Hydraulics Research
Wallingford

LABORATORY EXPERIMENTS ON A NEAR-BED TURBID LAYER

Report No SR 88
June 1987

Registered Office: Hydraulics Research Limited,
Wallingford, Oxfordshire OX10 8BA.
Telephone: 0491 35381. Telex: 848552

This report describes work funded by the Department of the Environment under Research Contract PECD/7/6/58 for which the DoE nominated officer was Dr R P Thorogood. It is published on behalf of the Department of the Environment, but any opinions expressed in this report are not necessarily those of the funding department. The work was done in Mrs M P Kendrick's Section of the Tidal Engineering Department of Hydraulics Research, Wallingford, under the management of Mr M F C Thorn. Mr R Clarke and Mr M A Shuttler carried out the flume tests supervised by Mr B V Derbyshire who processed the results.

ABSTRACT

A few years ago a study was carried out to determine the optimum layout of a major port enlargement and redevelopment project. Included in the terms of reference were the determination of the siltation mechanism for the existing port and the prediction of siltation rates and dredging requirements for the redeveloped port and offshore approach channel. Results from a 20-month field programme demonstrated that neither fluvial nor marine sediments fully suspended in the flow could account for the scale of siltation experienced.

It was observed from field records that when moderate wave activity occurred, near-bed suspended loads increased. A laboratory flume study was carried out on local mud and it was found that under certain wave conditions a highly-concentrated, turbid layer developed just above the bed which could be transported by relatively weak tidal currents. Using local wind records, hindcasts were made to determine the height, period and frequency of occurrence of waves capable of generating a turbid layer. The movement of the layer was determined from tidal flow path data. The results demonstrated that siltation on the scale that occurred in the port could be explained by the existence of such a turbid layer. It was also appreciated that such a mechanism might well be responsible for some of the high siltation rates experienced in other port approach channels.

Although the laboratory tests were crude, the results were taken into account in the formulation of a siltation mechanism and the construction of a conceptual model which yielded siltation rates in sufficiently close agreement with those being experienced in the port to justify attempts to predict siltation following port development. It was, however, acknowledged that the range and combination of wave and tidal conditions under which the turbid layer could form had not been fully explored. It was also appreciated that although existing equipment could measure the in-situ density of muddy deposits, no instrumentation had yet been developed to confirm the formation and record the movement of a fluid mud layer in nature.

A series of flume tests were conducted on four muds of different origin under the separate and combined action of mono-frequency waves and uni-directional currents. The object of the tests was to establish the conditions needed for the creation of a highly turbid, near-bed layer capable of being transported by weak currents with minimal mixing with the water above.

It was found that the initiation of erosion was very dependent on the consolidation age of the mud bed. With waves alone, once values significantly higher than the critical near-bed orbital velocity were reached, bed consolidation age was less important in the formation of a near-bed turbid layer. The turbidity with all muds tested increased rapidly with successive increases in orbital velocity above 0.15m/s. With currents alone, the corresponding near-bed velocities required to initiate formation of the layer with one-day old and three-day old beds were respectively about 0.07m/s higher. With waves and currents combined, the situation reverted to that of waves alone, the role of the currents being primarily to transport the newly-eroded sediment thereby increasing the sediment transport rate to any potential deposition zones.

The study is to proceed in a three-dimensional facility set up to represent a schematized shallow water coastal zone and a dredged channel. Tests will be carried out using a wave generated turbid layer transported by weak longshore tidal currents. The near-bed layer will be monitored as it approaches and flows into the dredged cut. Experiments will be made to establish practical engineering solutions to prohibit or reduce the inflow of the turbid layer into the dredged channel.

CONTENTS

CONTENTS (CONT'D)

FIGURES:

APPENDICES:

1 INTRODUCTION

A recurring problem in port development studies is the establishment of the reasons for siltation and the prediction of future siltation rates. A recent hydraulic investigation of a major port redevelopment proposal carried out at Hydraulics Research included in the terms of reference the determination of the existing port siltation mechanism and prediction of post-development siltation rates. To assist with this part of the study, simple exploratory tests were carried out in a wave flume on a sample of local mud. The tests revealed that under certain wave conditions a highly-concentrated turbid layer developed just above the bed which was capable of being transported by weak tidal currents. Although the results from these tests were taken into account in formulating the siltation mechanism and in estimating future siltation rates, it was acknowledged that the overall range and combination of wave and tidal conditions under which the layer would form had not been fully explored. It was also appreciated that no suitable field instruments were available to confirm the formation and movements of a similar turbid layer in nature.

To provide a better understanding of fluid mud movements a 3-year research study was formulated with four main objectives.

(i) To establish by experiment the range of wave and tidal conditions under which near-bed fluid mud suspensions are created and transported.

(ii) To develop a general theory which describes the motion of a fluid mud layer and to incorporate it in an existing computational mud transport model.

(iii) To formulate, through laboratory studies, engineering solutions to inhibit or prevent fluid mud from depositing in dredged navigation channels.

(iv) To develop and construct a practical field instrument capable of accurate measurement of the flow of thin fluid mud layers, so as to provide benchmark data for the project.

This report describes the wave flume experiments carried out to meet the first objective.

2 THE EXPERIMENTAL FACILITY

An existing two-dimensional wave flume 23m long x 0.75m wide and 1.0m deep equipped with a paddle-type monochromatic wavemaker was modified by the addition of a closed-circuit pumping arrangement to generate reversible longitudinal currents up to a maximum velocity of 0.5m/s. The flume was also fitted with a false floor incorporating a trapezoidal trough 1.125m long at the base, 1.75m long at floor level and 0.1m deep to accommodate test mud samples. The trough was located midway along the flume in line with a full-height glass viewing panel.

At the opposite end of the flume to the wavemaker a spending beach was installed to dissipate wave energy. A schematic section along the flume is shown in Figure 1.

3 WAVE CALIBRATION

Throughout the period of wave calibration the mud sample trough was temporarily filled with cement mortar blocks to provide a continuous horizontal floor along the working length of the flume.

In a water depth of 0.55m, wave heights and wave periods were monitored over a range of settings using a twin-wire probe wave recorder which traversed a support bridge 3.4m long centred over the mud sample trough. The monitored length was greater than half the wavelength of the lowest frequency wave and variations in the waves height envelope embraced both the node and antinode of the partial standing wave.

The maximum horizontal velocity of bed water particles was subsequently calculated from the observed wave data using first order linear wave theory for small amplitude partial standing waves.

4 CURRENT CALIBRATION

The distribution of onshore uni-directional currents was checked on three verticals across a section located about 1m downstream of the mud trough. On each vertical, current velocity was monitored at 0.01, 0.05, 0.10, 0.25 and 0.45m above the bed by miniature propeller current meter. The measuring positions are shown on Figure 2. Additional check measurements were also made on verticals at a section located 0.5m downstream of the mud trough. The measurements embraced section-averaged, depth-mean current velocities ranging from about 0.035 m/s to 0.174 m/s in 12 increments representing manometric head settings between 0.013m and 0.492m. The check measurements carried out on the section nearer to the mud trough were made with heads set at one-third and two-thirds of the manometer head range. The results show that the flow distribution in the flume follows the usual logarithmic depth distribution but was slightly non-uniform across the width, being marginally slower than mid channel flow on the viewing panel side of the flume and marginally faster on the opposite side. The same trend was evident in the section used for check measurements. Values of the monitored current speeds together with depth-mean values are listed in Table 1.

5 MUDS EXAMINED

The original simple exploratory mud studies carried out several years ago used a mud sample from the Port of Belawan in Indonesia. For the present studies four different muds were used. the first sample originated from Kuching in East Malaysia, the second from Bristol Docks on the River Avon near Avonmouth, the third from an offshore bar in the navigation approach channel to Port Kelang in W. Malaysia and the fourth from the face of a wharf in Port Kelang.

Mud is composed of a widely-graded mixture of clay, silt and fine sand, and the mineral content varies from place to place. The approximate mineral content of the above muds was determined by X-ray diffraction analysis and the cation exchange capacity was established by a surface adsorption method to provide an indication of cohesive strength. The results of these analyses are shown in Table 2. From the cation exchange values, Belawan mud is the most cohesive and Avon mud the least. This is the result that would have been expected from the mineralogical analysis and reflects the proportions of negatively charged clay particles (montmorillonite/illite) present in the five mud compositions.

The particle size distribution curves of the five muds are shown in Figure 3. The proportions of sand, silt and clay in the Avonmouth, Belawan and Kuching muds and very similar whilst for Port Kelang the Wharf 8 mud has a high clay content and the Pintu Bar mud a high sand content. If part of the sand is removed from the Pintu Bar sample to lower the content to about ten percent of the total sample (ie comparable with the other muds), the particle size distribution of the remainder is quite similar to that of Kuching mud.

6 PREPARATION OF THE MUD BED

Consolidated mud was removed from its transit container, stirred to a smooth paste and diluted with water to produce a homogeneous slurry. A small sample of the slurry was reserved for settling column density profile measurements and the remainder used for wave flume tests.

Following removal of the temporary cement mortar blocks from the working section, the flume was filled with saline water mixed to a strength of 28 g/l - approximately the density of estuarine/coastal water. Temporary watertight partitions were fixed across the flume at the ends of the trough and mud slurry was poured into the enclosed area and stirred thoroughly. After a predetermined settling period the temporary partitions were removed and tests begun.

7 SETTLED BED DENSITY/DEPTH PROFILE

A small quantity of the mud slurry prepared for the wave flume tests was poured into a settling column and topped up with saline water to give a total depth of 0.65m - the operating depth in the flume above the base of the trough. The water and mud slurry were thoroughly mixed to uniform density suspension and allowed to settle.

After periods of 1 day and 3 days, the density/depth profile of the settled bed was determined using a nucleonic transmission probe. Fig 4 shows the mud profiles plotted in a dimensionless form of relative density (ρ_r) against relative height (h_r) where

ρ_r = $\rho/\bar{\rho}$

h_r = h/H

ρ = bed density at height h above the bottom of the bed

$\bar{\rho}$ = mean bed density, and

H = total bed thickness.

Although the results show that the relative density of Avonmouth mud is highest over a large part of the mud depth and Kuching mud lowest, all four samples generally have a similar profile.

8 THE MUD STUDIES

8.1 Belawan mud

Although the tests on Belawan mud were not part of the present study, a summary of the findings has been included in Appendix 1 for purposes of comparison and reference.

8.2 Kuching mud

The quantity of mud available for this study was severely limited and the test programme was accordingly restricted. To this end each of the main tests was carried out under wave action only but at the end of the programme a uni-directional current was superimposed.

Three wave periods were examined and in each case the wave height was increased in ten increments. The values used are listed in Table 3 together with the maximum horizontal water velocity (Ub max) which was calculated from first order linear wave theory for small amplitude partial standing waves using the relationship:

$$Ub\ max = \frac{H}{T.\ Sinh\ 2\ d/L}$$

where H = wave height

T = wave period

d = water depth

and L = wavelength in a water depth of d.

Before the start of each test, water samples were taken on a vertical to describe the background turbidity profiles. Sampling was carried out at levels of 0.01, 0.02, 0.05, 0.1, 0.2, 0.3 and 0.4m above the surface of the settled bed. Subsequent samples collected during the course of the test were obtained from the same positions irrespective of changes in bed level. Sampling was carried out when it was considered that the mud movements were approaching a state of quasi-equilibrium. This was usually about 30 minutes after wave height adjustment. In a few cases additional samples were taken after shorter or longer running times.

All samples were analysed for optical density using an EEL photo-electric absorptiometer and a representative selection of the samples were further analysed for dry weight concentration.

8.2.1 Test 1

Before the wavemaker was started the water in the flume appeared to be clean but was subsequently found to have a depth-uniform suspended solids concentration of 144m g/l.

After the wavemaker was switched on to generate a low wave, 0.0267m high (Ub_{max} = 0.05m/s), micro-ripples formed on the mud surface. The application of successive incremental increases in wave height formed first a single near-bed layer of low concentration, then a 2-layer system and then a 3-layer system. The third layer to appear was fluid mud and this occurred with a wave height of 0.0767m (Ub_{max} = 0.1469m/s). Subsequent increases in wave height increased the thickness of the fluid mud layer.

Notes on the state of the bed and the turbidity of the water column are given in Appendix 2.

Results from this test suggest that the threshold of mud erosion commenced when the maximum horizontal velocity at the bed reached a value in the range 0.0760-0.1053m/s. The corresponding velocity range for the formation of a fluid mud layer was 0.1277-0.1469m/s. Substantial fluid loads would be available for transport at velocities in excess of 0.22m/s.

Figure 5 shows the relationship between the horizontal velocity of water at the bed and the turbidity of the water column at 0.01, 0.02, 0.05 and 0.1m above the bed. The data recorded at 0.2, 0.3 and 0.4m above the bed have been omitted for clarity of presentation. At these higher levels the water turbidity remained at or near the initial background concentration of 144m g/l throughout the entire test.

8.2.2 Test 2

This test was carried out with a wave period of 2.21s. The background water turbidity immediately prior to the tests showed a variation in the vertical water column, and in the bottom 0.2m, concentrations increased from 148mg/l to 271mg/l. The profile suggested that settling was incomplete and the tests were carried out on a weaker bed than that of Test 1.

Confirmation of a weaker bed was evident from the first test result, for with a wave 0.04m high (Ub_{max} = 0.0716 m/s), bed erosion had become well established.

The relationship between the horizontal velocity of bed water and water turbidity is shown on Figure 6. The principle difference between this test and Test 1 was that greater quantities of sediment were transferred into the upper layers and transported along the flume. Notes on the behaviour of the mud bed are included in Appendix 2.

8.2.3 Test 3

For this test the wave period was shortened to 1.77s. Results from the analysis of pre-run background water samples once again indicated that settling was incomplete with turbidity values in the lower 0.1m increasing from 169mg/l to 231mg/l.

Due to material losses along the flume in Test 2 and the non-availability of additional mud supplies, the settled bed thickness at the start of this test was some 0.02m less than in the previous studies.

The behaviour of the mud with programmed increases in wave height and horizontal velocity followed a similar pattern to the previous tests. Notes on experimental observations are given in Appendix 2.

The relationship between near-bed velocity and turbidity is shown on Figure 7.

At the end of the test a longitudinal current was superimposed on the wave action. Although the suspended sediments were observed to leave the viewing panel area as stratified layers, no firm conclusions on the extent of vertical mixing with distance could be drawn because the progressive increase in background water turbidity during the test made visibility poor at the next viewing panel situated about 3m further downflow.

8.2.4 Discussion of Kuching mud results

The near-bed velocity-turbidity curves on Figures 5, 6 and 7 clearly illustrate that the incompletely settled beds of Tests 2 and 3 resulted in a lower threshold for sediment movement. Beyond the threshold, the stronger bed of Test 1 soon exhibited erosion properties similar to those of Tests 2 and 3. For example at a height of 0.01m above the bed, a concentration of 3000mg/l was created by velocities of 0.21m/s, 0.23m/s and 0.21m/s in Tests 1, 2 and 3 respectively, whilst the corresponding values associated with a concentration of 6000mg/l increased to 0.34m/s, 0.35m/s and 0.33m/s - ie they were virtually identical.

This result suggests that the age of the mud bed may not be an important factor with regard to fluid mud formation, the cyclical variation in positive and negative lift forces on surface mud particles under wave action being sufficient to agitate the surface layer to a uniform density irrespective of consolidation history.

8.3 Avonmouth mud

Being a mud of local origin, a virtually unlimited supply was available for study purposes and no restraints were necessary to conserve test samples. The study programme was therefore devised to provide comparable results with the muds already examined in the flume and also to determine the effect of consolidation period on the threshold of movement under wave action, uni-directional currents and waves and currents combined.

The first two tests were carried out under wave action alone. In Test 1 the mud was settled from suspension and allowed to consolidate for three days: in Test 2 the consolidation period was reduced to one day.

These were followed by tests with uni-directional currents only. Test 3 was carried out on a mud bed consolidated for one day and Test 4 on a three-day-old mud bed.

The study then continued using a combination of wave and current action. Tests 5 and 6 were made with waves and a longitudinal current of 0.1m/s, the variable being the mud bed consolidation period - one day for Test 5 and three days for Test 6. The final test, Test 7, was similar to Test 6, but the longitudinal current strength was reduced to 0.05m/s.

The tests, which included wave activity, were carried out with a 2.83s wave period and eight wave heights (Table 3).

Details of the changes in the condition of the mud bed and variations in water column turbidity during the course of the tests are given in Appendix 3.

8.3.1 Test 1 - waves

This study was carried out with a wave period of 2.83s and eight wave heights ranging from 0.032m to 0.156m giving near bed velocities of 0.061m/s to 0.298m/s (Table 3).

During the early stages of this test the horizontal orbital velocity of the waves was less than the critical value for erosion and initially, individual flocs moved over the mud surface. Later the flocs formed into organized ripple-like fronts.

At a wave-height setting of 0.0634m (Ub = 0.1214m/s) sediment was entrained, causing a turbidity increase in the bottom 20mm of the water column. Mud fluidization developed under a wave height of 0.077m (Ub = 0.1475m/s) and the thickness of the layer increased with time - 15mm thick after 20 minutes of wave generation increasing to 27mm thick after 60 minutes.

Subsequent increases in wave height created various combinations of turbidity layers in the water column. Details of these can be obtained by reference to Appendix 3. The relationship between near-bed velocity and water turbidity is shown on Figure 8.

8.3.2 Test 2 - waves

Test 2 was a repeat of Test 1 except that it was carried out on a weaker mud bed that had been allowed to settle and consolidate for only one day.

Entrainment of the sediment from the mud surface into the water column occurred with a wave height setting of 0.0453m (Ub = 0.0868m/s) and fluid mud was formed when the wave height was increased to 0.0634m (Ub = 0.1214m/s). Subsequent increases in wave height further developed the fluid mud layer. Under a wave of 0.1224m (Ub = 0.2344m/s), distinct turbidity stratification appeared in the form of an oscillating mud overlaid first with fluid mud and then with a turbid suspension. Although the highest sediment concentrations were found within 0.05m of the bed, significant quantities were present at higher levels - 400mg/l at a height of 0.1m and 125mg at 0.2m.

The relationship between near-bed velocity and turbidity is shown on Figure 9.

8.3.3 Test 3 - currents

This test was carried out with uni-directional currents on a mud bed which had been allowed to consolidate for 24 hours. During the test, six different flows were generated having section mean values in the range of 0.105m/s to 0.258m/s.

At the low end of the flow range little activity was observed over the mud bed although the results of water sample analysis indicated that turbidity had increased by a few mg/l over the initial background concentration. It is not known whether the increase in suspended load was derived from the entrainment of fine grains from the mud sample or from residual materials in other parts of the system.

During the next three current settings, which increased the flow strength from 0.105m/s to 0.199m/s, very little additional activity occurred although a marginal but progressive turbidity increase was recorded in the water column.

The last two current settings showed large changes and gave a positive indication that the threshold of mud erosion occurred with a current of about 0.222m/s. Substantial erosion and transport in a near-bed layer occurred with a current of 0.258m/s.

Figure 10 shows the vertical turbidity distribution throughout the lower 0.4m of the water column for a selection of flow settings. The profiles on the lefthand-side of the figure were monitored 0.5m downstream of the mud bed under three current settings. Those on the right-hand-side were monitored during a higher flow at positions 0.5m downstream of the mud bed, at the centre and 0.5m upstream. The upstream profile shows the turbidity of the water column on approach to the mud bed and the other two show the progressive entrainment of sediment with distance downstream.

8.3.4 Test 4 - currents

For this test, mud was allowed to settle and consolidate for a period of three days and was then subjected to a stage-by-stage increase in uni-directional current strength similar to that of Test 3.

Figure 11 shows vertical turbidity profiles in the bottom 0.4m of the flume. The initial background concentration of the water immediately before the start of the test was 97mg/l. During the first three current settings of 0.110m/s, 0.141m/s and 0.175m/s the depth mean concentration in this part of the water column reduced to 87mg/l, 92mg/l and 96mg/l respectively. With a current strength of 0.203m/s, the mean turbidity increased further to 109 mg/l. Under the final current speed of 0.250m/s, the depth mean turbidity rose to 135mg/l.

