 2

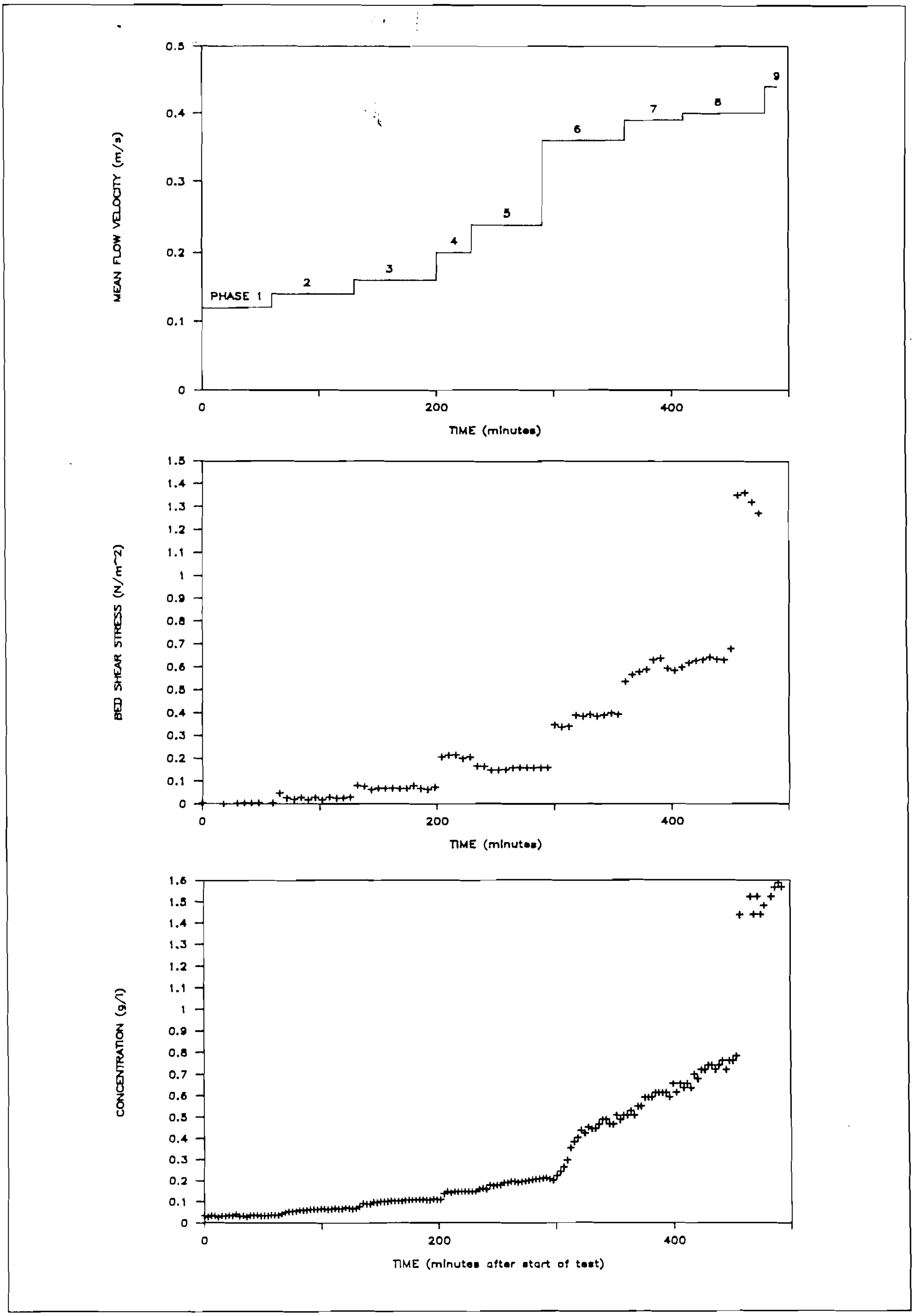

Fig 11 Concentration, mean flow velocity and bed shear stress with time-Erosion Test 2

