Hydraulics Research
Wallingford

DISPERSAL OF DREDGED MATERIAL

River Tees Mud Properties

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CONTRACT

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ABSTRACT

This report describes laboratory tests to determine the properties of River Tees mud, conducted as a part of a study on the dispersal of dredged material. The tests comprised particle size measurement, organic matter and cation exchange capacity measurement, determination of mineralogical properties, self-weight consolidation tests, erosion by uni-directional currents and erosion under waves. The results are to be used in numerical models being developed to predict the movement of dredged material.

Four drums of bulk mud samples were collected; two from Seal Sands at the mouth of the River Tees and two with material dredged from opposite Beach Wharf in the River Tees. Both muds consisted of approximately 75% silt ($\leqslant$ 63 microns diameter).

Four settling column tests were conducted to investigate the consolidation of mud beds formed by continuous deposition of a suspension of dredged material pumped into the column. A difference in the final beds was noted which may result from the rate of deposition in the input phase and the thickness of the final bed. The tests indicated relationships between the effective stress, σ', and dry density, ρ_d, of

$\sigma' = 0.00045\rho_d^2 - 0.018\rho_d + 0.18$ for tests TC1, TC2 (bed thickness 30-35mm)

and

$\sigma' = 0.0008\rho_d^2 - 0.016\rho_d + 0.08$ for tests TC3, TC4 (bed thickness 70-80mm)

The tests also gave relationships between permeability, k, and dry density, ρ_d, of

$\log k = -0.017\rho_d - 5.0$ (bed thickness 30-35mm)

and

$\log k = -0.011\rho_d - 5.0$ (bed thickness 70-80mm)

Five uni-directional current erosion tests were carried out in the carousel flume on deposited mud beds; three on mud from Seal Sands, two on the dredged material. A relationship between the erosion shear strength, τ_e, and the dry density of the exposed mud surface, ρ_h, was determined for each mud. These were

$\tau_e = 0.0025\rho_h^{1.0}$ (Seal Sands)

$\tau_e = 0.00014\rho_h^{1.7}$ (Dredged material)

The erosion constant, m_e, was evaluated from all the runs in the erosion tests. The mean value for both Seal Sands mud and the dredged material was approximately $0.0009 kgN^{-1}s^{-1}$.

Four tests were run in a wave flume; one on a placed bed and three on high density slurries of the dredged material. Conditions of wave height and water depth were chosen to give peak bottom orbital velocities in the range $0.05 ms^{-1}$ to $0.30 ms^{-1}$, with corresponding peak bed shear stresses in the range $0.1 Nm^{-2}$ to $0.5 Nm^{-2}$. The rate of erosion under waves was found to increase with applied shear stress.

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1. INTRODUCTION

The fate of dredged material disposed of at open water sites is of interest from both an engineering and an environmental point of view. It is important to be able to predict the movement of the material in order to assess the suitability of an existing or proposed disposal site.

Maintenance dredging often takes place in industrial areas, where significant concentrations of pollutants may have accumulated in the sediment. These pollutants are then moved with the dredged material, and may become concentrated in the disposal area or be released into the open water to be dispersed over a wider area.

In recent years, Hydraulics Research (HR) has been involved with a study on the fate of dredged material, with the aim of creating an economic means of predicting both the short-term and the long-term dispersion of dredged material. This study is being supported by Tees and Hartlepool Port Authority who provide survey craft, free access to data, cooperation in the use of the dredging plant and scheduling of dredging operations to fit in with the scientific needs of the study.

The computational techniques being developed at HR use several parameters to describe the erosional and consolidation properties of the sediment being modelled. To determine these parameters laboratory tests were run at HR on samples of actual dredged material, taken from a dredger in the Tees estuary (Fig 1). Samples of mud from a nearby site at Seal Sands were also tested.

This report describes the tests and gives the results of the mud properties tests. The characteristics of the mud are given in Chapter 2. The self-weight consolidation tests with results are reported in Chapter 3, erosion by unidirectional currents in Chapter 4 and erosion by waves in Chapter 5. These are followed by discussion, with recommendations, and conclusions.

Two 60 litre drums of bulk mud samples were collected on 23 August 1988 from a position on Seal Sands close to Greatham Creek (see Fig 1). A further two drums were filled with dredged material taken from opposite Beach Wharf in the River Tees on 31 January 1989. The drums were transported to HR for the laboratory tests.