The reason for the fall in turbidity from its initial background concentration is not known but it was assumed to be due to a non-uniform longitudinal distribution prior to the start of the tests.

From Figure 11 it can be seen that the threshold for erosion is very close to 0.25m/s.

8.3.5 Tests 5 - 7 - waves and currents

Three tests were carried out using the same wave period and wave height settings as in the studies with waves alone (Table 3). The longitudinal currents were chosen to be well below the threshold for erosion established in the tests with currents only.

In the first two tests, a longitudinal current of 0.1m/s was generated, the period of mud consolidation being one day for the first (Test 5) and three days for the second (Test 6). In the last study (Test 7) the consolidation period was three days but the longitudinal current was reduced to 0.05m/s. The tests were therefore designed to demonstrate the effects of both consolidation period and longitudinal current strength on mud erosion, transport and dispersion through the water column. Notes on observations made during the tests are given in Appendix 3.

Figures 12-14 show the monitored turbidity in the lowest 0.4m of water 0.5m downstream of the mud bed for a number of wave orbital velocities (or wave height settings). It is evident from the figures that both mud consolidation period and flow strength influence the turbidity distribution. During each test the recently eroded material was almost entirely confined to a layer 0.1m above the bed of the flume, the suspended sediment above this level being of uniform concentration due to the mixing which occurred in the flume recirculation system.

In the test on the weaker mud bed (Test 5), when the orbital velocity was 0.14m/s, the turbidity in the lowest 0.1m was different from that recorded in the other tests. No near-bed turbid layer was monitored but the sediment concentration in the water layer above was greater - possibly a reflection of the lower density of surface particles.

Figure 15 depicts the progressive decrease in mud bed thickness during the three tests as measured at the glass viewing panel. In each test the decrease began at the initiation of water movement. Under the first four wave settings the rate of bed erosion progressed fairly uniformly with each test. On the weaker bed (Test 5) material was removed at a rate of about 2.60mm/h while on the stronger beds the rate was 0.74mm/h and 0.84mm/h for Tests 6 and 7 respectively. Around the fifth wave setting the rate of bed erosion increased significantly. This corresponded with a near-bed orbital velocity of 0.127m/s and generally with the first observations of fluid mud formation.

8.3.6 Discussion of Avonmouth mud test results

The first two tests were carried out under wave action alone using identical wave periods and wave height settings. The variable was the age of the mud bed. In Test 1 a consolidation period of 3 days was used while in Test 2 the consolidation time was limited to one day. Figures 8 and 9 show the relationship between turbidity at four heights above the mud bed and near-bed orbital velocity.

From Figures 8 and 9 the first conclusion is that the weaker bed (Test 2) has a lower velocity threshold for erosion. The second conclusion is that significantly higher horizontal velocities are required over the weaker bed to produce comparable turbidity values 0.01m above the bed. Although at first sight a curious result, closer inspection of the figures suggests that it is not unreasonable. In the case of the stronger bed (Fig 8) the eroded mud tends to stay in the lowest water layer while with the weaker bed

(Fig 9) it is transported into higher layers. This result is consistent with mud ageing, the flocs being progressively dewatered (and hence forming a denser bed) with time.

From the limited number of water samples taken at points along the flume it would appear that under wave action there is a small net seaward transport of mud. This might be due either to asymmetry in the generated waveform or to the location of the mud bed relative to the position of nodes and antinodes in the flume.

Tests 3 and 4 were carried out under similar uni-directional currents on mud beds which had been allowed to consolidate for one day and three days respectively. The results indicate that the weaker bed has a threshold for the development of a near-bed turbid layer between 0.22m/s and 0.25m/s (Fig 10) while in the case of the denser bed a current slightly above 0.25m/s is required (Fig 11).

The results of tests using both waves and currents (Figs 12-14) indicate that the wave conditions dominate the bed erosion process. The bed consolidation period has a marginal influence at low wave heights when the surface of a weak, freshly deposited bed may be eroded at smaller near-bed orbital velocities than are required with a better-consolidated bed. However, by the time the near-bed turbid layer is established, the density of the mud bed appears to be of less importance e.g. with an orbital velocity of 0.29m/s Figures 12 and 13 indicate that the dry weight of sediment eroded from the bed is virtually identical (as given by the area to the left of the 0.29m/s turbidity-depth profile).

Within the values of uni-directional currents examined, it would appear that the strength of the current does not influence the point at which the near-bed turbid layer is formed (Figs 13 and 14) but it does affect the rate at which the layer is transported along the bed and hence the mud erosion rate.

8.4 Port Kelang muds

Two samples were made available for the tests. The first was dredged from Pintu Bar, a prominent shoal in the port approach channel and the second from the face of Wharf 8, one of the berthing areas in the port which requires regular maintenance dredging to retain an operational working depth.

The composition of the two bed samples differed quite markedly, with the offshore bar material having a much higher sand content and a significant organic content mainly in the form of leaves and timber fragments. The port sample was mainly fine grain sediments with an untypically high clay fraction. Particle size distribution curves are shown on Figure 3 and discussed in Section 5 of this report.

The results of settling column tests on a sample of wharf mud are shown on Figure 4 in the form of a relative density-depth profile after 24 hours of settling. The profile is broadly similar to those for Avonmouth, Belawan and Kuching muds. The Wharf 8 relative density-depth profile is also shown on Figure 16 together with profiles for the Pintu Bar sample.

It is apparent from Figure 16 that the vertical distribution of the settled bed of the Pintu Bar sediments have little similarity with the relative densities of the other muds examined. This is due to the high sand and organic content which settled out rapidly to form a dense bottom layer. If the sand fraction is ignored and the relative density-depth profile recalculated, the relationship is in better agreement with the other muds. During the wave tests, the bed erosion was mainly in the mud fraction and the edited clay/silt relative density profile probably provides a more realistic description of the material under examination.

8.4.1 Wave tests

In both series of tests the mud sample was deposited from suspension with a period of 24 hours allowed for settlement and consolidation. Water had an operational depth of 0.55m and a salinity of 25g/l.

The wave conditions used were identical to those of the Avonmouth mud studies viz a 2.83s wave period with wave height settings in the range 0.0320m to 0.1558m. A complete list of the settings is given in Table 3.

8.4.2 Wharf 8 mud

At the start of the test the initial bed thickness was 0.098m and the flume water had a mean background turbidity of 38mg/l.

Unlike the other muds examined under wave action, Wharf 8 mud began to form both a fluid mud layer and a turbid layer at heights of 0.01m and 0.02m above the bed with the lowest wave height setting.

Successive increases in wave height added to the near-bed turbid layer and to the general turbidity of the water column.

Figure 17 shows the relationship between maximum near-bed velocity and vertical turbidity profile. The reason for the apparently low final reading 0.02m above the bed is unknown.

One possible reason for the early formation of fluid mud could be associated with incomplete settling of the mud bed due to the abnormally high clay content of the mud.

Notes on the fluid mud layer development and mud bed erosion are given in Appendix 4.

8.4.3 Pintu Bar mud

This test commenced with a settled mud bed 110mm thick and a background water turbidity of 11mg/l.

Although the mud displayed oscillating movements from the initiation of wave action and a thick fluid mud layer formed on the second wave setting, it was not until the height was raised to 0.077mm (U_b = 0.1475m/s) that significant increases in sediment were recorded in the lowest 0.02m of the water column.

Figure 18 shows the near-bed velocity-turbidity relationship in the lowest 0.2m of the wave flume. Between 0.05m and 0.2m the water turbidity is comparable to the levels monitored in previous tests, but nearer the bed the sediment concentration is very much lower.

Notes on the changes to the mud bed as the tests proceeded are given in Appendix 4.

Although the Wharf 8 mud sample initially appeared to be extremely mobile, this impression was not borne out in practice. The general suspended sediment concentration in the water column compared favourably with the levels attained during similar tests on other mud samples (Figs 5 and 9) but the recorded concentrations in the near-bed turbid layer were much lower.

The Pintu Bar mud sample resulted in turbidity levels in the upper water column comparable with those obtained with Wharf 8 mud, but the near-bed layer had a lower concentration. The further turbidity reduction in the near-bed layer could possibly be associated with the high sand content of this sample.

8.4.4 Discussion of Port Kelang test results.

Although Wharf 8 mud sample initially appeared to be extremely mobile, this impression was not borne out in practice. The general suspended sediment concentration in the water column compared favourably with the levels attained during similar tests on other mud samples (Figs. 5 and 9) but the recorded concentrations in the near-bed turbid layer were much lower.

The Pintu Bar mud sample resulted in turbidity levels in the upper water column comparable with those obtained with Wharf 8 mud, but the near-bed layer had a lower concentration. The further turbidity reduction in the near-bed layer could possibly be associated with the high sand content of this sample.

9 CONCLUSIONS

1. Tests with waves alone established that the initiation of erosion of a mud bed is influenced by the consolidation age of the bed, occurring at lower orbital velocities with recently settled beds.

2. At orbital velocities significantly above threshold, bed consolidation age become less important, probably due to the greater particle

disturbance resulting from the cyclical variation in positive and negative wave-induced lift forces.

3. The turbidity of the near-bed layer begins to increase when the orbital velocity reaches about 0.15m/s and develops rapidly with successive velocity increases. At an orbital velocity of 0.2m/s, the respective concentrations were:

Kuching mud	2500 mg/l
Avonmouth mud	2500 mg/l
Port Kelang mud (Wharf 8)	1400 mg/l
Port Kelang mud (Pintu Bar)	800 mg/l

The two lower values may be a consequence of the abnormally high sand and clay fractions in the mud.

4. Tests with uni-directional currents alone demonstrated that the initiation of erosion requires a higher near-bed velocity than with waves alone. The near-bed turbid layer begins to form at a velocity of about 0.22m/s and becomes well established at 0.25m/s.

5. Tests with combined waves and weak uni-directional currents showed the development of the near-bed turbid layer to resemble its development under wave action alone. The main role of the current is in transporting the newly-eroded sediment as a near-bed layer (Figs 12-14).

10 ACKNOWLEDGEMENTS

The co-operation of the Port Authorities of Belawan, Bristol, Port Kelang and Kuching in supplying mud samples for these studies is greatly appreciated. Mineralogical analyses of the samples were carried out by the Institute of Geological Sciences (Belawan and Avonmouth) and the Institute of Hydrology (Port Kelang and Kuching).

The studies and the production of this report relied on the support of colleagues in many of the services areas of Hydraulics Research.

TABLES

TABLE 1: Current velocities (m/s) for calibrated manometer head settings (cm

Meter position Vertical	Height above bed (cm)	Manometer head setting 1.3	3.0	4.7	6.5	10.1	13.5	17.8	24.4	29.7	34.5
A	45	3.54	4.89	5.76	5.86	7.65	8.94	9.43	11.21	12.40	13.8
	25	3.60	4.73	5.32	6.03	7.65	8.94	10.13	11.64	13.05	14.1
	10	3.38	4.41	5.27	5.86	7.05	8.08	9.21	10.29	12.13	12.9
	5	3.33	4.03	4.62	5.32	6.51	7.27	7.65	9.27	11.21	11.3
	1	2.73	3.38	4.19	4.78	5.43	6.08	6.73	8.29	8.67	9.2
Depth-mean vel.		3.47	4.59	5.36	5.81	7.37	8.47	9.30	10.85	12.27	13.3
B	45	3.70	4.89	5.76	6.46	7.97	9.21	10.29	12.24	13.45	14.6
	25	3.49	4.84	5.70	6.57	8.13	9.32	10.51	12.34	13.64	14.5
	10	3.27	4.41	5.38	6.30	8.19	9.43	10.62	12.56	13.75	14.9
	5	3.16	4.03	4.62	5.65	7.05	8.51	9.48	12.00	13.10	14.2
	1	2.46	3.49	4.30	4.62	5.92	7.16	8.13	9.86	10.18	11.7
Depth-mean vel.		3.45	4.63	5.52	6.33	7.88	9.10	10.23	12.16	13.41	14.4
C	45	3.70	5.05	5.97	6.67	8.24	9.48	10.56	12.51	13.91	15.3
	25	3.65	5.00	5.81	6.62	8.24	9.59	10.67	12.67	14.07	15.3
	10	2.95	4.95	5.92	6.62	8.29	9.64	10.72	12.67	14.13	15.1
	5	2.84	4.46	5.38	6.08	7.48	8.83	9.86	11.97	12.88	13.9
	1	2.41	3.87	4.51	5.05	6.30	7.48	8.51	10.08	9.97	10.5
Depth-mean vel.		3.41	4.92	5.79	6.51	8.06	9.38	10.48	12.43	13.71	14.9
D	45	–	–	–	–	7.65	–	–	11.72	–	–
	25	–	–	–	–	7.40	–	–	11.98	–	–
	10	–	–	–	–	7.60	–	–	11.72	–	–
	5	–	–	–	–	7.35	–	–	10.60	–	–
	1	–	–	–	–	7.60	–	–	9.40	–	–
Depth-mean vel.		–	–	–	–	7.53	–	–	11.58	–	–
E	45	–	–	–	–	7.50	–	–	11.78	–	–
	25	–	–	–	–	7.60	–	–	11.98	–	–
	10	–	–	–	–	7.85	–	–	12.65	–	–
	5	–	–	–	–	7.40	–	–	12.30	–	–
	1	–	–	–	–	6.32	–	–	10.70	–	–
Depth-mean vel.		–	–	–	–	7.52	–	–	11.99	–	–
	45	–	–	–	–	7.90	–	–	12.30	–	–
	25	–	–	–	–	7.90	–	–	12.40	–	–
F	10	–	–	–	–	8.15	–	–	12.50	–	–
	5	–	–	–	–	7.80	–	–	12.10	–	–
	1	–	–	–	–	6.70	–	–	10.12	–	–
Depth-mean vel.		–	–	–	–	7.87	–	–	12.23	–	–

Table 2: Clay mineral consituents of the > 20μm fraction of the muds examined

Mineral	Clay mineral percentage				
	Belwan	Kuching	Avonmouth	Port Kelang (Pintu Bar)	Port Kelang (Wharf 8)
Montmorillonite/ Smectite	15-20	23	10	20	20
Kaolinite	30	13	10	55	55
Illite/Mica	30	19	30	25	25
Chlorite	trace	-	30	-	-
Total clay minerals (2 m)	75-80	55	67	69	63
Total non-clay minerals (2 m-20 m)	20-25	45	33	31	37
Cation exchange capacity meq/100g	25	21	19	24	24

Table 3: Wave conditions used in mud studies

(a) Kuching mud

Wave Paddle Setting	Wave Properties					
	T = 2.83s		T = 2.21s		T = 1.77s	
	H(m)	Ub_{max}(m/s)	H(m)	Ub_{max}(m/s)	H(m)	Ub_{max}(m/s)
1	0.0267	0.0511	0.0400	0.0716	0.0367	0.0591
2	0.0400	0.0760	0.0600	0.1073	0.0500	0.0805
3	0.0550	0.1053	0.0717	0.1282	0.0667	0.1074
4	0.0667	0.1277	0.0933	0.1669	0.0800	0.1288
5	0.0767	0.1469	0.1117	0.1998	0.1000	0.1611
6	0.0600	0.1149	0.1071	0.1916	0.0914	0.1472
7	0.0886	0.1696	0.1543	0.2760	0.1314	0.2116
8	0.1171	0.2243	0.1943	0.3476	0.1700	0.2738
9	0.1514	0.2900	0.2314	0.4139	0.2029	0.3268
10	0.1829	0.3503	0.2714	0.4855	0.2243	0.3613

(b) Avonmouth and Port Kelang muds

Wave paddle setting	Wave Properties	
	T = 2.83s	
	H(m)	Ub_{max} (m/s)
1	0.0320	0.0613
2	0.0453	0.0868
3	0.0634	0.1214
4	0.0770	0.1475
5	0.0924	0.1770
6	0.0953	0.1825
7	0.1224	0.2344
8	0.1558	0.2984