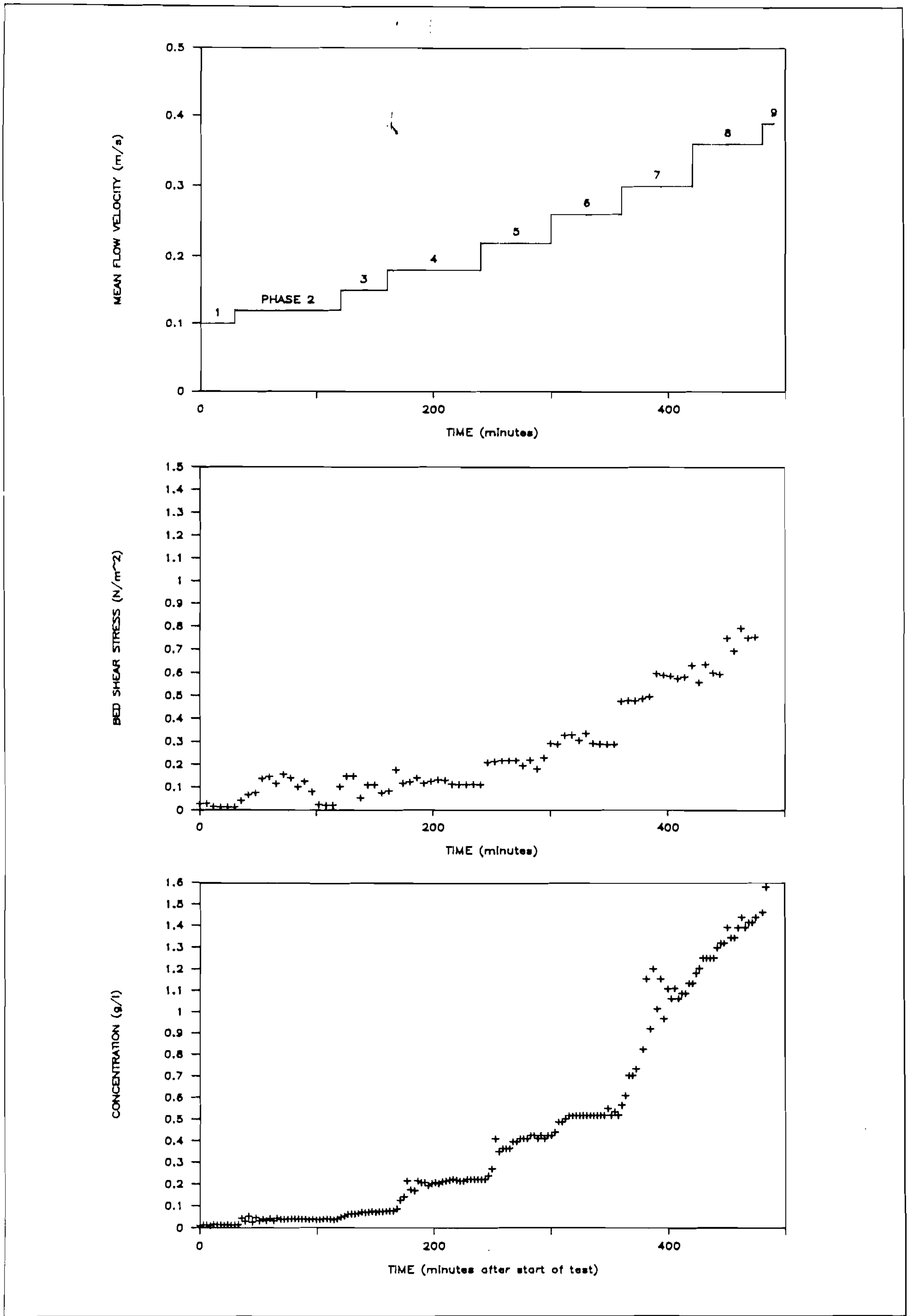

Fig 12 Concentration, mean flow velocity and bed shear stress with time- Erosion Test 3