2. CHARACTERISATION OF THE MUD

2.1 Bulk density

The Sedimentology Laboratory at Hydraulics Research analysed the bulk mud samples for bulk density. For the Seal Sands mud the average bulk density was $1550 kgm^{-3}$, equivalent to a dry density of approximately $880 kgm^{-3}$. Individually the two Seal Sands drums, Tees1 and Tees2, had bulk densities of $1530 kgm^{-3}$ and $1580 kgm^{-3}$ respectively. The two drums of dredged material had bulk densities of $1390 kgm^{-3}$ (Tees3) and $1470 kgm^{-3}$ (Tees4), with an average bulk density of $1430 kgm^{-3}$, equivalent to a dry density of approximately $700 kgm^{-3}$.

2.2 Particle size grading

Sub samples from the four drums of bulk samples were analysed for particle size distribution. The results are shown in Figure 2. This shows that, for both drums from Seal Sands (Tees1 and Tees2), approximately 75% by weight of material is silt (ie less than 63 microns in diameter), with the remainder being sand with some shell. For the dredged material (Tees3 and Tees4) approximately 75% of the material is silt, with the remainder being fine sand.

2.3 Organic content

A sub sample from each drum was analysed for organic carbon by using the acid digestion procedure. The percentage of organic matter of the samples was 4.0% and 4.5% for drums Tees1 and Tees2 respectively. The percentage of organic matter was considerably higher for the dredged material at 10.1% and 11.1% for Tees3 and Tees4 respectively.

2.4 Cation exchange capacity

The cation exchange capacity of a sample of mud from each drum was determined on the sub 20 micron fraction, which contains the clay minerals. The cation exchange capacity was 15.1meq/100g and 15.7meq/100g for drums Tees1 and Tees2 respectively, and 17.6 and 18.1meq/100g for Tees3 and Tees4 respectively.

2.5 Mineralogical content

The Institute of Hydrology analysed a sub sample from drum Tees2 for mineralogical content. The mud was passed through a 20 micron sieve before undergoing semi-quantitative x-ray diffraction analysis.

The mud was transferred to a glass beaker and dried at 50°C, before being lightly ground in an agate mortar. The x-ray diffractograms of the sample were compared with those of several standard minerals to identify the minerals present. The percentage of each mineral present was determined using calibration curves obtained by diffracting known mixtures of standard minerals. The fraction less than 2 microns was prepared by centrifugation, filtered onto an unglazed ceramic tile, allowed to dry overnight at room temperature and diffracted as before. The tile sample was glycolated and then diffracted again.

The sample from drum Tees2 (Seal Sands) contained the following minerals: 19% quartz, 1% calcite, 32% kaolinite, 44% illite, 2% dolomite and 2% non-expandable 14Å minerals.

The sample from drum Tees3 (dredged) contained the following minerals: 22% quartz, 3% calcite, 35% kaolinite, 36% illite, 1% dolomite and 3% non-expandable 14Å minerals.

3. CONSOLIDATION TESTS

3.1 Objectives

The objectives of the consolidation tests were to determine two relationships which would describe the behaviour of a consolidating bed of material dredged from the Tees estuary. These relationships will be used in numerical models to predict the movement of dredged material on the bed.

The first relationship is between effective stress and dry density. The effective stress is the stress between individual mud particles and is the total stress minus excess pore pressure. This relationship defines how the effective stress at any point in the bed affects its density during the consolidation process.

The second relationship, between permeability and dry density, is a measure of the rate at which water can pass through the bed. This influences the rate at which the bed consolidates to its final density profile.

3.2 Description of apparatus

The tests were carried out in a 2 metre settling column of 0.092m internal diameter, constructed of perspex (see Fig 3). At a height of 0.5m above the base of the column there was a sampling port for extracting small volumes of the suspension for concentration and salinity analysis. At the same height a steady stream of a mixed suspension was injected into the column, which was initially full of saline water. An outlet at 1.75m above the base of the column was used to extract the excess clear water above the settling bed. The suspension to be injected was kept constantly mixed by a recirculating pump. It was then extracted from the bottom of the mixing tank by a variable speed peristaltic pump and injected into the column. A constant rate of input over a set period of time was chosen for each test.