F I G U R E S

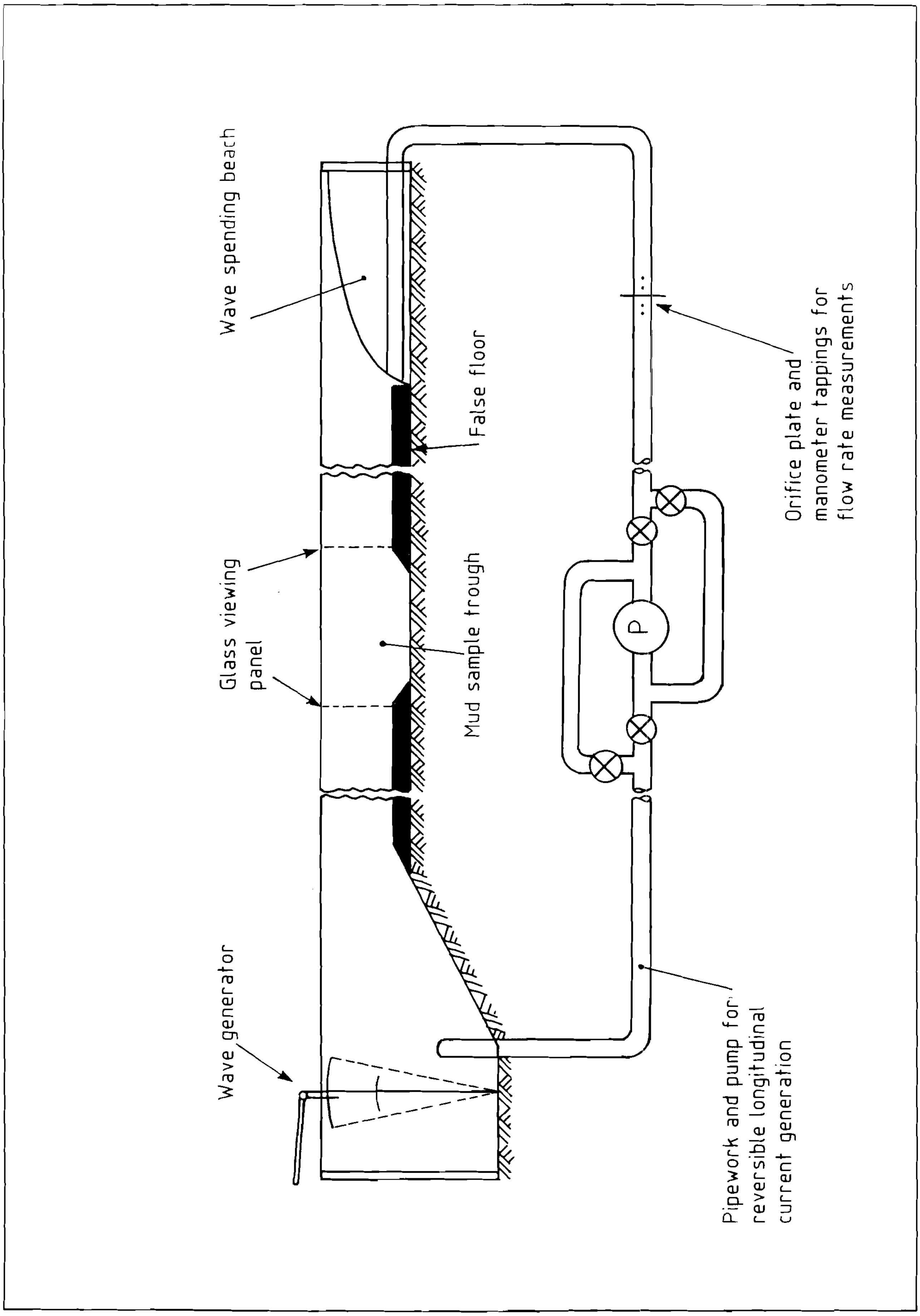

Fig 1 Schematic layout of experimental facility

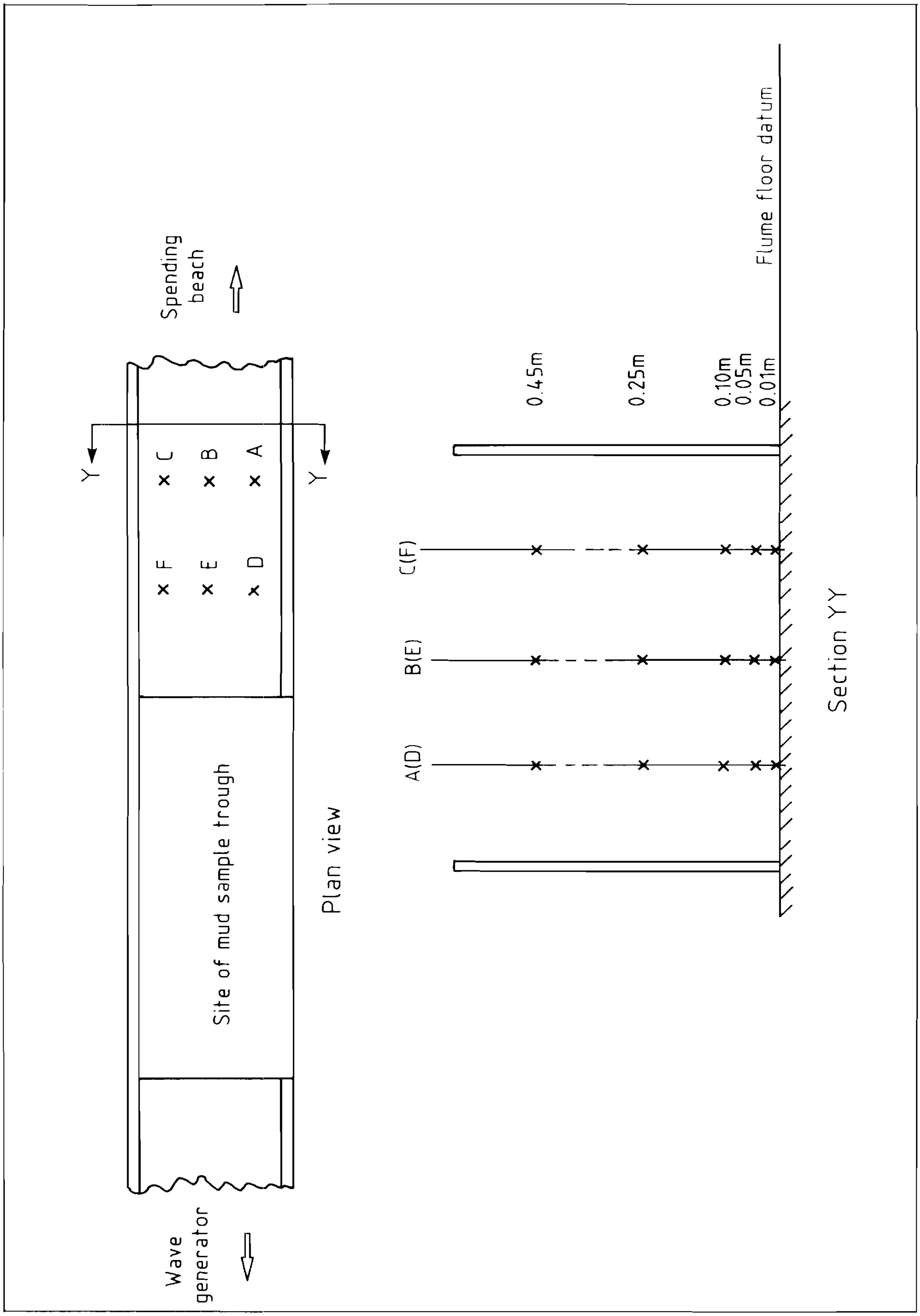

Fig 2 Location of current meters for flow calibration - plan and section

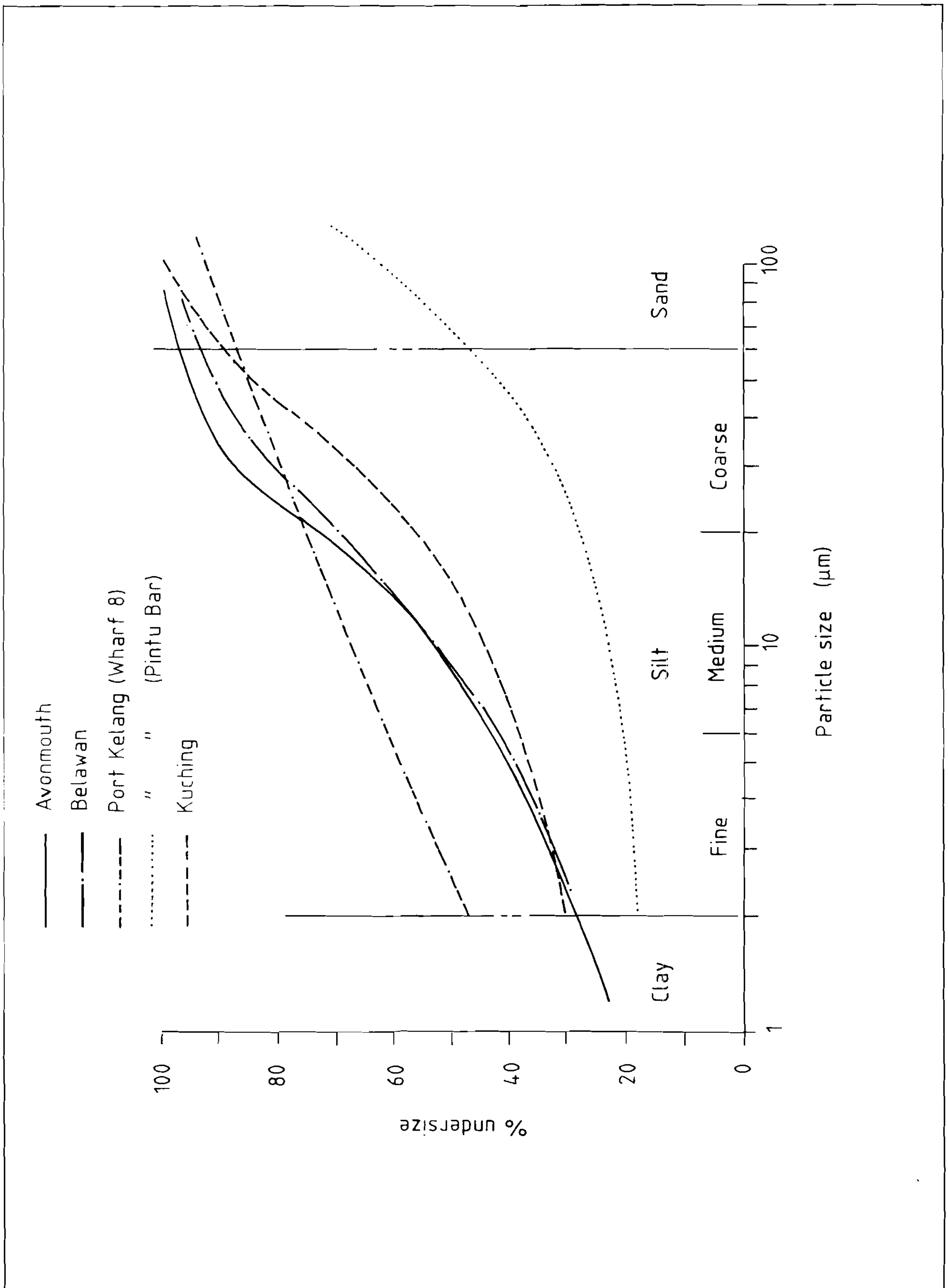

Fig 3 Particle size distribution of mud samples

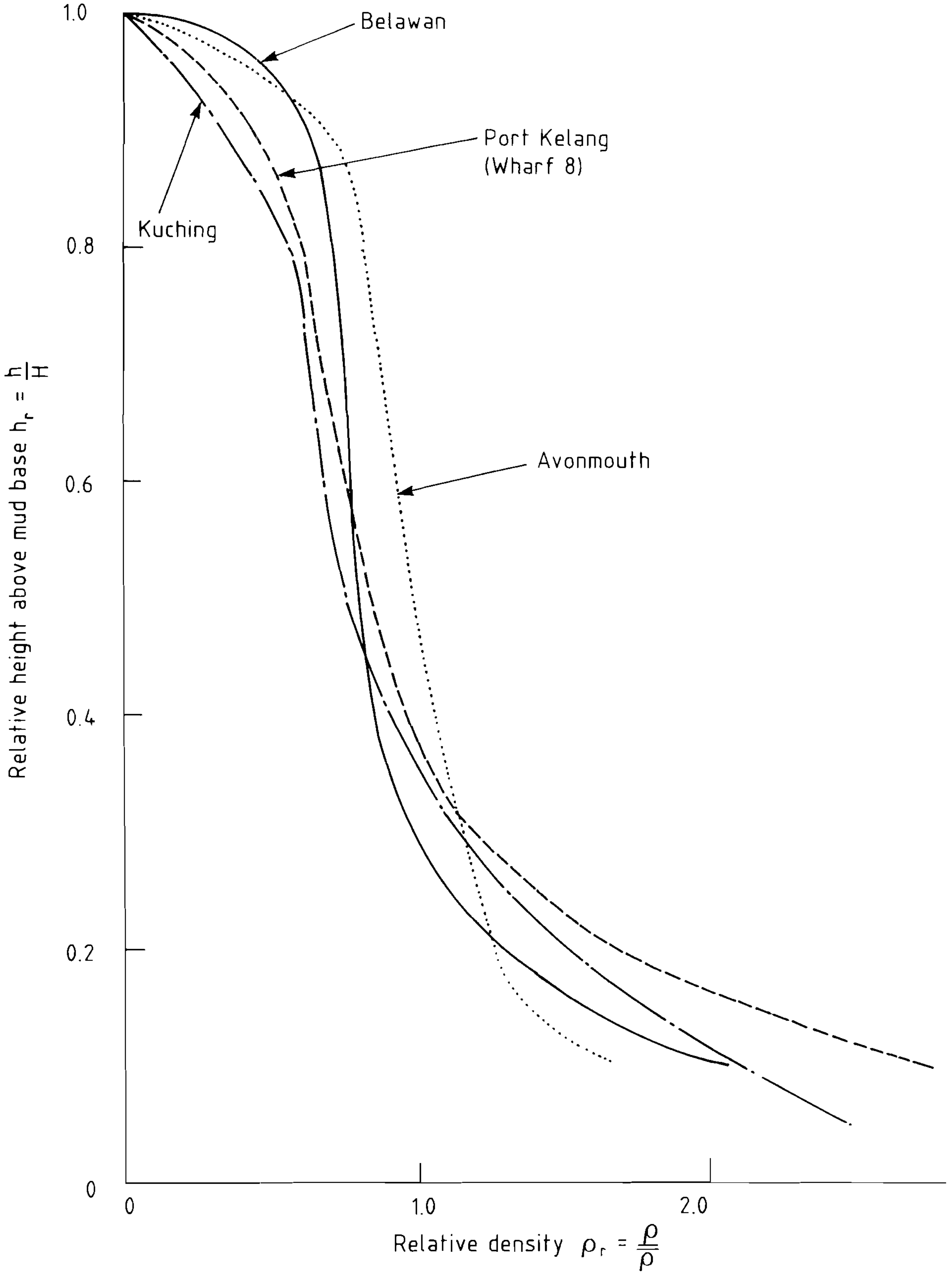

Fig 4 Mud density-depth relationship

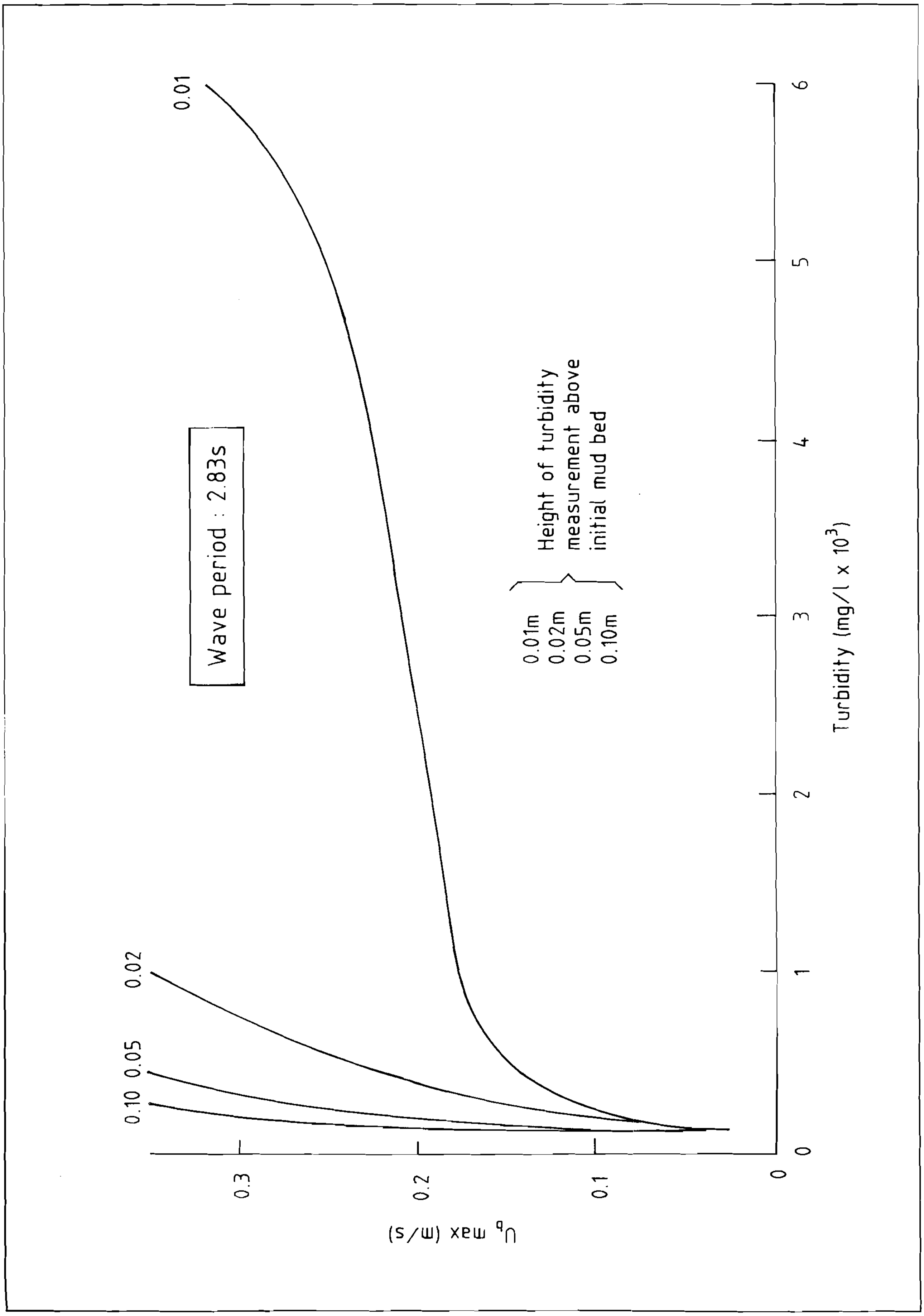

Fig 5 Near-bed velocity-turbidity relationship
Kuching mud - Test 1

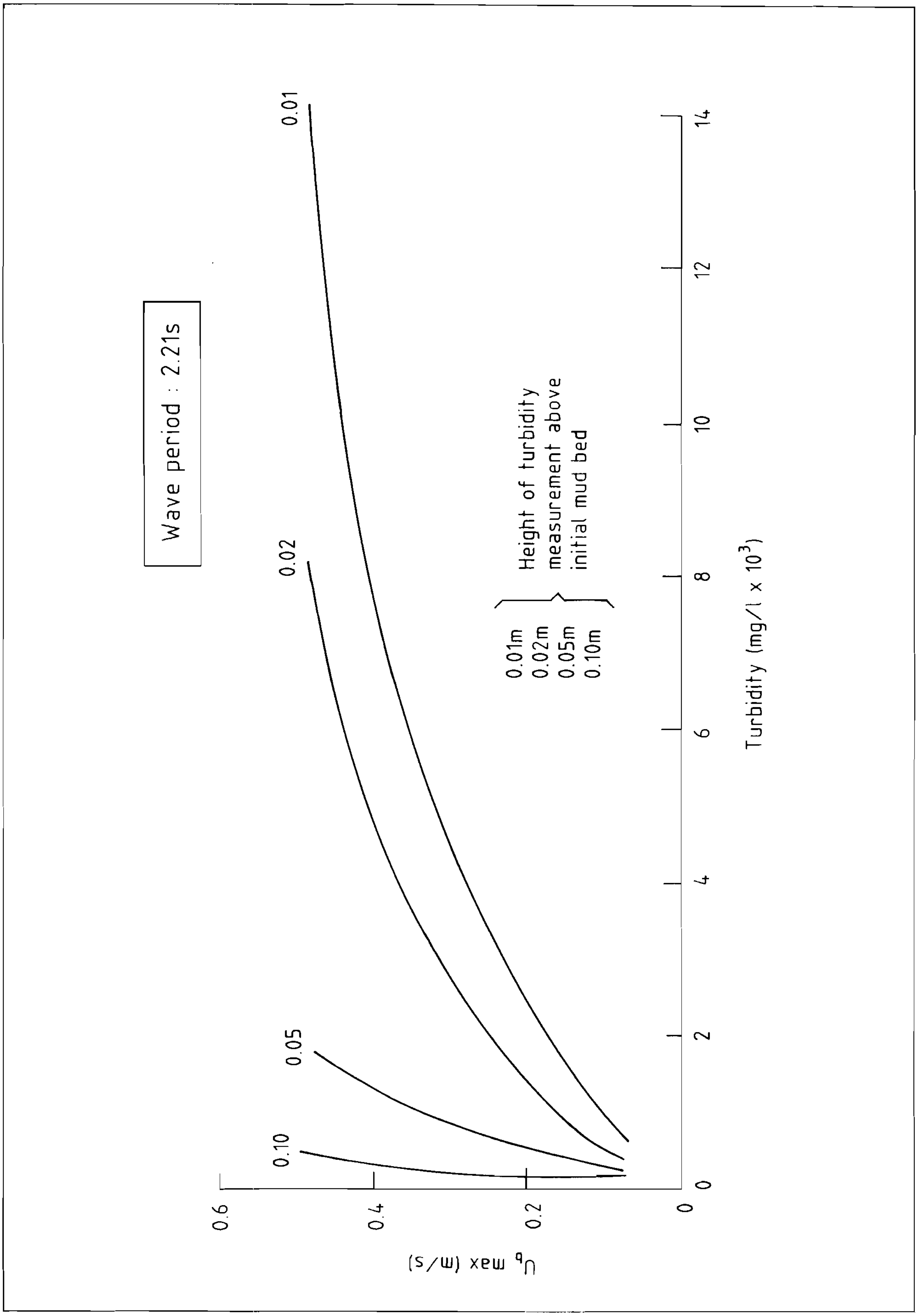

Fig 6 Near-bed velocity-turbidity relationship
Kuching mud - Test 2

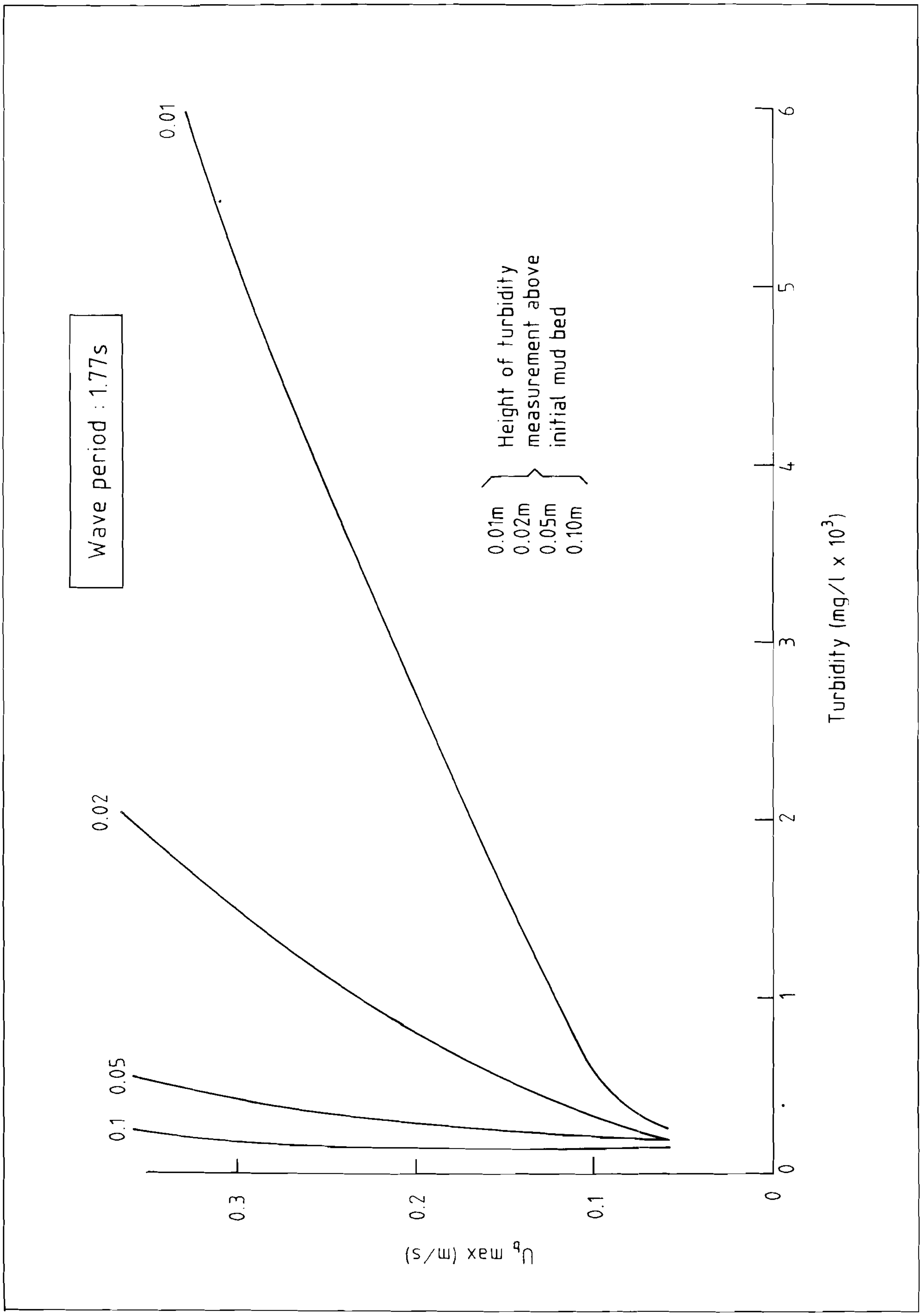

Fig 7 Near-bed velocity-turbidity relationship
Kuching mud - Test 3

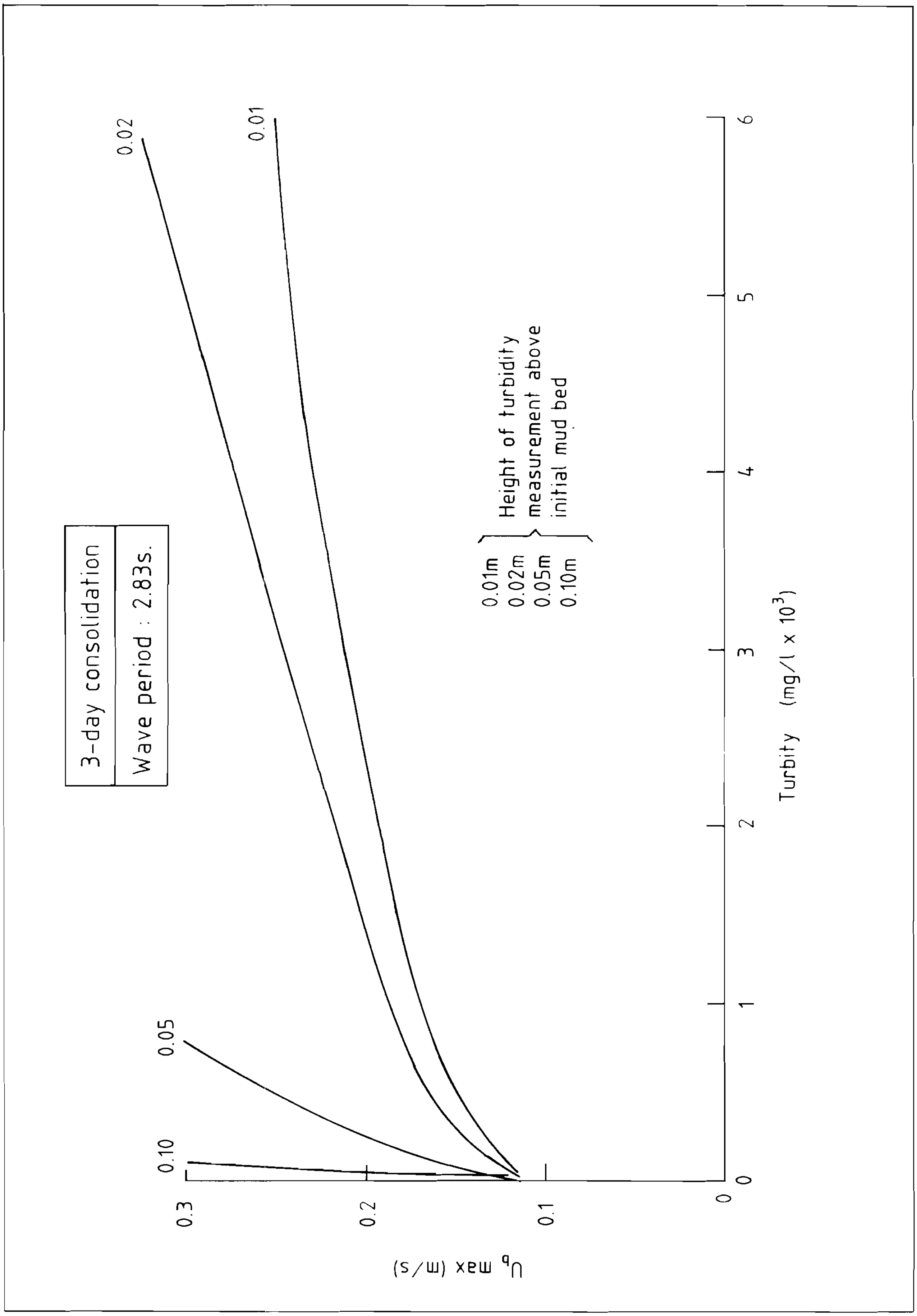

Fig 8 Near-bed velocity-turbidity relationship
Avonmouth mud - Test 1

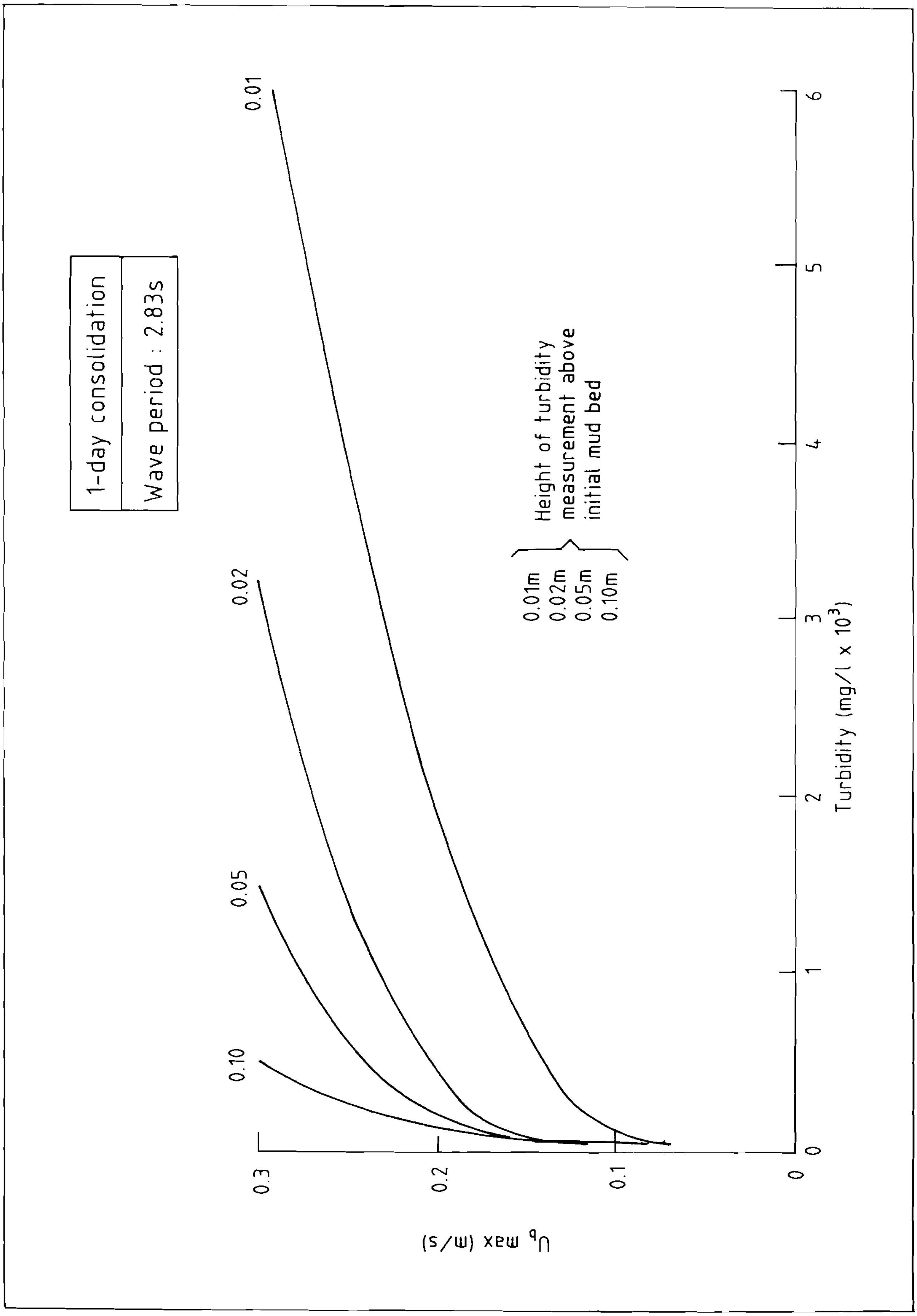

Fig 9 Near-bed velocity-turbidity relationship
Avonmouth mud - Test 2

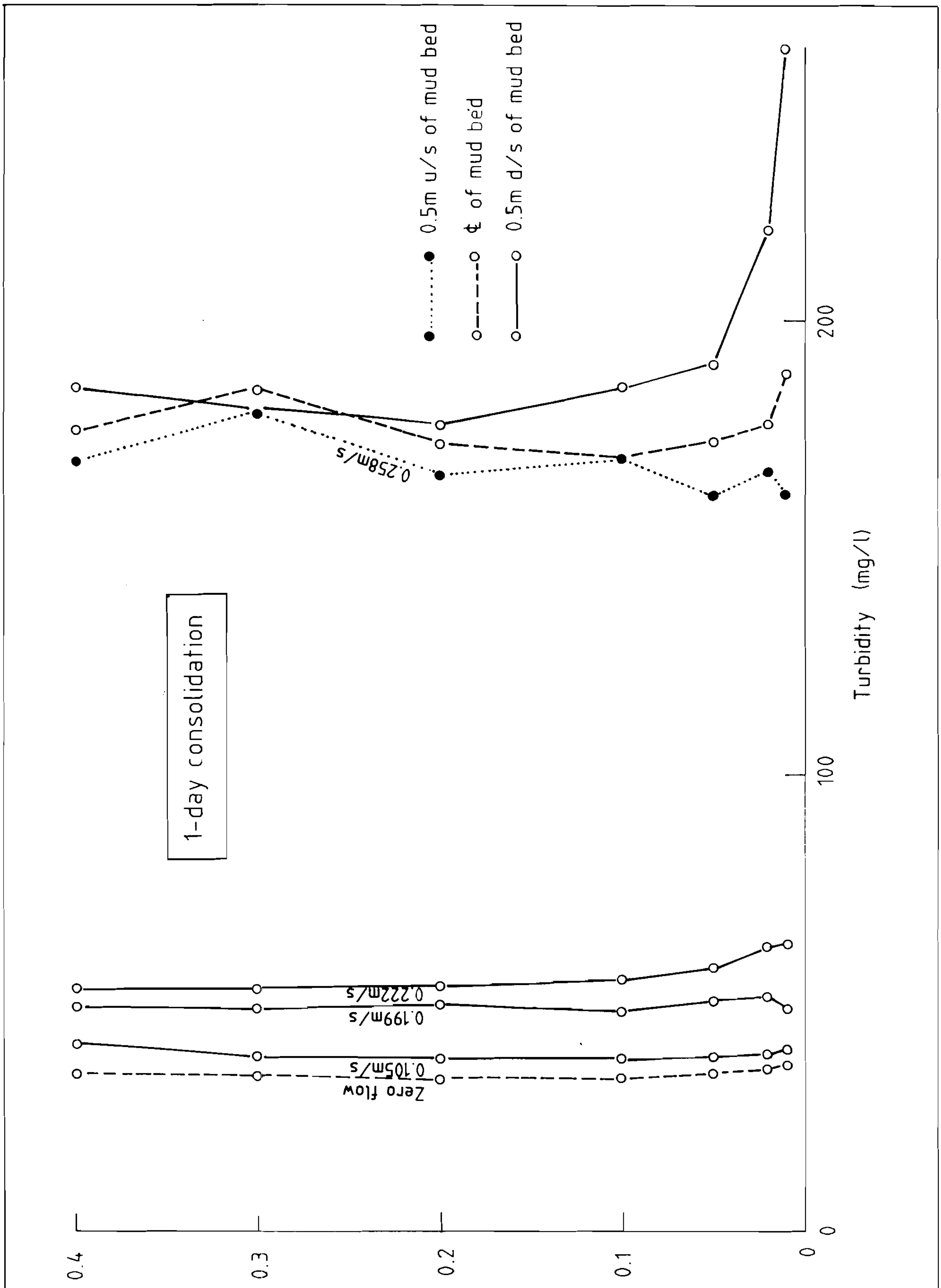

Fig 10 Turbidity profile-flow relationship
Avonmouth mud - Test 3

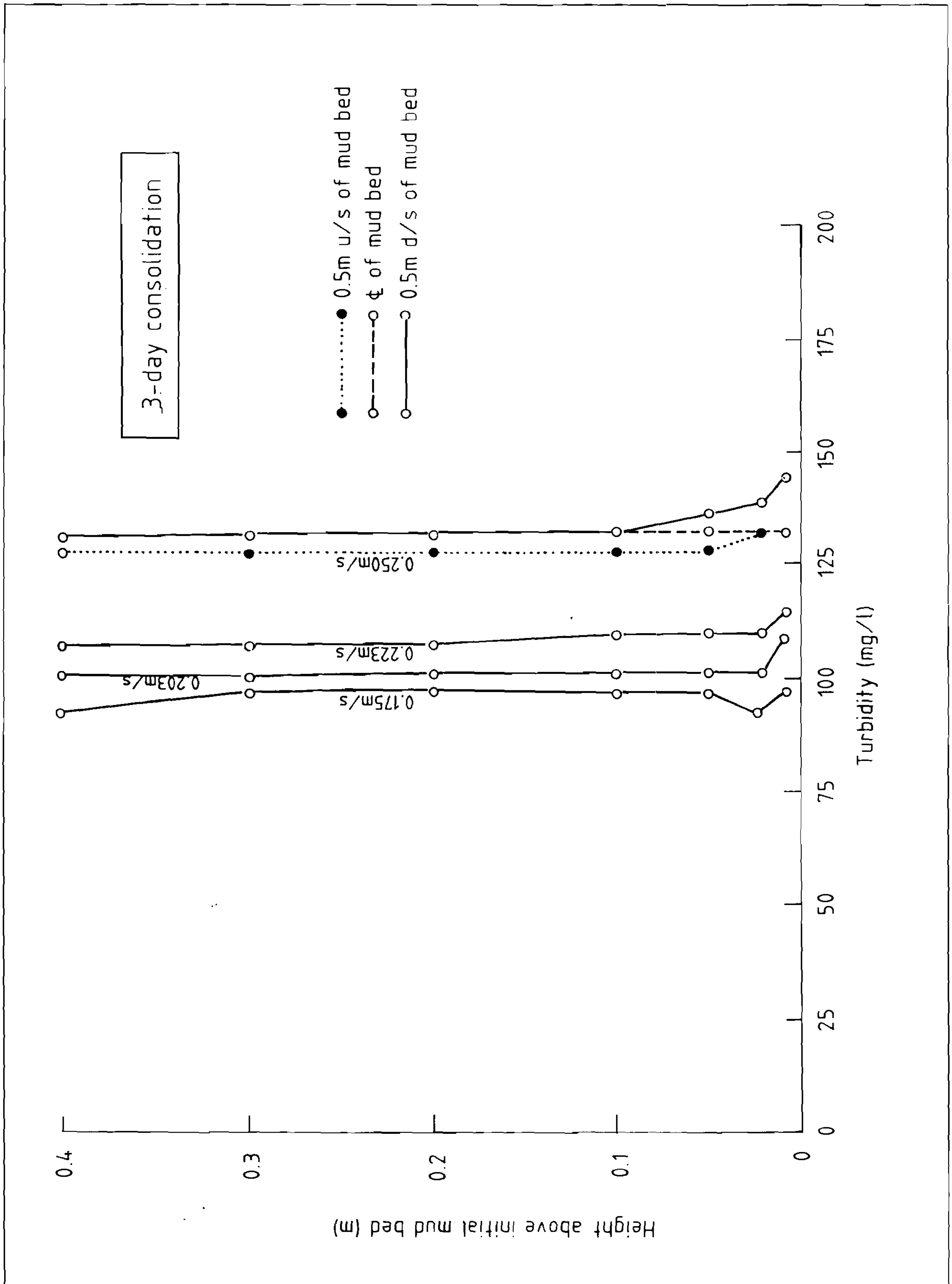

Fig 11 Turbidity profile-flow relationship
Avonmouth mud - Test 4

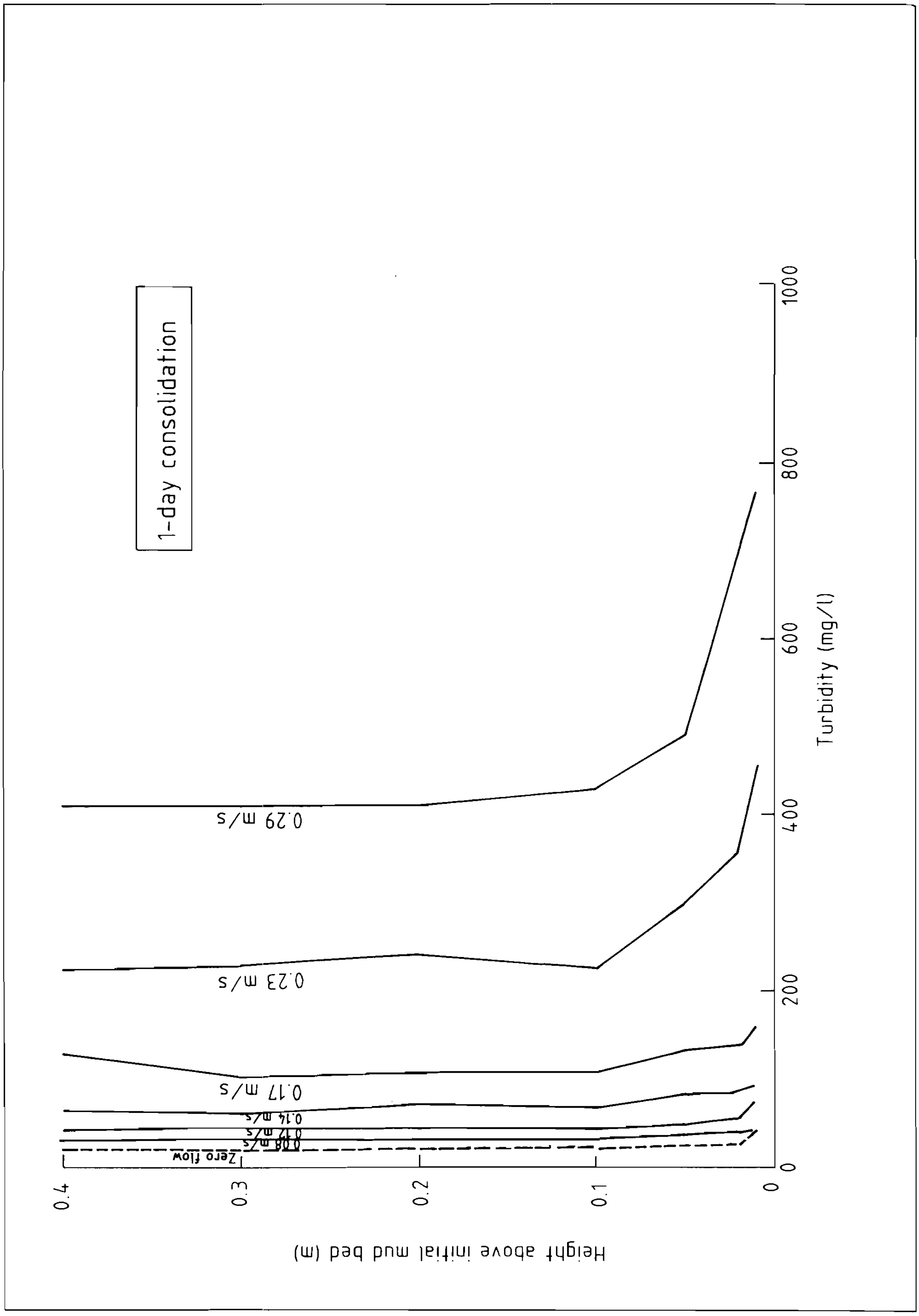

Fig 12 Turbidity profile - orbital velocity relationship in 0.1 m/s current Avonmouth mud - Test 5