Density profiles were obtained for the bed in the settling column by measuring the transmission of emissions from a Ba^{133} source (having a 7.5 year half life) over a 30 second time period. This was measured at 5mm, 10mm or 20mm vertical intervals throughout the depth of the bed. The interval used was dependent on the thickness of the bed and was chosen to give approximately 10 readings for each bed.

It was assumed that there was no significant change in density over the time period taken to read the complete profile. The standard deviation of a density reading had been found in a previous investigation to be approximately 1%. The vertical height of the transmission probe was read to the nearest 0.5mm. The transmission probe was calibrated regularly by measuring the count rate in saline solutions of known density. This indicated a linear relationship over the density range applicable in the tests of the form

$$\rho_d = K_1 r + K_2 \qquad (3.1)$$

where

ρ_d = dry density (kgm^{-3})
r = count rate per minute
K_1, K_2 = constants.

Because the total quantity of sediment put into the column during each test was recorded, integration of the density profiles should indicate the distribution of mass through the column and check the total mass in the column.

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

3.3 Test procedure

The column was filled with a saline solution of $30kgm^{-3}$ NaCl to the height of the overflow outlet. A suspension was made up of approximately $18kgm^{-3}$ mud at $30kgm^{-3}$ NaCl. This was kept thoroughly mixed in the conical mixing tank by the recirculating pump. At the start of the test the peristaltic pump was switched on to allow the suspension into the column. The speed of the pump was chosen according to the thickness of bed required and was left running for 2 or 4 hours. To reduce the likelihood of the suspension mixing upwards in the column the inlet was angled towards the column base, thereby allowing clearer fluid to be drawn off at the overflow outlet.

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

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

3.4 Method of analysis

The consolidation of a mud bed is governed by two physical relationships, the variation of its effective stress with density and permeability with density. These two relationships are determined from the density-depth profiles and excess pore pressure measurements taken during the consolidation tests.

For each test, and for each time profiles were measured, the depth from the surface and the density at five percentage mass points are calculated from the density profile. The percentage mass points are 20% (ie the point in the bed with 20% of the total mass beneath it), 40%, 60%, 80% and 100%. The particular choice of percentage points is not important; these five were chosen for convenience.

The excess pore pressure is plotted against the square of the depth from the surface of the bed for each time readings were taken. Linear regression is used on each of these plots to calculate the excess pore pressure at the depth of the percentage mass points. The effective stress at each of these points (total stress minus excess pore pressure) is then calculated. The total stress at a point is the total submerged weight of the bed above that point; for a percentage mass point this is constant with time. The effective stress against dry density is then plotted for the percentage mass points. Each mass point is represented by a line section, which corresponds to the time series for that point. A quadratic function (f_1) may be approximated for the range of values covered, giving the relationship

$$\sigma' = f_1(\rho_d) \tag{3.2}$$

where

σ' = effective stress (Nm^{-2})
ρ_d = dry density of mud (kgm^{-3})

A relationship between permeability and dry density is also determined. The same percentage mass points (20% mass below, 40%, 60%, 80% and 100%) were used, with the density at any time calculated for these points from the density profiles.

The permeability at any point at a specific time is found from Darcy's law

$$k = v/i \tag{3.3}$$

where

k = permeability (ms^{-1})

v = vertical velocity of consolidating particles at that point (ms^{-1}) = water velocity upwards

i = hydraulic gradient at that point.

The velocity of the water is equal and opposite to the velocity of the mud particles (the rate of change of height of a point with time). From previous studies it has been found that the height of a percentage mass point is proportional to the square root of time after the start of the test. These are therefore plotted against one another and linear regression is used to find the actual relationship for each mass point. The differential of this relationship then gives the water velocity at that point at any time.

The excess pore pressure is plotted against the square of the depth from the bed surface for each density profile. This gives a linear relationship for each time readings were taken. This relationship, for a fixed time, (determined by linear regression) is differentiated to give the hydraulic gradient at the percentage mass points in the bed for that time. The hydraulic gradient for each mass point is found to decrease linearly with $time^{0.3}$. Again, linear regression is used to determine the actual relationship for each mass point.

Finally, from the relationships for the velocity with time and the hydraulic gradient with time, the permeability at each point is calculated (from 3.3). This is plotted on logarithmic axes against dry density, as a time series. This enables permeability to be described as a function (f_2) of dry density, in the form

$$\log (k) = f_2(\rho_d) \qquad (3.4)$$

3.5 Test details and results

The mud used throughout the consolidation tests came from the drum marked Tees3. Details of the input suspension for each test, rate and duration of input and resulting bed thickness are given for all four tests in Table 1. The tests resulted in a range of bed thicknesses from 30mm to 83mm.

The change in bed thickness with time is given for all four tests in Figure 4. For each test, this shows a peak which roughly coincides with the end of the injection period. At this time material is still settling to the bed, but the material already on the bed is consolidating faster than any material remaining in suspension is depositing. Virtually all the material has settled to the bed within 2 hours of the end of the injection period. The rate of consolidation tails off as the time increases and the bed reaches a near constant thickness. Once all the material has deposited, the total mass in the bed remains constant, so a reduction in bed thickness also indicates an increase in the mean dry density of the bed.

Figure 5 shows the development of the density profile for Test TC3. The test exhibits the normally expected increase of density with corresponding increase in depth from the mud bed surface. Figure 5 clearly shows the reduction in bed thickness with increasing time and the corresponding increase in density. The dry density of the mud bed after 6 days was 90kgm^{-3} just below the surface and 320kgm^{-3} at 0.01m above the bottom of the bed.

Figure 6 shows the final densities for each test against depth from the surface. The points show some scatter but also indicate a trend of increasing density with depth. The density of the upper layer during formation of the bed was approximately $50kgm^{-3}$.

Effective stress against dry density is plotted for the percentage mass points for tests TC1 and TC2 in Figure 7a. Each mass point in each bed is represented by a line which shows the increase in density (and effective stress) of the point with time. A quadratic curve, fitted by eye through the line sections, (shown on the figure by a dashed line) gives a relationship between effective stress, σ', and dry density, ρ_d, of

$$\sigma' = 0.00045\rho_d^2 - 0.018\rho_d + 0.18 \qquad (3.5)$$

An effective stress of about $19Nm^{-2}$ occurred for a dry density of $230kgm^{-3}$ (the maximum recorded value in tests TC1 and TC2).

Figure 7b shows the effective stress with density relationship for tests TC3 and TC4. The fitted curve (the dashed line in the figure) gives a relationship for tests TC3 and TC4 of

$$\sigma' = 0.0008\rho_d^2 - 0.016\rho_d + 0.08 \qquad (3.6)$$

In this case the effective stress at a density of $230kgm^{-3}$ is about $40Nm^{-2}$, which is approximately double that for the thinner beds of tests TC1 and TC2. This suggests that the manner in which the bed is formed may affect the final density profile. The bed formation details are given in Table 1, which shows that the rate of deposition in tests TC1 and TC2 was considerably less than for tests TC3 and TC4.
Figure 7b indicates that for the tests TC3 and TC4 an effective stress of $90Nm^{-2}$ corresponded to a dry density of approximately $330kgm^{-3}$.

Figure 8 shows the relationship between permeability and dry density for the dredged material. The percentage mass points for each test are represented as short lines, each corresponding to a time series of points for that mass point. For all the tests, as the density at each mass point increases, the permeability decreases. Once again a difference can be seen between the thin beds of tests TC1 and TC2, and the thicker beds of TC3 and TC4. For a fixed dry density, the tests TC1 and TC2 indicate a lower permeability than TC3 and TC4. Two lines of best fit (by eye) are drawn through the data, shown on the figure by two dashed lines. These give the relationships between permeability and dry density of

$$\log k = -0.017\rho_d - 5.0 \quad \text{for TC1 and TC2} \qquad (3.7)$$

and

$$\log k = -0.011\rho_d - 5.0 \quad \text{for TC3 and TC4} \qquad (3.8)$$

where

k = permeability (ms^{-1})
ρ_d = dry density (kgm^{-3})

4. EROSION BY UNI-DIRECTIONAL CURRENTS

4.1 Objectives

The objectives of the erosion tests were to determine a relationship between the erosion shear strength, τ_e, and dry density, ρ_d, of the mud and to establish a representative value for the erosion constant, m_e. These relationships will be used in numerical models to predict the dispersion of dredged material.

A homogeneous mud slurry was allowed to settle out in the carousel to form a bed of between 0.01m and 0.02m. The bed was allowed to consolidate to give a range of densities typical of those found on site. Known shear forces were applied to the mud bed, in order to determine its erosion shear strength and erosion constant.