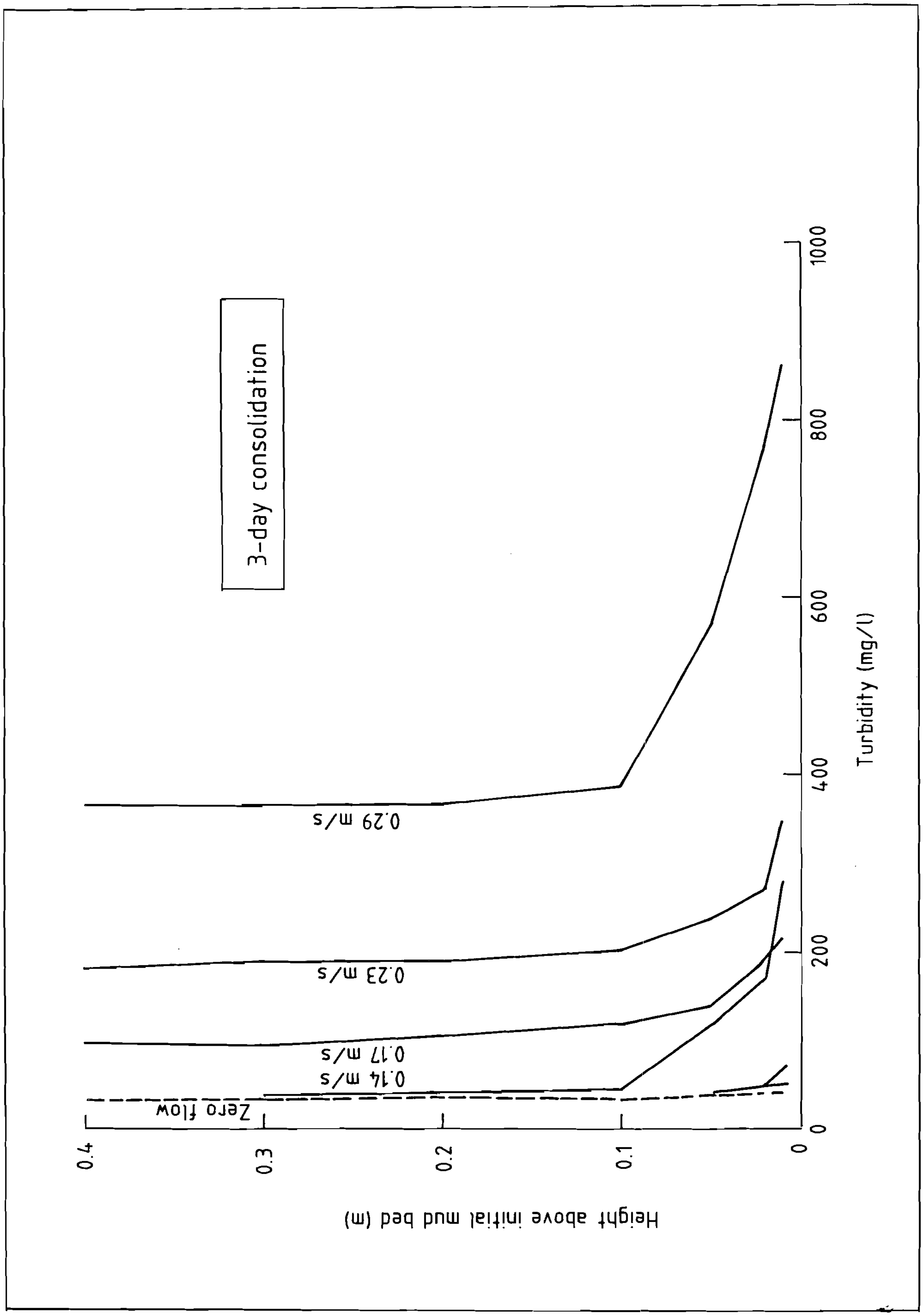

Fig 13 Turbidity profile-orbital velocity relationship in 0.1 m/s current Avonmouth mud - Test 6

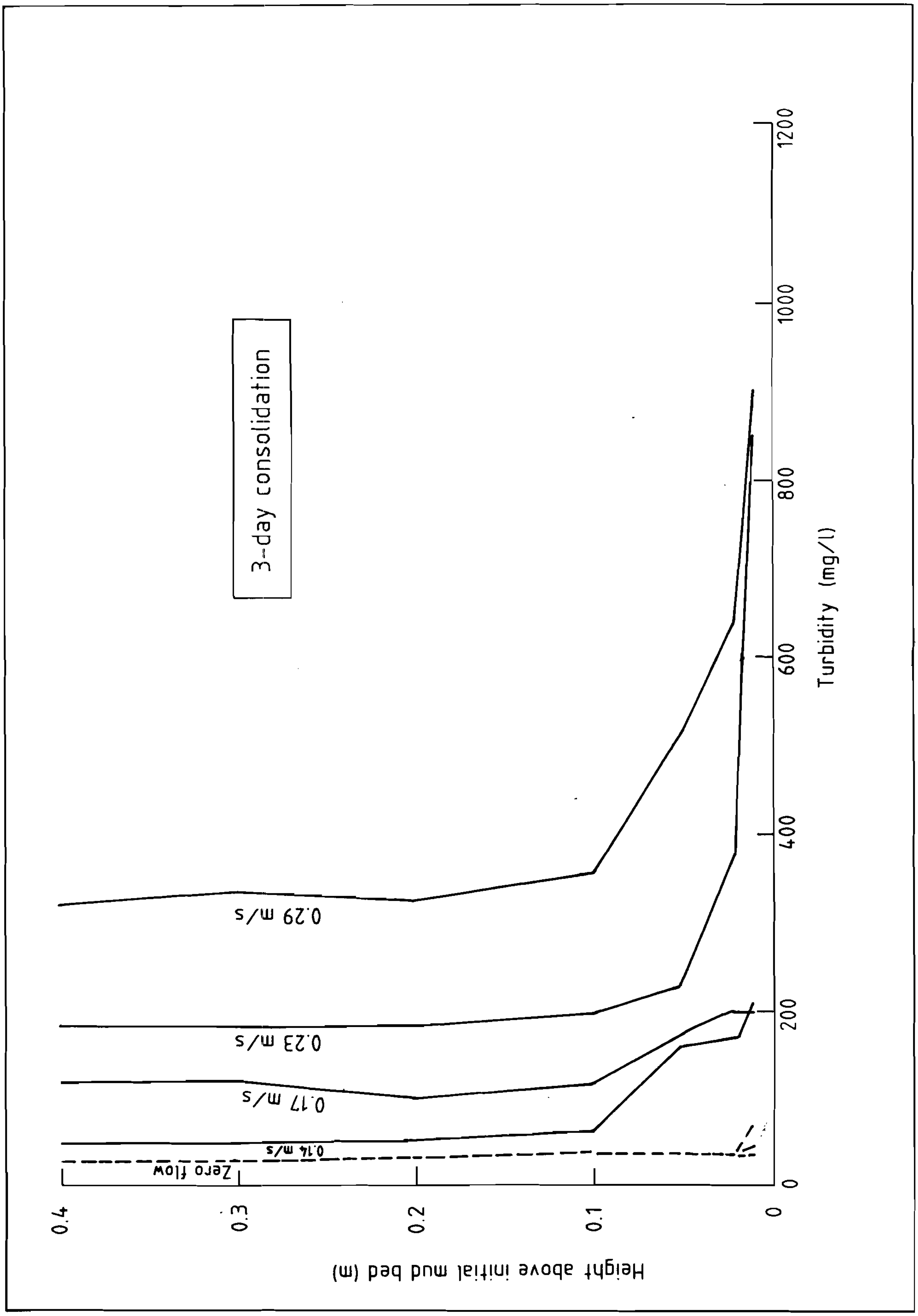

Fig 14 Turbidity profile - orbital velocity relationship in 0.05 m/s current Avonmouth mud - Test 7

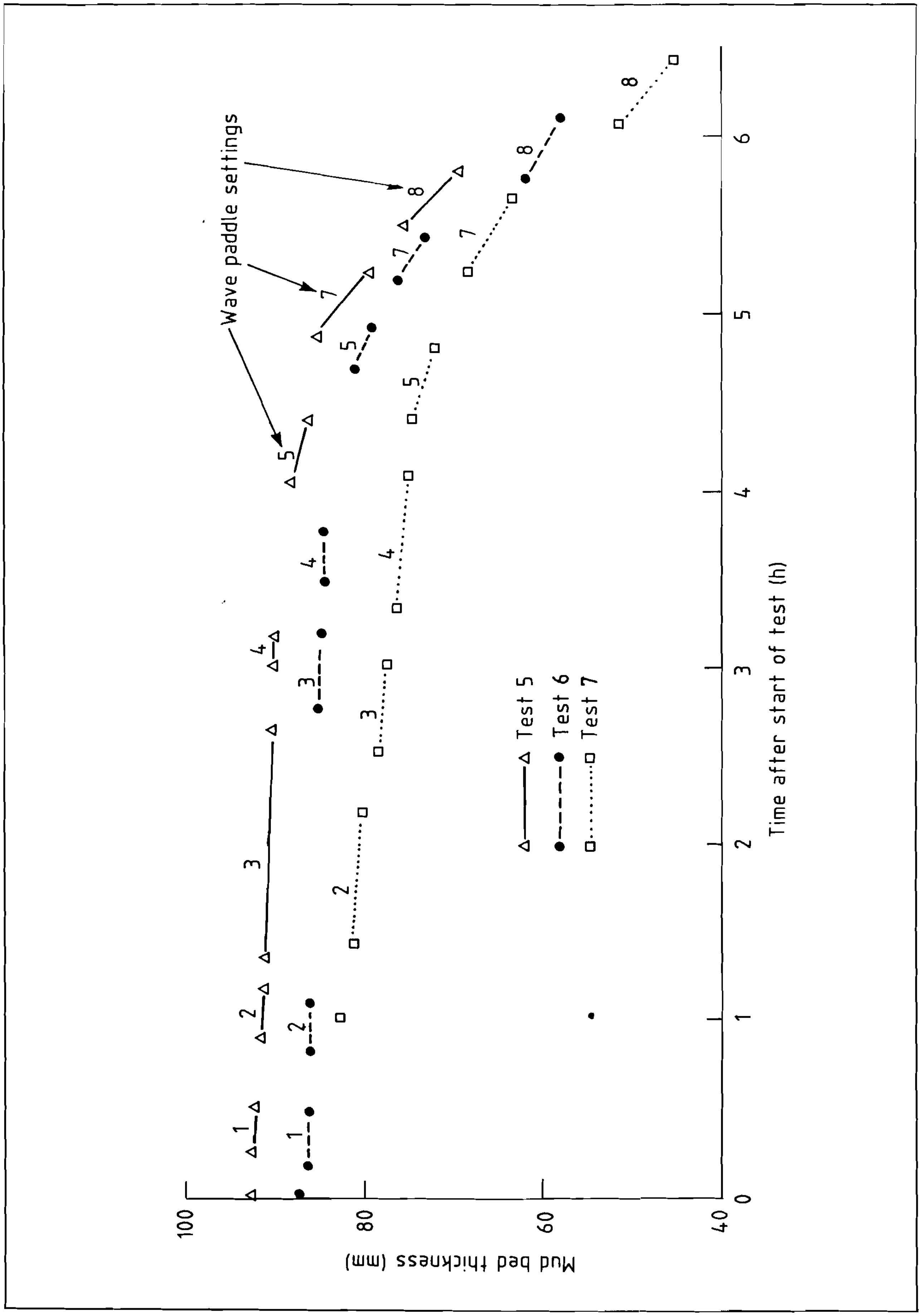

Fig 15 Progress of bed erosion Avonmouth mud - Tests 5-7

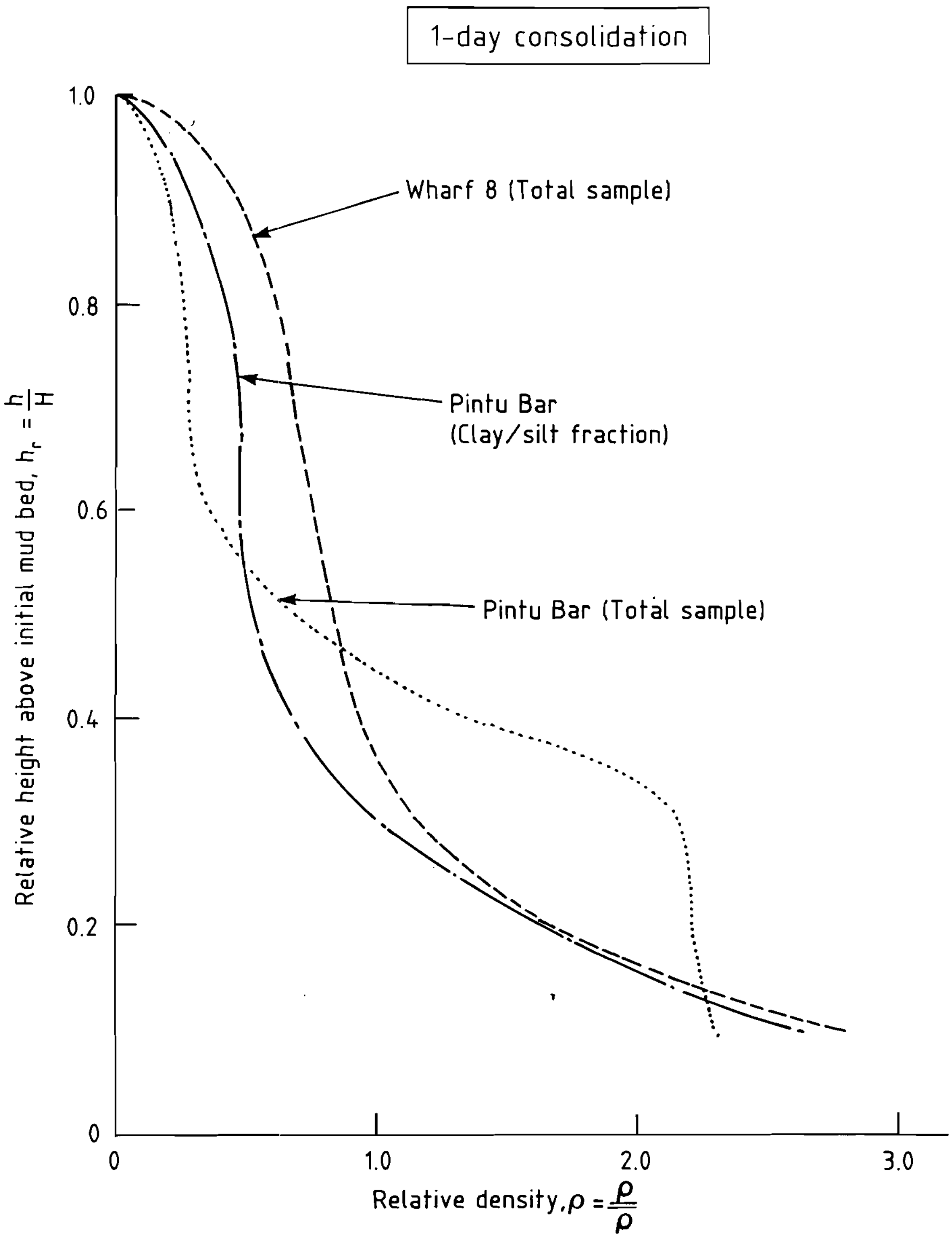

Fig 16 Density-depth relationship of Port Kelang muds

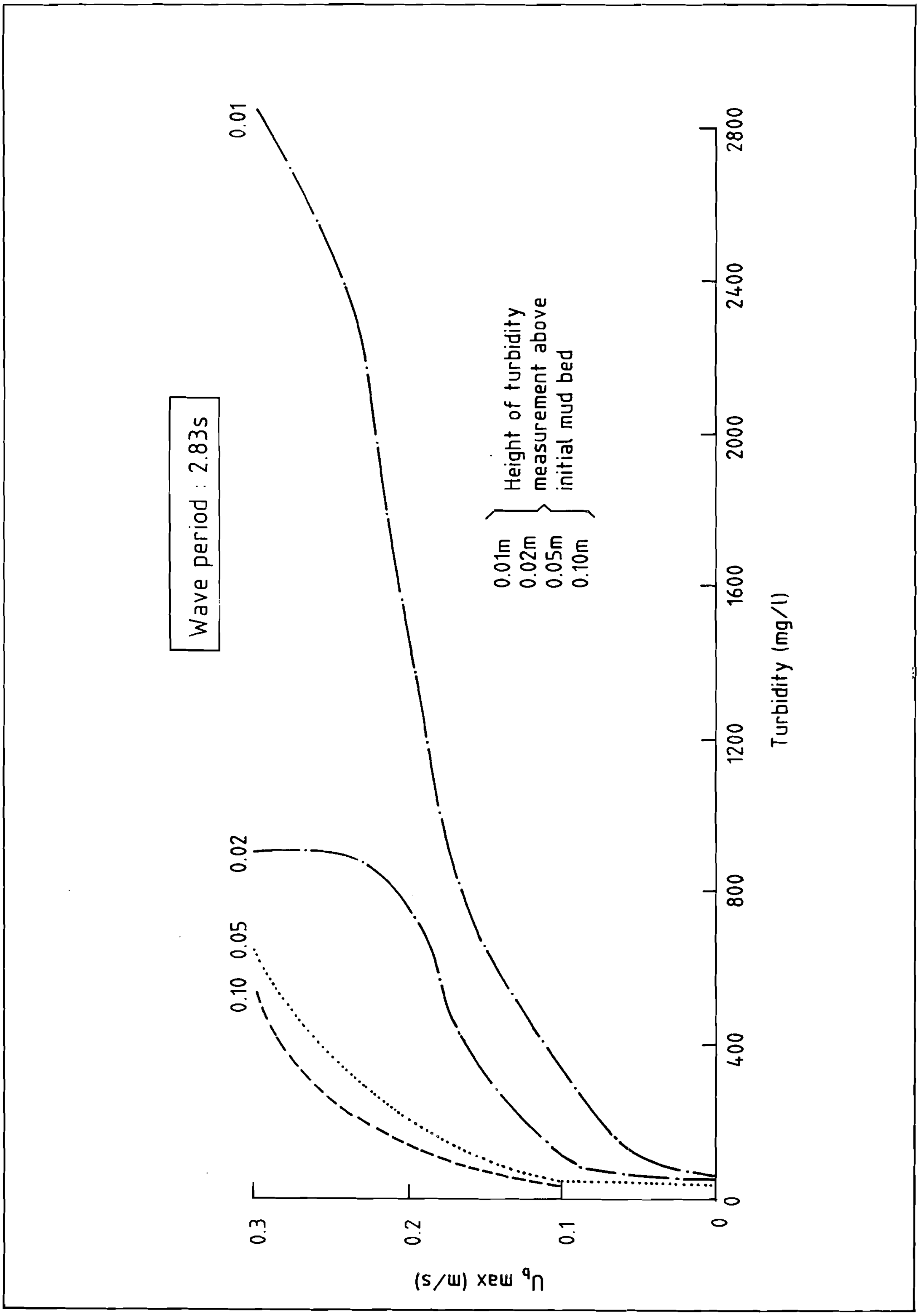

Fig 17 Near-bed velocity-turbidity relationship
Port Kelang mud (Wharf 8)

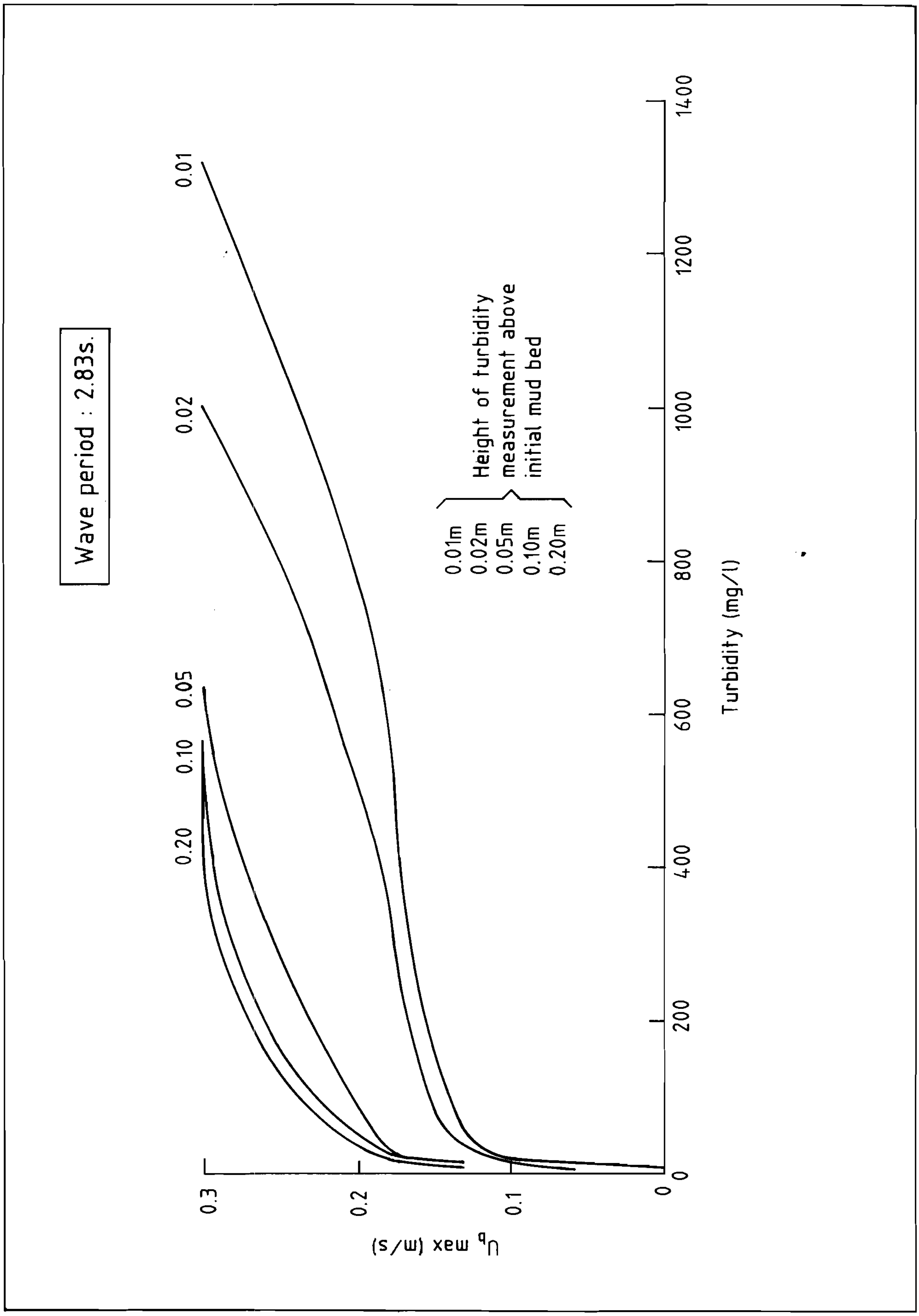

Fig 18 Near-bed velocity-turbidity relationship
Port Kelang mud (Pintu Bar)

A P P E N D I C E S

APPENDIX 1

Belawan mud studies

Tests carried out on a sample of Belawan mud in a unidirectional flow erosion flume indicated that the critical shear stress at the bed both for erosion and deposition was relatively low. Against the background of the current strengths measured in the field it was reasoned that siltation could not be due solely to the erosion by tidal currents, transport in suspension and deposition of discrete particles of the shoal material. Additional tests were therefore concluded to be necessary in which the behaviour of Belawan mud under wave action was examined.

To avoid difficulties of scaling when dealing with cohesive sediment movement, it was decided at the outset that the studies would be conducted as nearly as possible at full scale, i.e. under conditions that obtain in the field. The wave period selected for the tests was 2s - being the most common period noted in the limited number of observations made by surveyors during the 1977-78 field survey.

Three tests were included in the experimental programme. Test 1 examined the behaviour of the mud under a range of wave heights in salt water at full sea salinity (32g/l). Test 2 considered the behaviour of the mud in freshwater, i.e. in the absence of the electro-chemical bonding of particles which occurs in saline water. Test 3 examined the behaviour of the mud laid in seawater (32g/l) on a sloping bed having a gradient of 1/10, i.e. representative of the seabed at the top of the side slopes of the sea channel.

The mud sample under test was placed mid-way along the wave flume in line with a glass viewing panel. At this position the level cement floor was excavated to a depth of 40mm over a length of 0.75m and filled with a well-stirred sample of Belawan mud.

In Test 1 the flume was slowly filled with salt water (32g/l) to an operating depth of 0.55mm. It was then left overnight to allow settlement of fine suspended particles and partial consolidation of the mud bed.

The test began with the generation of waves of 2s period and 20mm height. Under this condition fine clay particles were entrained into a whitish, cloudy layer which extended for 30mm above the bed and oscillated to and fro with the wave motion. With the wave height increased to 25mm the cloudy layer extended upwards by a further 10mm and the particles travelled in a horizontal orbit covering 30-50mm. During this stage the upper 10mm of the mud bed had started to move as a gel, out of phase with the suspended sediment and covering an orbit length of about 5mm. In the descriptions which follow, the upper limit of this gel was taken as the surface of the mud bed.

Further increases in wave height produced increases in the depth and movement of the cloudy layer. With 40mm waves, the cloud was 150mm thick and moved some 120mm: the mud gel movement was unchanged but small mud lumps of up to 2mm diameter appeared on the surface and moved to and fro as free-rolling bed load covering a distance of 20-30mm.

Further increases in wave height again increased the movement and depth of the cloudy layer and produced larger mud lumps on the surface of the gel. With a wave height of 80mm the gel continued to move but the mud lumps dispersed to form a turbid layer about 80mm thick and having a concentration of 2000mg/l: the cloud of fine material now extended to 450mm above the bed. Hereafter, an increase in wave height produced larger mud lumps which added to the depth and concentration of the near-bed turbid layer.

When a wave height of 150mm was generated a third, dense mud layer formed having a thickness of about 50mm and a general concentration of 10 000mg/l: large lumps of mud up to 20mm in diameter raised local concentrations to 30 000mg/l. The layer immediately above extended at an average concentration of 2000mg/l for a distance of 210mm above the bed, and the water above this was clouded with fine material. When the flume recirculating pump was used to generate a weak current of 0.03m/s, the dense, near-bed layer travelled along at approximately the speed of the current with little or no mixing with the layers above.

After half an hour, the situation was still the same: the pump was stopped and the wave height was increased in stages to a maximum of 230mm. The dense, near-bed layer increased in depth, finally reaching 80mm, the sediment concentration remaining sensibly constant.

From the results of this test it was concluded that in 0.55mm of water a 2s wave, 150mm high was adequate to form a sediment supply source that could be transported by tidal currents. Application of first order linear wave theory (Section 8.2) indicated that these conditions produced a theoretical maximum horizontal velocity of water particles at the bed of 0.26m/s.

In the fresh water test (Test 2) a similar procedure was followed and under low waves the behaviour of the mud was comparable to that in salt water. When the wave height reached 65mm, however, a turbid band developed having a concentration of 1000mg/l and a thickness of 40mm: its length of oscillation along the bed was between 100 and 150mm. Under 80mm-high waves the concentration in this near-bed layer increased to 1500mg/l, and with 90mm-high waves the bed began to break up, 20mm lumps of mud starting to roll along the surface. When the wave height was increased to 110mm, a dense layer formed above the bed 50-60mm thick, with a general concentration of 10,000mg/l (local concentrations reached much higher values, the maximum 25 900mg/l, clearly indicating that the sample contained mud lumps which had not dispersed into the dense layer). It was apparent that the wave 100mm high had just exceeded the critical value for general erosion of Belawan mud in fresh water.

The final stage in the test was to lower the wave height to 50mm for a period of 2 hours, and at the end of this time it was noted that the water had once again assumed a cloudy white appearance throughout the depth, approximating to its state during the early part of the test when this wave condition had been applied.

In the final test (Test 3) a lead-in ramp of slope 1/40 was fixed to the floor level. From the crest of the ramp a mud bed was laid to a slope of 1/10 along the longitudinal axis of the flume. The test was conducted in salt water (32g/l) having a depth of 0.55m.

Application of a 2s wave, 50mm high suspended the fine particles into a cloudy layer 400mm thick: there was no apparent movement within the mud bed but small lumps 1.2mm in diameter moved to and fro along the mud surface in a net down-slope direction. At the toe of the slope a thin turbid layer having an average concentration of 2000mg/l had formed. Increasing the wave height to 75mm increased the size of the mud lumps rolling down-slope to between 2.5mm but there was still no apparent movement within the mudbed.

With the wave height at 100mm, the turbid layer increased in thickness to 85mm and the gel-like movement of the bed began.

Application of a 125mm wave led to the break-up of the surface of the bed, with lumps of mud about 20mm in diameter moving down-slope, a dense turbid layer forming about one-third of the way down. Thus, the erosion of a sloping bed of Belawan mud under the conditions applied in this test is initiated by 2s waves of between 100 and 125mm in height.

Main findings of the tests

1. Wave action on Belawan mud could create a highly turbid layer of material just above the bed which was capable of being transported by tidal currents.

2. The horizontal velocity of flow at the bed required to form the near-bed turbid layer was about 0.26m/s in seawater. In the test zone of the wave flume, concentrations of 10,000mg/l were recorded with a layer thickness of 100mm. In the field, where offshore mud supplies are virtually unlimited, both concentration and turbid layer thickness would probably be greater.

3. In fresh water, a layer of similar concentration and thickness forms in 2s waves, but at lower wave heights, i.e at a lower critical velocity for erosion. The main reason for this was that

in freshwater, the bonding characteristics of particles forming the bed were reduced due to the absence of the electro-chemical properties of salt water, hence the bed was less resistant to erosion.

4. Mud would be eroded at lower velocities on slopes than on level banks. It was therefore likely that any mud entering the channel would remain entrained in the near-bed flow until the water depth became too great for wave-induced motion to be felt near the bed.

APPENDIX 2

Kuching Mud

Test 1

Water depth	0.55m
Water salinity	28 g/l
Initial bed thickness	50mm
Consolidation period	24h
Wave period	2.83s
Water temperature	11.1 ^{0}C

Waves only

0850 h	Water samples
0900	Wavemaker started 0.0267m wave height
0904	Surface micro-ripples of 2cm wave length; non-progressive oscillatory movement of 1cm of negligible height
0909	Movement confined to mud surface. No entrainment
0924	Water samples
0930	Wave height adjusted to 0.04m
0933	Signs of erosion at upstream concrete/mud floor interface. Similar mud movement to 0904h
0948	Water samples
0958	Wave height adjusted to 0.055m
1002	Near upstream concrete/mud interface a white cloudy layer is forming with a non-progressive oscillation of 50mm
1013	Particles from micro-ripples now being entrained. Two layers have formed, the denser bottom layer 3mm thick and above another layer 2cm thick. Layers have a vertical rise and fall of 4mm in sympathy with the waves

Bed thickness 49mm

1014 Evidence of erosion at concrete/mud interface

1018 Water samples

1044 Water samples

1050 Wave height adjusted to 0.0667m

1055 Layers are now 25mm (dense dark layer) and 40mm (cloudy layer) thick with vertical rise and fall of 12mm

1115 Water sample

1125 Wave height adjusted to 0.0767m

1131 Bottom layer now reduced to 20mm thick but has become denser. Small fissures have developed in mud surface spaced at horizontal orbit length intervals

1135 Brown fluid mud layer forming at bed. Third white layer is now about 7cm thick

1139 At the bed the fluid layer is 3.5mm thick oscillating with the wave action
Bed thickness 48mm

1141 Water samples

1151 Wavemaker switched off and crank throw adjusted

1158 Wave height adjusted to 0.06m

1203 Fluid mud layer has disappeared

1210 No fluid mud

1219 Water samples

1320 Water samples

1326 Wave height adjusted to 0.0886m

1328 Reappearance of fluid mud layer

1338 Water samples

1345 Wave height adjusted to 0.1171m

1348 Mud bed appears to be oscillating with wave action

1356 Water samples

1402 Fluid mud layer of variable thickness reaching a maximum of 14mm at downstream end of mud bed

1406 Horizontal travel of fluid mud approx 10mm

1410 Bed thickness 44.5mm

1415 Water samples

1420 Wave height adjusted to 0.1514m

1423 Fluid mud layer dense and widespread. Three layers present have thicknesses of 10mm,40mm and 75mm

1428 Water samples

1447 Three layers are now 15mm,55mm and 85mm thick. The centre layer is darker and denser than earlier and has a horizontal movement of 100-150mm

1500 Water samples

1500 Bed thickness 40mm

1505 Wave height adjusted to 0.1829m

1507 Fluid mud layer is now 15mm thick, dense dark centre layer 30-40mm thick and white cloudy layer up to 2000mm in places. Centre and top layers oscillate with an orbit of 500mm horizontally and 15-20mm vertically

1512 Erosion occurring 100mm-250mm from upstream end of mud sample. Cloudy layer is non-progressive

1513 Water samples

1538 Fluid mud layer is 20mm thick oscillating 5mm-10mm horizontally. There is no clear interface between fluid mud and centre layer. Centre layer now about 50mm thick and as dense as fluid mud in places. Cloudy layer 140-160mm thick

1541 No apparent progress of any layer down-flume

1545 Bed thickness 35mm

1550 Water samples

1600 End of test

Kuching Mud

Test 2

Water depth	0.55m
Water salinity	28g/1
Initial bed thickness	60mm
Consolidation period	24h
Wave period	2.21s
Water temperature	12.8°C

Waves only

0909h	Bed thickness 60mm
0932	Water samples
0938	Wave maker started. Wave height 0.04m
0939	Non-progressive micro-ripples. Top 10-15mm of mud sample swaying with the wave action
0942	Fluid mud layer has formed in upstream part of mud sample. Thickness 5mm
0945	Fluid mud now covers whole length of bed
0952	It appears that fluid mud is being taken into suspension
0956	Water samples
1006	Wave height adjusted to 0.06m
1007	Fluid mud oscillating about 50mm and being taken into suspension from the central part of the mud bed
1009	Mud in suspension all along the flume
1010	Surface of mud bed oscillating out of phase with fluid mud movements
1012	A non-progressive light brown but dense patch about 25mm thick is forming at the upstream end of mud sample
1015	Fluid mud layer 5mm thick. Dark dense layer above about 25mm thick and a cloudy layer above about 40mm thick . All layers oscillating freely under wave action.

1019	Fluid mud layer now 10mm thick
1030	Water samples
1034	Wave height adjusted to 0.0717m
1034	Virtually instantaneous response to new wave setting with erosion occurring at the upstream end of the mud sample
1041	Settled mud bed is oscillating about 7mm horizontally
1042	Dense dark layer about 40mm thick at upstream end of sample reducing in thickness and becoming lighter in a downstream direction
1052	Water samples
1101	Wave height adjusted to 0.0933m
1102	No distinct interfaces between mud layers. Moving settled mud and fluid mud about 40mm thick with a dark denser layer above extending over the entire length of the mud sample
1104	Fluid mud observed to release pulses of sediment into the overlying dense dark layer which could be moving along the flume
1107	Cloudy layer about 45mm thick now more visible. Bed thickness 53.5mm
1117	Water samples
1121	Wave height adjusted to 0.1117m
1125	Increased erosion at upstream end of bed. Although the fluid mud is unchanged in appearance the denser layer above is darker and the cloudy layer greyer
1135	Measurement of layer thickness very difficult because of the vertical and horizontal orbital movements of the suspensions
1139	Settled bed is moving to a depth of 15mm
1141	Water samples
1152	The bed is now composed of 38mm of stationary mud and 30mm of oscillating mud and fluid mud

1219 Wave height adjusted to 0.1071m

1225 Suspended solids concentration is relatively high throughout the water column.

1227 Fluid mud layer 5mm with a horizontal movement of 100mm. Darker denser layer 25mm with a horizontal movement of 200mm. Settled mud oscilating to a depth of 25mm

1229 Water samples

1302 Water samples

1310 Wave height adjusted to 0.1542m

1312 Water samples

1322 Dark layer about 50mm thick. No trace of cloudy layer

1324 Fluid mud 10mm thick

1325 Wave action has transported sediments along the whole length of the flume. Bed thickness 46mm

1331 Water samples

1339 Wave height adjusted to 0.1943m

1339 Fluid mud 20mm thick
Dense layer 50mm thick
Cloudy layer (reappeared) 60mm thick

1341 Bed sample is now composed of 40mm stationery mud and 15mm of oscillating mud

1344 Water samples

1351 Fluid mud 25mm thick and dense layer 30mm thick

1359 Dense layer 75mm thick. Upstream end of concrete bed slope exposed

1401 Water samples

1408 Wave height adjusted to 0.2314m

1413 Water samples

1422 Bed thickness 34mm. No appreciable changes in suspended load conditions

1426 Water samples

1431 Wave height adjusted to 0.2714m

1431 Erosion occurring over first one-third of the bed from the upstream end. In the erosion area bed thickness is 28mm. At the downstream end the bed is 44mm thick

1434	Fluid mud/dark dense layer 75mm thick
1435	Water samples
1445	Fluid mud layer 30mm thick
1448	Water samples
1454	End of test

Kuching Mud

Test 3

Water depth	0.55m
Water salinity	26.5g/l
Initial bed thickness	45mm
Consolidation period	24h
Wave period	1.77s
Water temperature	12.4°C

Waves only

0904h	Bed thickness 45mm
0912	Water samples
0920	Wavemaker started. Wave height 0.0367m
0920	Non-progressive surface micro-ripples oscillating over a horizontal distance of 20mm
0922	Formation of a fluid layer 2mm thick
0931	Small quantities of sediment going into general suspension at the ends of the mud sample
0939	Settled bed is oscillating with the wave activity
0941	Water samples
0943	Wave height adjusted to 0.050m
0945	Mud eroded from the downstream end of the sample is being entrained into the upper water layers

0950	Fluid mud 8mm thick. Material is being removed from the layer to add to the general suspended load
0952	Water samples
1006	Surface micro-ripples and fluid mud has a 40mm horizontal movement
1019	Wave height adjusted to 0.0667m
1021	Increased erosion towards downstream end of mud sample
1022	Stationery mud bed now 25mm with 18mm of oscillating settled mud/fluid mud above
1024	Erosion occurring along upstream one-third of mud sample increasing the thickness of the fluid mud layer
1028	Water samples
1032	Erosion has ceased. Fluid mud 12mm thick
1035	Suspended sediments evident along the length of the flume
1044	Water samples
1052	Sediments in suspension from bed to surface
1053	Wave height adjusted to 0.080m
1054	Bed composition - 24mm of stationary mud with 16mm of settled oscillating mud and 12mm of fluid mud above
1058	Cloudy layer has developed about 20 mm thick
1107	Fluid mud 15mm thick
1112	Water samples
1123	Wave height adjusted to 0.100m
1123	Increase in the rate that sediments are being re-entrained from the fluid mud layer into the water column above
1125	Water samples
1130	Fluid mud layer 15mm thick with a 25mm thick dark layer above
1132	No signs of bed erosion but transport of sediment is obvious along the flume
1148	Water samples

1158 Wave height adjusted to 0.0914m

1159 Stationary mud bed 33mm thick. Oscillating settled bed and fluid mud 19mm thick (movement 75mm horizontal and 10mm vertical). Dark dense layer 30mm thick (movement 100m horizontal and 15mm vertical).