4.2 Description of apparatus

4.2.1 Operation and instrumentation

The carousel (Fig 9) is an annular flume, with an outer diameter of 6m, a channel width of 0.4m and depth of 0.35m, and has a detachable roof 0.09m thick. The flume stands approximately 1.1m off the ground, supported by 12 brick pillars. The channel and the roof are constructed of fibre glass, with a 0.12m long perspex section in the channel for viewing. The roof fits into the channel, and floats on the fluid. Fluid motion in the carousel is induced and continued by the drag between the roof and the fluid surface as the roof rotates.

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

A strain gauge is used to measure the force applied to the roof of the carousel as it rotates. It consists of a spring and displacement transducer arrangement attached to the driving arm at the point of contact with the roof. The magnitude of the applied force is determined by the displacement transducer deflection, which is displayed on a chart recorder. The strain gauge is calibrated by applying known forces via a pulley system.

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

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

Fluid is continuously extracted from the carousel by a peristaltic pump and passed through a constant temperature water bath and a densiometer before being returned to the carousel. The densiometer works on the principle of determining the frequency of a thin vibrating glass tube through which the fluid is pumped and comparing this to the frequency of clean water pumped through a second densiometer. The readings obtained are analysed and displayed on a chart recorder. Bottle samples of the fluid are taken from time to time and analysed gravimetrically to maintain an accurate calibration. In this manner the suspended sediment concentration of the fluid in the carousel is measured continuously to within a few percent. Previous measurements by Burt and Game (Ref 1) have shown that the mean suspended solids concentration of the fluid in the carousel is very close to the suspended solids concentration at the centre of flow, certainly less than 5% difference.

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

4.2.2 Bed shear stress measurement

Two methods were employed for measuring the average shear stress exerted by the fluid on the bed. The first method was simple and involved direct measurement of the energy input to the roof through the calibrated strain gauge for a number of different speeds of rotation of the roof.

The second and more complex way of determining the bed shear stress was by measurement of the near bed velocity profiles in the flume using laser doppler anemometry. The operation of the laser is explained in detail by Delo (Ref 2). The friction velocity at the bed was determined from a log-linear plot of height above bed and tangential velocity. Velocities were determined at three sections across the width of the flume for different speeds of rotation of the roof. The bed shear stresses were then computed from the logarithmic portion of the velocity-depth profiles.

The average bed shear stress across the width of the flume measured by the laser velocity is shown in Figure 10. Also given in Figure 10 is the shear stress on the wetted perimeter as given by the power input measured through the strain gauge. These two curves show reasonable agreement and indicate a steady increase in bed shear stress with increasing speed of rotation of the roof. For the purpose of estimating the bed shear stress during an erosion test the curve representing the average shear stress as calculated from the power input was used. However, it must be appreciated that the eroding fluid in an erosion test may have a high concentration of suspended solids and will not exhibit the same hydrodynamic behaviour as the clean water used in the calibration.

Nevertheless, for the concentrations of suspended solids present in the carousel during an erosion test ($\leqslant 4 kgm^{-3}$), we believe that this factor would not significantly affect the calculation of the erosion properties of the mud.

4.3 Test procedure

To prepare a mud bed in the carousel, the mud is first mixed homogeneously in a mixing tank with a recirculating pump. The suspension is then pumped into the flume from the tank until the required depth of suspension in the flume is reached. The roof is lowered onto the suspension surface and the mud in suspension is allowed to deposit and consolidate. The period of consolidation is usually in the range of 2-10 days and the resulting bed has a thickness of 15-25mm. The depth of fluid above the bed is adjusted to be close to 100mm which corresponds to the depth of flow for which the bed shear stress measurements were made.

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

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

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

4.4 Method of analysis

The basic data obtained from a test are the suspended solids concentration with time, the depth of erosion at the mid-section of the flume with time and the depths of erosion across the flume at the equilibrium point in each run. The objectives of the analysis are to calculate the relationships for the shear strength of the mud with density and the rate of erosion with applied shear stress.

The shear strength with density relationship is described by the discrete values, at the equilibrium point in each run, of the speed of rotation of the roof, the suspended solids concentration of the fluid and the average depth of erosion across the flume. Using the results presented in Figure 10 the average bed shear stress is then estimated for the prescribed speed of rotation of each run. At equilibrium in each run, the shear strength of the exposed surface of the bed is equal to the applied shear stress. Therefore, the shear strength against depth relationship of the eroded portion of the bed can be described by these points and expressed in a functional form

$$\tau_e = f_3(h) \qquad (4.1)$$

where

τ_e = erosion shear strength of bed (Nm^{-2})
h = average depth of erosion below original surface (m)
f_3 = function.

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

$$\rho_h = (dm/dh)A^{-1} \tag{4.2}$$

where

ρ_h = dry density of mud at a depth h (kgm^{-3})
m = mass of solids in suspension (kg)
A = area of erosion (m^2).

Expressing the mass of suspended solids eroded from the bed in terms of the concentration of suspended solids, equation (4.2) can be rewritten as:

$$\rho_h = (dc/dh)(V/A) \tag{4.3}$$

where

c = concentration of suspended solids (kgm^{-3})
V = volume of suspension (m^3).

The ratio of V/A in equation (4.3) will be nearly constant during a test and is the depth of flow, d. By plotting the concentration of suspended solids against the average depth of erosion, a quadratic function (f_4) may be approximated, giving

$$c = f_4(h) \tag{4.4}$$

Differentiating equation (4.4) and substituting into equation (4.3) leads to the relationship

$$\rho_h = K_3 + K_4 h \tag{4.5}$$

Combining equations (4.1) and (4.5) leads to an expression which relates the erosion shear strength to the density of the exposed mud, and which can be approximated to the form

$$\tau_e = K_5 \, \rho_h^{k_6} \tag{4.6}$$

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

$$dm/dt = Am_e(\tau - \tau_e), \qquad \text{for } \tau \geqslant \tau_e \tag{4.7}$$

where

m_e = erosion constant ($kgN^{-1}s^{-1}$)
τ = applied shear stress (Nm^{-2}).

This means that erosion is gradual which is not necessarily the case for certain types of newly formed slack water deposits. Although there is no physical reason for assuming erosion rate to be directly proportional to the excess shear, Delo and Burt (Ref 3) showed that this is a better variable for describing mud erosion than others. In any event it is not critically important in tidal conditions to know the erosion rate precisely because the erosion process is self correcting in the sense that if the erosion constant (m_e) is too high then too much erosion occurs in the early stages, but this exposes stronger bed material and erosion slows down accordingly. The opposite happens if m_e is under-valued. The ultimate result in any case would be erosion down to the bed level, where the strength of the exposed material corresponds to the maximum bed stress of the tidal cycle or of the spring-neap cycle, if longer periods are being considered.

A useful analysis of the erosion constant can be made by assuming that the shear strength of the bed during any discharge run is proportional to the eroded mass (Ref 4). The constant of proportionality for a run is given by

$$\alpha = (\tau_b - \tau_o) / (c_e - c_o) \qquad (4.8)$$

where

τ_b = applied bed stress for the run
τ_o = shear strength of bed at start = equilibrium from previous run
c_e = equilibrium concentration at the end of run
c_o = initial concentration = equilibrium concentration at end of previous run.

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

If it is further assumed that the erosion rate for the exposed mud surface area is given by equation (4.7) we obtain, using (4.8) and replacing m by cV

$$dc/dt = Am_e\alpha(c_e - c_o)/V \qquad (4.9)$$

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

$$(c_e - c) = (c_e - c_o) \exp (-Am_e \alpha t/V) \qquad (4.10)$$

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

4.6 Test details and results

Five erosion tests were carried out, three on mud from Seal Sands (TE1, TE2 and TE3) and two on dredged material (TE4 and TE5). For the Seal Sands tests the mud came from the drum marked Tees2. The carousel was filled to a depth of 0.106m with a suspension of 34.9kgm^{-3} mud, 28.8kgm^{-3} salt. The consolidation period for each of the three tests TE1, TE2 and TE3 was 2.7 days. At the end of a test the bed was totally remixed into suspension and allowed to deposit and consolidate again for the next test on that mud. For the dredged material tests the mud came from drum Tees4. The carousel was filled to a depth of 0.109m with a suspension of 44.7kgm^{-3} mud, 27.7kgm^{-3} salt. The consolidation period was 2.7 days for Test TE4 and 7 days for Test TE5. Details of the resulting test beds are summarised for all the tests in Table 2.