1201 Various layers visible throughout depth

1219 Water samples

1220 Wave height adjusted 0.1314m

1222 Water samples

1226 Fluid mud 6mm thick (movement 150-200mm horizontal and 3mm vertical)

1228 Cloudy layer 65mm thick

1230 Stationary bed 29mm thick. Oscillating settled bed 15mm thick moving with waves. Fluid mud 5mm thick movement 180^0 out of phase

1231 Water samples

1232 Dark layer thickness increased to 30mm

1244 Water samples

1248 Wave height adjusted to 0.170m

1249 Increased wave height produced little change in orbit movements. Fluid mud 7mm thick

1254 Water samples

1259 Water samples

1301 Dark layer 65mm thick. Mud going into suspension. Bed thickness 20.5mm

1406 Wave height adjusted to 0.2029m

1413 Water samples

1431 Water samples

1449 Fluid mud layer 30mm thick

1458 Water samples

1515 Water samples

1530 End of test

APPENDIX 3

Avonmouth mud - Test 1

Water depth	0.55m
Water salinity	28g/1
Initial bed thickness	88mm
Consolidation period	72h
Wave period	2.83s

<u>Waves Only</u>

1130h	Water samples
1142	Wavemaker started. Wave height 0.0320m
1148	Some sign of local bed disturbance at upstream cement/mud interface but no movement elsewhere
1150	Water samples
1155	Stationary bed with light brown flocs oscillating on surface. No sign of erosion
1205	Water samples
1210	No change. Bed thickness 88mm
1211	Wave height adjusted to 0.0453m
1211	Very slight (just discernable) movement in upper 15mm of mud bed. No erosion
1220	Water samples
1225	About 25mm of mud bed showing very slight signs of movement. No erosion
1228	Water samples. No change in bed conditions
1235	Wave height adjusted to 0.0634m
1236	Some erosion at cement/mud interface. Bed oscillating to a depth of 50mm
1239	Erosion confined to cement/mud interface. Bed oscillating to a depth of 60mm. Bed thickness 88mm
1240	Water samples
1305	No sign of erosion but bed thickness now seems to be 87mm

1310 Water samples

Top 60mm of the bed is oscillating but horizontal movement at the surface is less than 1mm

1315 Wave height increased to 0.0770m

1316 Further erosion from the upstream cement/mud interface

1320 Suspended sediment near the bed

1320 Water samples

1325 Water samples from 0.5m upstream of mud bed. (Background turbidity concentration only)

1335 Top 6mm of bed oscillating like a wave. Top 15mm very fluid; this fluidization is slowly moving along the mud sample from the upstream end

1335 Water samples

1350 Fluid mud not covering more than the upstream half of the mud bed. Fluid suspension up to 45mm thick with mud bed 55mm thick at upstream end and 87mm thick over downstream half of bed

1350 Water samples

1405 Fluid mud not moving further downstream

1405 Water samples

1410 Wave height increased to 0.0924m

1415 Stationary mud bed is 20mm thick with 35mm of oscilllating settled mud above, then 35mm of fluid mud followed by 25mm with mud in suspension

1415 Water samples

1425 Water samples

1425 Fluid mud along whole length of the working section. 25mm stationary mud, 35mm oscillating mud, 35mm fluid mud and 30mm of suspended mud.

1440 Water samples

1455 Wave height increased to 0.0953m

1505 No change in mud bed or fluid mud but suspension layer now 35mm thick

1505	Water samples
1520	Water samples 0.5m upstream of mud sample
1525	Water samples 0.5m downstream of mud sample
1535	Water samples 0.5m downstream of mud sample
1535	Wave height increased to 0.1224m
1540	Stationary mud bed 20mm thick, oscillating settled mud 55mm thick, fluid mud 15mm and suspension layer 50mm
1540	Water samples
1555	Mud distribution similar to above
1555	Water samples
1600	Considerable difficulty in determining interfaces between layers. Of the settled bed the top 10-15mm is very fine and fluid the 10-15mm below has a "grainy" appearance but moving freely about 5mm in horizontal plane. Below this, movement decreases with depth and around 20mm above the cement floor no movement is discernable
1610	Under this wave setting the whole water column became dirty. No longer possible to see bed from above even with side or top floodlighting
1610	Water samples
1615	Wave height increased to 0.1558m
1620	Water samples
1620	At upstream end of sample fluid mud and turbid suspension has a combined thickness of 100mm - interface not visible. At the downstream end of the sample the bottom 20mm of mud sample was stationary overlaid with 40mm of oscillating mud, 35mm of fluid mud and 45mm of turbid suspension
1635	Water samples
1635	Similar sediment distribution to above

1650 Water samples

1650 300mm below the water surface there is an interface. Above the interface the turbidity appears to be denser

1655 Water samples 0.5m upstream of the mud sample

1700 Water samples 0.5m downstream of mud sample

1700 Bottom 15mm of mud is static with 25mm of moving mud above and overlaid by 100mm of fluid mud and turbid suspension (no clear interface detected)

1710 Water samples from upstream and downstream extremities of flume 400mm above bed.

End of test

Avonmouth mud - Test 2

Water depth	0.55mm
Water salinity	28g/l
Initial bed thickness	51mm
Consolidation period	24h
Wave period	2.83s

Waves only

1050h Background water samples

1100 Wavemaker started. Wave height 0.320m

1108 Some erosion of light surface flocs. Erosion at upstream edge of working section creating turbid cloud over working section. No bed movement

1110 Water samples

1125 Water samples

1125 Seems to have reached equilibrium. Slightly cloudy turbid layer above bed about 10mm thick. Bed thickness 51mm

1140 Water samples

1140 No change in bed state. Bed thickness 51mm

1145 Wave height increased to 0.0453m

1150 Water samples

1150 Little change. Bed still stationary. Some surface erosion causing slightly cloudier layer above bed

1200 Water samples

1200 No significant change. Bed thickness 51mm

1210 Water samples

1215 Wave height increased to 0.0634m

1225 Water samples

1225 No bed movement. Bed thickness 51mm

1235 Water samples

1235 Signs of movement at mud surface

1255 Thin fluid mud layer on the downstream half of the mud sample about 4mm thick. Below the fluid mud there is no discernable movement

1305 Wave height increased to 0.0770m

1310 Water samples

1310 Fluid mud along downstream part of sample has increased to 5mm. Below this 15mm of the bed has a very slight oscillation (too small to measure)

Bed thickness 50mm

1325 Water samples

1340 Water samples

1340 Bed thickness 49mm, the top 15mm moving. Above the mud is 5mm of fluid mud

1345 Wave height increased to 0.0924m

1350 Water samples

1350 Bed thickness 49mm, the top 30mm oscillating and overlaid with 5mm of fluid mud increasing to 8mm in a wave motion

1410 Water samples

1410 Bed thickness 45mm, the top 30mm oscillating. Fluid mud layer has a waveform with a thickness ranging from 8mm to 11mm

1420 Water samples 0.5m upstream of working section

1425 Water samples

1430 Water samples 0.5m downstream of working section

1430 Bed thickness 45mm

1440 Wave height increased to 0.0953m

1450 Water samples

1500 Water samples

1500 Bed thickness 44mm, top 30mm oscillating. Fluid mud layer varying in thickness from 7mm to 10mm

1505 Wave height increased to 0.1224m

1515 Water samples

1515 Bed thickness 45mm with top 30mm moving. Fluid mud layer cleared from upstream end and now occupies downstream 2/3 of sample. Thickness varies from zero at upstream end to 10mm at downstream end

1530 Water samples

1530 No change in bed state. Bed thickness 45mm

1550 Bed thickness 44mm. Bottom 15mm stationary, next 29mm grainy with some movement. Fluid mud 12mm thick with a suspension above

1555 Wave height increased to 0.1558m

1605 Water samples

1610 Bed thickness 44mm with the bottom 5m stationary. Above this is a 3mm thick grainy layer moving small distances very gently. Another grainy layer appears above (9mm thick) moving much more rapidly with a horizontal displacement of 15mm. This is topped with a 16mm light brown fluid mud layer

1620	Whole bed is now moving. Interfaces not very distinct. Bed thickness about 36mm topped with 19mm of fluid mud
1620	Water samples
1630	Water sample 0.5m upstream of mud sample
1635	Water samples
1640	Water samples 0.5m downstream of mud sample
1645	Bed thickness 30mm - all moving - topped with 35mm of fluid mud
1655	Water samples from upstream and downstream extremities of flume at 400mm above bed.

End of test

<u>Avonmouth mud - Test 3</u>

Water depth	0.55m
Water salinity	28mg/1
Initial bed thickness	116mm
Consolidation period	24h
Wave period	0

Uni-direction currents only. No waves.

0940h	Switched on low flow $H_m = 0.08m_m$ $\bar{v} = 0.057m/s$
1120	Water samples for flume water background concentration
1122	Current generated H_m=0.245m $\bar{v}$ = 0.105m/s
1125	Water samples 0.5m upstream of mud sample. No obvious sign of erosion. Mud surface looks stable and has a sandy/grainy appearance
1130	Water samples at working section
1135	Bed thickness 115½mm
1145	Water samples 0.5m upstream of mud sample
1150	Water samples at working section
1155	Water samples 0.5m downstream of mud sample

Bed thickness 115m

1202 Current speed increased. H_m=0.435
$\bar{v}$ = 0.141m/s

1205 Water samples 0.5m upstream of mud sample

1210 Water samples at working section

1215 Water samples 0.5m downstream of mud sample

1220 Surface of mud moving back and forth (but not noticeable at window). Movement about 1mm about 20mm inside flume

1222 Current speed unchanged H_m=0.435m
$\bar{v}$ = 0.114m/s. Bed thickness 114mm

1225 Water samples 0.5mm upstream of mud sample

1230 Water samples at working sections

1235 Water samples 0.5m downstream of mud sample

1235 Mud surface oscillating a little. Bed thickness 113mm

1307 Current speed increased H_m=0.710m
$\bar{v}$ = 0.177m/s

1310 Water samples 0.5m upstream of mud sample

1315 Water samples at working section

1320 Water samples 0.5m downstream of mud sample

1320 Top 60mm of bed now has jelly-like to-and-fro movement. Horizontal displacement at surface near viewing panel is 1mm and at 60mm below zero. In mud flume horizontal surface movement is about 3mm. Bed thickness 112mm

1330 Water samples 0.5m upstream of mud sample

1335 Water samples at working section

1340 Water samples 0.5m downstream of mud sample top 65mm of mud moving. Bed thickness 112mm

1350 Current speed increased H_m=0.91m $\bar{v}$ = 0.199m/s

1355 Water samples 0.5m upstream of mud sample

1400 Water samples at working section

1405 Water samples 0.5m downstream of mud sample. Top 80mm of mud vibrating. Bed surface is not oscillating uniformly, mud particles are sliding over surface. Movement about 4mm

1420	Water samples 0.5 upstream of mud sample
1425	Water samples at working section
1430	Water samples 0.5m downstream of mud sample. No change in bed state. Bed thickness 110mm
1600	Current speed increased. H_m=1.130m $\bar{v}$ = 0.222m/s
1605	Water samples 0.5m upstream of mud sample
1610	Water samples at working section
1615	Water samples 0.5m downstream of mud sample. Bed movement now extends to a depth of 90mm. Bed thickness 109mm
1625	Water samples 0.5m upstream of mud sample
1630	Water samples at working section
1635	Water samples 0.5m downstream of mud sample Top 85mm vibrating as before. Bed thickness 107mm
1642	Current speed increased. H_m=1.54m $\bar{v}$ = 0.258m/s
1645	Water samples 0.5m upstream of mud sample
1650	Water samples at working section
1655	Water samples 0.5m downstream of mud sample. Top 5mm fluid mud moving easily with fluctuations. Next 35mm grainy and moving but not fluid. Virtually the whole of the mud bed is showing some movement. Bed thickness 104mm
1710	Water samples 0.5m upstream of mud sample
1715	Water samples at working section
1720	Water samples 0.5m downstream of mud sample. Bottom 44mm of bed has very little movement. Above is a 30mm layer with some movement. This layer has many fissures which look like the drainage paths in consolidating mud. Above is a 20mm grainy layer moving freely followed by a fluid layer 5mm thick.
1725	End of test

Avonmouth mud - Test 4

Water depth	0.55m
Water salinity	28g/1
Initial bed thickness	69mm
Consolidation period	72h
Wave period	0

Uni-directional currents only. No waves

1045h	Pump switched on and minimal current generated to allow flume to settle down. Current speed $H_m = 0.07$m $\bar{v} = 0.053$m/s
1120	Background water samples over working section
1128	Current increased $H_m = 0.25$ m $\bar{v} = 0.105$m/s
1130	Water samples 0.5m upstream of mud sample
1135	Water samples at working section
1140	Water sample 0.5m downstream of mud sample
1155	Water sample 0.5m upstream of mud sample
1200	Water sample at working section
1205	Water samples 0.5m downstream of mud sample No bed movement. Bed thickness 69mm
1208	Current speed increased $H_m = 0.425$m $\bar{v} = 0.136$m/s
1210	Water samples 0.5m upstream of mud sample
1215	Water samples at working section
1220	Water samples 0.5m downstream of mud sample. No bed movement or obvious erosion. Bed thickness 69mm
1230	Water samples 0.5m upstream of mud sample
1235	Water samples at working section
1240	Water samples 0.5m downstream of mud sample Bed stationary. No obvious erosion. Bed thickness 68½mm
1412	Current speed increased H_m=0.690m $\bar{v} = 0.172$m/s
1415	Water samples 0.5m upstream of mud samples
1420	Water samples at working section

1425	Water samples 0.5m downstream of mud sample. No erosion. Bed stationery. Bed thickness 68½mm
1435	Water samples 0.5m upstream of mud sample
1440	Water samples at working section
1445	Water samples 0.5m downstream of mud sample. No obvious bed movement. Bed is slightly raised (½mm) next to glass, like a meniscus
1453	Current speed increased $H_m = 0.92$m $\bar{v} = 0.201$m/s
1455	Water samples 0.5m upstream of mud sample
1500	Water sample at working section
1505	Water sample 0.5m downstream of mud sample No bed movement. Bed thickness 68mm
1515	Water samples 0.5m upstream of mud sample
1520	Water samples at working section
1525	Water samples 0.5m downstream of mud sample No bed movement. Bed thickness 68mm
1558	Current speed increased $H_m = 1.11$m $\bar{v} = 0.22$m/s
1600	Water samples 0.5m upstream of mud sample
1605	Water samples at working section
1610	Water samples 0.5m downstream of mud sample Bed stationary. Bed thickness 68mm
1620	Water samples 0.5m upstream of mud sample
1625	Water samples .5m downstream of mud sample
1630	Water samples 0.5m downstream of mud sample
1638	Current speed increased $H_m = 1.50$m $\bar{v} = 0.256$m/s
1640	Water samples 0.5m upstream of mud sample
1645	Water samples at working section
1650	Water samples 0.5m downstream of mud sample No bed movement. Bed thickness 68mm
1700	Water samples 0.5m upstream of mud sample
1705	Water samples at working section
1710	Water samples 0.5m downstream of mud sample Bed stationary. Bed thickness 68mm

	Throughout test the only difference is that the bed surface started as a plane and now has scores and grooves
1720	End of test

Avonmouth mud - Test 5

Water depth	0.55mm
Water salinity	28 g/l
Initial bed thickness	85mm
Consolidation period	24h
Wave period	2.83s

Uni-directional current of 0.1 m/s and waves

0930h	Pump switched on to low flow setting H_m=0.14m $\bar{v}$ = 0.075m/s
1040	Background water samples at working section
1046	Current speed increased. H_m = 0.215m $\bar{v}$ = 0.1m/s
1050	Water samples 0.5m d/s of mud sample
1055	Water samples at working section
1100	Water samples 0.5m d/s of mud sample No sign of bed movement. Bed thickness 85mm
1109	Wavemaker started. Wave height 0.0320m. Bed thickness 85mm
1110	Water samples 0.5m u/s of mud sample
1115	Water samples at working section
1120	Water samples 0.5 d/s of mud sample. Bottom 25mm now moving. Next 52mm moving backwards and forwards with 7mm of fluid mud above with an oscillatory orbital movement
1135	Water samples 0.5m u/s of mud sample
1140	Water samples at working section
1145	Water samples 0.5m d/s of mud sample. Bottom 20mm of mud stationary. Above a layer of swaying mud with 1mm horizontal movement and a

layer of fluid mud of varying thickness within a wave from 1mm-8½mm
Bed thickness 82½mm

1154 Wave height increased to 0.0453m

1155 Water samples 0.5m u/s of mud sample

1200 Water samples 0.5m d/s of mud sample. Bottom 20mm of mud stationary. Next layer has an average depth of 2mm with a 3mm waveheight. Maximum mud activity is at end of sample.
Bed thickness 81½mm

1240 Water samples 0.5m u/s of mud sample

1245 Water samples at working section

1250 Water samples 0.5 m d/s of mud sample. Bottom 20mm of mud stationary. Next layer has 1½mm horizontal movement. Fluid layer thickness under wave trough is 8mm at u/s end of sample and 2mm at d/s end. Fluid mud wave height 13mm
Bed thickness 80mm

1259 Waveheight increased to 0.0634m

1300 Water samples 0.5m u/s of mud sample

1305 Water samples at working sections

1310 Water samples 0.5m d/s of mud sample. Bottom 15mm of mud stationary. Next layer has a horizontal movement of 2mm. Fluid layer has a trough thickness of 10mm-3mm with a maximum wave height of 16mm.
Bed thickness 78½mm