In each test the bed was subjected to the same set of roof speeds (and hence also the same applied shear stresses), each kept constant until no further erosion occurred. Figure 11 shows the typical pattern of roof speed, suspended solids concentration and depth of erosion for Test TE5. Each step in roof speed corresponds with a large increase in suspended solids concentration and depth of erosion, which both level off as the equilibrium condition is reached at the end of each run.

The shear strength of the exposed bed surface against density is plotted for tests TE1, TE2 and TE3 in Figure 12a. Error bars of ± 30% are shown for the calculation of density and ± 10% for the calculation of shear strength. The best fit line through the data in Figure 12a indicates that there is a power law relationship between the parameters for the Seal Sands mud (see Eqn 4.6) which can be expressed as

$$\tau_e = 0.0025\rho_h^{1.0} \qquad (4.11)$$

Figure 12b shows the corresponding relationship for the dredged material; the shear strength of the exposed bed surface against density for Tests TE4 and TE5, also with error bars. A best fit line through the data gives a relationship for the dredged material of

$$\tau_e = 0.00014\rho_h^{1.7} \qquad (4.12)$$

The normalised results of erosion rate (see section 4.5) are presented in Figure 13 for all five tests. The individual values for each run of each test varied from approximately 0.0005 to 0.0014kgN^{-1}s^{-1}. For calculation purposes a typical erosion constant value of 0.0009kgN^{-1}s^{-1} is suggested for Tees dredged material.

5. EROSION BY WAVES TESTS

5.1 Objectives

Laboratory tests were carried out to assess the behaviour of Tees mud under wave action. The objective was to determine the relationship between the bed density and the critical peak bed shear stress for erosion. In addition, it was intended to determine the rate of erosion at shear stresses above the critical value. A placed bed was used in one test and high density slurry beds in the other three tests. This method was adopted rather than depositing the bed from suspension so that there would be less density gradient within the bed, and hence one fewer variable in the analysis.

5.2 Test procedure

The tests were run in a wave flume 25m long, 0.75m wide and 0.55m water depth, with a wave generator at one end. For a distance of 3.5m, beginning 18m from the wave generator, the flume was partitioned along its length into two channels, 0.40m and 0.34m wide. On the wider side of the partition a trough 1.5m long, 0.1m deep and 0.2m wide was formed to contain the placed beds.

During each test the concentration of suspended sediment throughout the flume was measured every 20 minutes. This was done by taking nephelometer readings at 1m intervals along the flume, at 0.05m and 0.25m above the bed (also at 0.45m in Test 3). The suspended sediment concentrations, multiplied by their respective water volumes, were integrated over the length of the flume to give a total mass in suspension.

For the duration of the test (approximately 2 hours) the position of the mud surface was monitored using an ultrasonic detector. This monitored the vertical movement of the mud with the passage of each wave, and hence, the depth of erosion (if any) with time. The wave height was recorded using a twin wire wave recorder. The output from the ultrasonic detector and the twin wire wave probe were logged on a UV chart recorder for some of the tests. This enabled the phase difference between these movements to be calculated.

The vertical density profile of the bed was determined using a conductivity probe. The conductivity of the mud was proportional to its density. Readings were taken every 60 minutes and changes in bed density caused by consolidation or wave action were thereby monitored.

5.3 Test details and results

A placed bed of dry density $560kgm^{-3}$ and a slurry bed of density $375kgm^{-3}$ were tested, in order to get an indication of the effect of bed density on erosion. The wave height/water depth combinations were chosen such that the peak bottom orbital velocities were in the range $0.05ms^{-1}$ to $0.30ms^{-1}$, with corresponding peak bed shear stresses in the range $0.1Nm^{-2}$ to $0.5Nm^{-2}$.

The dry density of the bed, wave height, wave period, water depth and peak bottom orbital velocity for each test are summarised in Table 4.

The conductivity readings showed that there was generally little significant change in density during the tests; Figure 14 shows the bed profiles at the start and end of Test 2, indicating that the waves had little effect on the bed density profile during the two hours of the test.

In Test 1, which had a bed density of 560kgm^{-3} and a bed shear stress, τ_{bm}, of 0.45Nm^{-2} (peak bottom orbital velocity U_{bm} = 0.29ms^{-1}), there was comparatively little erosion. The critical shear stress for erosion of Tees mud at a dry density of 560kgm^{-3} was therefore higher than 0.45Nm^{-2}.