1330 Water samples 0.5m u/s of mud sample

1335 Water samples at working section

1340 Water samples 0.5m d/s of mud sample. No change in mud state. Bed thickness 77½mm

1349 Wave height increased to 0.0770m

1350 Water samples 0.5m u/s of mud sample

1355 Water samples at working section

1400 Water samples 0.5m d/s of mud sample. No significant change in mud state. Erosion is evident at upstream concrete/mud interface

Bed thickness 76mm

1435 Water samples 0.5m u/s of mud sample

1440 Water samples at working section

1445 Water samples 0.5m d/s of mud sample. Fluid layer has a trough thickness of 10mm at u/s end and 4mm at d/s end with a maximum wave height of 17mm.
Bed thickness 75mm

1454 Wave height increased to 0.0924m

1455 Water samples 0.5m u/s of mud sample

1500 Water samples 0.5m d/s of mud sample. No significant change in mud bed. Fluid layer now has a maximum wave height of 23mm
Bed thickness 74mm

1520 Water samples 0.5m u/s of mud sample

1525 Water samples at working section

1530 Water samples 0.5m d/s of mud sample. Fluid layer trough thickness now increased to 11mm at u/s end and 5mm at d/s end. Max wave height has decreased to 19mm
Bed thickness 73mm

1540 Wave height increased to 0.1224m

1545 Water samples 0.5m u/s of mud sample

1550 Water samples at working section

1555 Water samples 0.5m d/s of mud sample. Bottom 5mm of mud not moving. Middle layer has horizontal displacement of 6mm. Fluid layer varies in trough thickness from 13mm at u/s end to 6mm at d/s end with a maximum wave height of 20mm. Bed thickness 68mm

1610 Water samples 0.5m u/s of mud sample

1615 Water samples at working section

1620 Water samples 0.5m d/s of mud sample. Small change in fluid mud state. Trough thickness now 12mm at u/s end and 8mm at d/s end with maximum wave height of 22mm.
Bed thickness 63mm

1634 Wave height increased to 0.1558m

1635	Water samples 0.5m u/s of mud sample
1640	Water samples at working section
1645	Water samples 0.5m d/s of mud sample. Whole of mud bed moving. Fluid mud trough layer now varies from 10mm at u/s end to 5mm at d/s end with a maximum wave height of 10mm. Indications are that fluid layer is being transported along flume. Bed thickness 51mm
1655	Water samples 0.5m u/s of mud sample
1700	Water sample at working section
1705	Water samples 0.5m d/s of mud sample. All mud has horizontal orbit of 10mm. Fluid layer and wave height reduced. About 4mm thick below trough and of 4mm wave height. Bed thickness 45mm
1710	End of test

Avonmouth mud - Test 6

Water depth	0.55m
Water salinity	28 g/l
Initial bed thickness	87½mm
Consolidation period	72h
Wave period	2.83s

Uni-directional current of 0.1 m/s and waves

1030h	Pump switched on to low flow setting
1125	Background water samples at working section
1130	Current speed increased. $H_m = 0.215$m $\bar{v} = 0.1$m/s
1138	Wavemaker started. Wave height 0.320m
1140	Water samples 0.5m u/s of mud sample
1145	Water samples at working section
1150	Water samples 0.5m d/s of mud sample. Bottom 56mm of mud stationary. Top 30mm moving to and fro. No fluid mud

Bed thickness 86mm

1200 Water samples 0.5m u/s of mud sample

1205 Water samples at working section

1210 Water samples 0.5m d/s of mud sample. No change in bed condition or bed thickness

1217 Wave height increased to 0.453m

1220 Water samples 0.5m u/s of mud sample

1225 Water samples at working section

1230 Water samples 0.5 m d/s of mud sample. No change in bed condition. Bed thickness 86mm

1235 Water samples 0.5m u/s of mud sample

1240 Water samples at working section

1245 Water samples 0.5 d/s of mud sample. Trace of fluid mud otherwise no change in bed state Bed thickness 86mm

1413 Wave height increased to 0.0634m

1415 Water samples 0.5m u/s of mud sample

1420 Water samples at working section

1425 Water samples 0.5m d/s of mud sample. Bottom 25mm of mud stationary. Top 60mm moving about 1mm at surface. No fluid mud.
Bed thickness 85mm

1440 Water samples 0.5m u/s of mud sample

1445 Water samples at working section

1450 Water samples 0.5m d/s of mud sample. Bottom 30mm of mud not moving. Top 55mm moving. Surface grooved and uneven. No fluid mud
Bed thickness 85mm

1458 Wave height increased to 0.0770m

1500 Water samples 0.5m u/s of mud sample

1505 Water samples at working section

1510 Water samples of 0.5m d/s of mud sample. Bottom 29½mm not moving, top 55mm oscillating. Movement at surface 1.5mm. No fluid mud
Bed thickness 84½mm

1515 Water samples 0.5m u/s of mud sample

1520 Water samples at working section.

1525 Water samples 0.5m d/s of mud sample. No change in bed condition. Bed thickness 84½mm

1603 Wave height increased to 0.0924m

1605 Water samples 0.5m u/s of mud sample

1610 Water samples at working section

1615 Water samples 0.5m d/s of mud sample. Bottom 26mm of mud stationary. Top 55mm oscillating. Fluid layer beginning to develop

1620 Water samples 0.5m u/s of mud sample

1625 Water samples at working section

1630 Water samples 0.5m d/s of mud sample. Bottom 5mm not moving. Top layer, 74mm, moving. Fluid mud above over u/s half of mud sample with average thickness of 7mm and wave height of 11mm. Bed thickness 79mm

1637 Wave height increased to 0.1224m

1640 Water samples 0.5m u/s of mud sample

1645 Water samples at working section

1650 Water samples 0.5m d/s of mud sample. Bottom mud layer stationary. Next layer moving 4½mm and fluid layer over most of mud sample mean depth 12mm with wave height of 10mm
Bed thickness 76mm

1655 Water samples 0.5m u/s of mud sample

1700 Water samples at working section

1705 Water samples 0.5m d/s of mud sample. Little change in bed state but fluid mud wave height decreased to 6mm
Bed thickness 73mm

1713 Wave height increased to 0.1558m

1715 Water samples 0.5m u/s of mud sample

1720 Water samples at working section

1725 Water samples 0.5m d/s of mud sample. All mud bed moving with 12mm of fluid mud above. Bed thickness 62mm

1735	Water samples 0.5m u/s of mud sample
1740	Water sample at working section
1745	Water samples 0.5m d/s of mud sample. All mud bed moving with 5mm of fluid mud above. Bed thickness 58mm
1750	End of test

Avonmouth mud - Test 7

Water depth	0.55mm
Water salinity	28g/1
Initial bed thickness	92mm
Consolidation period	72h
Wave period	2.83s

Uni-directional current of 0.05m/s and waves

0930h	Pump switched on at very low discharge
1055	Current increased to 0.05m/s
1120	Water samples at working sections (background level)
1132	Wavemaker started. Wave height 0.032m
1135	Water samples 0.5m u/s of mud sample
1140	Water samples at working section
1145	Water samples 0.5m d/s of mud sample. No bed movement. Bed thickness 92mm
1155	Water samples 0.5m u/s of mud sample
1200	Water samples at working section
1205	Water samples 0.5m d/s of mud sample. No bed movement. Bed thickness 92mm
1216	Wave height increased to 0.453m
1220	Water samples 0.5m u/s of mud sample
1225	Water samples at working section
1230	Water samples 0.5m d/s of mud sample. Bottom 51mm not moving. Top 40mm moving with surface oscillating about 1mm. No fluid mud Bed thickness 91mm
1235	Water samples 0.5m u/s of mud sample

1240 Water samples at working section

1245 Water samples 0.5m d/s of mud sample. No change in bed state. Bed thickness 91mm

1342 Wave height increased to 0.0634m

1345 Water samples 0.5m u/s of mud sample

1350 Water samples at working section

1355 Water samples 0.5m d/s of mud sample. Bottom 40mm of mud stationary. Top 50mm moving with max. oscillation at surface of 1.5mm. No fluid mud. Bed thickness 90mm

1405 Water samples 0.5m u/s of mud sample

1410 Water samples at working section

1415 Water samples 0.5m d/s of mud sample. No change in bed condition. Bed thickness 90mm

1422 Wave height increased to 0.077m

1425 Water samples 0.5m u/s of mud sample

1430 Water samples at working section

1435 Water samples 0.5m d/s of mud sample. First signs of obvious erosion. Clouds of particles being carried along the working section. Bottom 10mm of bed stationary. Next layer has a surface movement of 2.5mm. Fluid mud along upstream half of working section with a thickness of 15mm and a rise and fall of 10mm to 14mm. Bed thickness 90mm

1445 Water samples 0.5m u/s of mud sample

1450 Water samples at working section

1455 Water samples 0.5m d/s of mud sample. No significant change in bed state. Bed thickness 87mm

1528 Wave height increased to 0.924m

1530 Water samples 0.5m u/s of mud sample

1535 Water samples at working section

1540 Water samples 0.5m d/s of mud sample. Bottom 5mm of bed stationary. Next layer has a horizontal surface oscillation of 4mm. Fluid mud along ¾ of sample - no fluid mud at d/s end - of thickness 13mm and 14mm-17mm vertical rise and fall

1550 Water samples 0.5m u/s of mud sample

1555 Water samples at working section

1600 Water samples 0.5m d/s of mud sample. No change in bed conditions. Bed thickness 86mm

1618 Wave height increased to 0.1224m

1620 Water samples 0.5m u/s of mud sample

1625 Water samples at working section

1630 Water samples 0.5m d/s of mud sample. Entire mud bed moving up to 5mm. Fluid mud layer 15mm thick and vertical rise and fall of 16mm. Fluid mud moving along bed. Bed thickness 85mm

1640 Water samples 0.5m u/s of mud sample

1645 Water samples at working section

1650 Water samples 0.5m d/s of mud samples. Bed conditions virtually unchanged. Bed thickness 79mm

1653 Wave height increased to 0.1558m

1655 Water samples 0.5m u/s of mud sample

1700 Water samples at working section

1705 Water samples 0.5m d/s of mud sample. Entire mud bed moving with a maximum oscillation of 7mm. Fluid layer 10mm thick with a vertical rise and fall of 5mm. Fluid mud being dispersed. Bed thickness 75mm

1715 Water samples 0.5m u/s of mud sample

1720 Water samples at working section

1725 Water samples 0.5m d/s of mud sample. Bed moving with 8mm of fluid mud above. Bed thickness 69mm

1730 End of test

APPENDIX 4

Port Kelang mud - Wharf 8

Water depth	0.55m
Water salinity	28 g/l
Initial bed thickness	98mm
Consolidation period	24h
Wave period	2.83s
Water temperature	11.1 ^{0}C

<u>Waves only</u>

1050h	Water samples at working section to establish background turbidity
1105	Wavemaker started. Wave height 0.032m.
1106	Surface sediments immediately entrained to form near bed layer - pale brown. Grey sediment exposed at downstream end.
1110	Fluid mud layer 3mm thick moving 50mm horizontally and between 2mm and 8mm vertically. Bed thickness 95mm.
11.20	Grey mud exposed for 250mm at both ends of mud sample. Mud surface smooth. No crack or micro-ripples.
1130	No change in fluid mud. Grey mud now exposed for 300mm at each end. Water column is hazy. Bed thickness 95mm.
1140	Water samples
1145	Wave height increased to 0.0453m
1146	Erosion at upstream end. Material put into suspension about 20mm above bed. Surface cracks developing 20mm long x 2mm wide.
1152	Reduction in upstream erosion and entrained particles have moved upstream.

1154 Bottom 25mm of mud stationary and appears to be sandy. Fluid mud layer 3mm thick. Bed thickness 94mm.

1205 There are two main splits on the mud surface - one in the centre and the other 500mm from downstream end.

1215 Water samples.

1220 Fluid mud 3mm thick. Bed thickness 92mm.

1225 Wave height increased to 0.0634m.

1235 Bottom 25mm of mud stationary. Fluid layer 5mm thick. Bed thickness 90mm.

1255 Fluid mud layer 6mm with a vertical movement of 5mm. Bed thickness 90mm.

1305 Water samples

1310 Wave height increased to 0.0770m.

1311 Grey turbid layer above fluid mud now 20m thick with clear water above.

1320 Bottom 25mm of mud stationary. Flud mud layer 7mm. Bed thickness 90mm.

1325 Water column still clear above grey turbid layer.

1340 Bottom 25mm stationary. Fluid mud 8mm thick with a vertical movement of 5mm. Top 300mm of the water column becoming milky. Bed thickness 89mm.

1405 Wave height increased to 0.0924m.

1406 Evidence of increased bed disturbance at the extremities of the mud sample.

1416 Bottom 25mm of mud stationary. Fluid mud 11mm thick with vertical movement of 6mm. Bed thickness 86mm.

1420 Grey turbid layer above the fluid mud appears to be thinner and less dense

1435 Bottom 25mm stationary. Fluid mud 15mm thick. Bed thickness 82mm

1440 Water samples

1446 Wave height increased to 0.0953m.

1447	Little change at bed or in the water column above.
1500	Bottom 25mm of sandy sediment stationary with 54mm of oscillating mud above. Fluid layer now 18mm thick topped by a turbid layer 30mm thick. A hazy turbid layer exists for the next 200mm covered by a pale grey denser surface layer. Bed thickness 79mm.
1520	No change in bed and water conditions. Bed thickness 79mm.
1525	Water samples.
1530	Wave height increased to 0.1224m.
1531	Increased disturbance at the mud surface and the fluid mud appears to be becoming entrained in the turbid layer above. Water column unchanged.
1540	Bottom 25mm of sediment stationary. Fluid mud layer 20mm thick. Above, the turbid layer is 30mm thick followed by 275mm of hazy water and then a denser pale grey surface layer. Bed thickness 78mm.
1600	Bottom 25mm of sediment stationary. Fluid layer 22mm thick and topped with a 35mm turbid layer. Above this the water column appears uniformly pale grey.
1606	Water samples
1610	Wave height increased to 0.1558m.
1611	Erosion at both ends of mud bed.
1620	Bottom 25mm of sediment stationary. Fluid mud 30mm thick, Turbid layer above is now 60mm thick and is topped with suspended silts grey in colour and appearing to become less dense near the surface. Bed thickness 69mm.
1640	Bottom 25mm of sediment stationary. Fluid layer 35mm thick. Above the fluid mud, layering has ceased. Turbidity in the water column increases with depth. Bed thickness 65mm.

1645	Water samples
1650	End of test

Port Kelang mud - Pintu Bar

Water depth	0.55m
Water salinity	28g/l
Initial bed thickness	110mm
Consolidation period	24h
Wave period	2.83s

Waves only

1100h	Water samples at working section to establish initial background turbidity.
1110	Wavemaker started. Wave height 0.032m
1115	Bottom 35mm of bed stationary. Remainder oscillating. Micro-ripples have formed on the pale grey surface.
1120	Fluid mud layer beginning to develop at upstream end - 1mm thick. Vertical oscillation of fluid mud 6mm. Bed thickness 108mm.
1135	Lateral splits on mud surface about 50mm long and 1mm deep. Mud surface clearly visible and is moving to and fro by 50mm. Downstream movement occurs under the rising wave front. Bottom 40mm of sample stationary the remainder oscillating in a horizontal plane topped by 2mm of fluid mud. Maximum vertical movement of fluid mud is 7mm and occurs near the upstream end. Stationary lower layer consists mainly of sand and organic matter. Bed thickness 106mm.
1150	Water samples
1155	Wave height increased to 0.0453m.

1157 Small mud clusters separated from the bed at upstream end oscillating as a near-bed load.

1159 Horizontal movement of bed surface 70mm. Downstream one-third of bed has changed colour from creamy pale brown to grey. Splits in the brown surface have opened revealing grey sediments beneath.

1203 Bed has reached equilibrium.

1214 Pale grey turbid cloud at upstream end of mud sample immediately above bed. It is roughly circular in plan and of 400mm diameter; thickness 15mm.

1216 Fluid mud layer 4mm thick with vertical movement of 11mm. Bed thickness 102mm. Turbid cloud is extending downstream.

1225 Water samples.

1230 No obvious changes. Bed thickness 101mm.

1235 Wave height increased to 0.0634m.

1237 Surface is now grey for 500mm from both ends. Increased activity at upstream end but free particles are not being entrained.

1245 Bottom 35mm of sandy/organic material stationary. Next layer has a horizontal surface oscillation of 80mm and a maximum rise and fall of 22mm towards upstream end of the sample. Fluid mud layer 6mm. Bed thickness 99mm.

1255 Mud surface no longer clearly visible through viewing panel due to increase in turbidity.

1305 Organic fragments rising out of sandy layer into the moving mud. Fluid layer 6mm thick with vertical movement of 25mm. Turbid cloud now covers all of the mud sample and is 25mm thick. Bed thickness 99mm.

1310 Water samples. No obvious changes at bed.

1315 Wave height increased to 0.0770m.

1317 There is little sign of sediments moving into suspension. Organic material now present in fluid mud layer.

1330 Slight movement on the surface of the sand layer. Fluid mud now 9mm thick with vertical movement of 25mm. Bed thickness 96mm.

1345 Water samples.

1350 Mobile mud moving 10mm at viewing panel and fluid mud moving 25mm horizontally. A vertical split has appeared in the moving mud extending to the sand/mud interface. The crack is located 100mm from the downstream end of the sample. Turbid cloud near the bed now 18m thick. The top 350mm of the water column has increased turbidity. A band of clear water exists between the surface and bed turbid layers. Bed thickness 96mm.

1400 Wave height increased to 0.0924m.

1402 Water column showing signs of increased suspended silt.

1410 Little change in bed condition.

1420 Suspended sediment concentration is highest in the layer 35mm thick above the fluid mud. Surface turbidity is also quite dense. Bed thickness 93mm.

1430 Sand is exposed at both concrete/mud interfaces.

1435 No change in bed conditions. Water samples.

1440 Bottom sandy layer 35mm thick and not moving appreciably. Moving mud has an even distribution of organic particles. Fluid mud layer 12mm thick. Bed thickness 90mm.

1445 Wave height increased to 0.0953m.

1447 No change in vertical split at downstream end of sample. Similar but finer split has appeared at same distance from the upstream end.

1455	Difficult to distinguish between fluid mud and overlaying suspension. Fluid mud possibly 15mm thick. Bed thickness 85mm.
1510	The surface turbid layer has reduced in thickness to 200mm and the near-bed turbid layer is 40mm thick.
1515	Bottom sandy layer is 35mm thick and stationary. A clear interface has re-appeared between fluid mud and overlaying suspension. Fluid mud 14mm thick with a horizontal movement of 120mm.
1522	Water samples. Bed conditions unchanged.
1530	Wave height increased to 0.1224m.
1532	Surface erosion increased especially at upstream and downstream ends. Sandy layer exposed for 160mm at upstream end but still appears to be stationary.
1535	Suspended sediments in water column unchanged being 200mm thick at the surface and 45mm thick near the bed.
1545	Fluid mud layer 10mm thick with 50mm of dense suspension above. Bed thickness 76mm.
1600	Water samples.
1605	Surface turbid layer reduced to 150mm thick while bed turbid layer has increased to 80mm. Fluid mud 9mm. Bed thickness 69mm.
1615	Wave height increased to 0.1558m.
1615	Above the fluid mud layer all turbidity stratification has disappeared.
1617	Water column now shows progressively higher concentrations of suspended silt with depth. Mud and organic material eroding.
1630	Interface between fluid mud and suspended silt indistinct. Fluid mud layer about 30mm thick. Sandy layer shows a movement of about 1mm in the top 5mm with no net movement. Bed thickness about 60mm.

1635 Bottom sandy layer still 35mm thick. Moving mud and organics now only 25mm thick. Fluid mud and near-bed suspended silt have merged into an 80mm-thick layer. In the water column above, the suspension is of medium grey colour apart from the top 80mm which is less dense and pale grey.

1645 Sandy layer still 35mm thick and moving as previously mentioned. Moving mud is now 23mm thick with a 47mm-thick layer of fluid mud/suspension above. Bed thickness 58mm.

1650 Water samples

1700 End of test