In Test 2 (τ_{bm} = 0.18Nm^{-2}) and Test 3 (τ_{bm} = 0.12Nm^{-2}) the erosion rate was in the range 0.00003 - 0.00009kgm^{-2}s^{-1} (see Table 5). In Test 4 (τ_{bm} = 0.38Nm^{-2}), however, the rate of erosion was an order of magnitude greater at approximately 0.001kgm^{-2}s^{-1}.

For the lower density tests the erosion rate is plotted against applied peak bed shear stress in Figure 15. The rate of erosion under waves was found to increase with applied shear stress. Figure 15 indicates that, for Tees mud with a density of 375kgm^{-3}, the critical shear stress for erosion under waves is between 0.2Nm^{-2} and 0.4Nm^{-2}. For the same density (375kgm^{-3}) under uni-directional currents, the critical shear stress for erosion would be in the range 1Nm^{-2} to 5Nm^{-2} (from Fig 12b and previous studies). The critical shear stress for erosion under waves is therefore significantly lower in these tests.

An erosion constant, similar to the coefficient m_e in equation 4.7, can also be applied to wave erosion. However, in this instance it could not be calculated as the critical shear stress for wave erosion was not sufficiently well defined.

The accuracy of the results was limited by the effect of the ends of the trough. The horizontal motion of the bed was converted into vertical motion by the solid end walls of the trough. This resulted in a small amount of mud being pushed out of the trough with each wave. The magnitude of this effect was more pronounced at high applied shear stresses. At the lowest applied shear stress there was no erosion caused by the end effects as the bed moved very little. At higher shear stresses it was suspected that most of the erosion was due to the end effects.

The total erosion calculated from the depth of erosion averaged approximately twice the erosion calculated from the mass in suspension. This was most likely due to transport of mud out of the trough along the bed rather than by suspension, although it could also be due to redeposition from suspension elsewhere in the flume during the test.

6. DISCUSSION

Table 3 is a summary of the mud properties of some of the muds tested recently at HR. The muds covered in the summary are: Cardiff (Taff/Ely), Cardiff (Rhymney), Fawley, Grangemouth, Harwich, Hong Kong, Ipswich, Kelang, Kingsnorth, Medway, Poole, Tees (Seal Sands) and Tees (dredged). As this study is particularly concerned with the fate of dredged material, the table can be used as an indication of how the Tees dredged material behaves compared to these other muds. The dredged material from the River Tees has a lower than average percentage of silt, a higher than average percentage of organic material, low cation exchange capacity and average bulk density. The erosion constant is about average compared with the other muds. It is not possible to compare the consolidation properties directly due to developments in the testing procedure.

The recent developments in the consolidation tests have allowed the effective stress and permeability to be calculated at times during the tests. The results of the tests on the Tees dredged material suggest that the way the bed is created may affect the final density profile of the fully consolidated bed. In particular, it may affect the relationships of effective stress with density and permeability with density. If such relationships are to be used in predictive mathematical models then it is important that the laboratory testing procedures attempt to match the field conditions, with respect to the rate of deposition of the bed, and duration of deposition. It would be useful to conduct further tests to investigate this possible dependence on the way the bed is created.

The accuracy of the results from the wave tests was limited by the end effects of the trough holding the bed. In future wave tests the test bed should be much longer, to avoid the distortion of the results by the end effects of the trough.

7. CONCLUSIONS

1. Four drums of bulk mud samples were collected from the River Tees; two were filled with Seal Sands mud and two with material dredged from the river (see Fig 1). These were transported to Hydraulics Research for laboratory tests to determine the mud properties. The bulk density, cation exchange capacity, organic content and size grading of the two muds were measured, and the mineralogical content was analysed. Laboratory tests were run to determine the

properties of consolidation, erosion by unidirectional currents and erosion by waves.

2. The mud from Seal Sands had a bulk density of approximately 1550kgm^{-3} and consisted of approximately 75% silt ($\leqslant$ 63 microns diameter). The percentage of organic matter of the samples was 4.0 - 4.5% and the cation exchange capacity was 15.1 - 15.7meq/100g. The dredged material had an average bulk density of 1430kgm^{-3}, with a silt content of approximately 75% (Fig 2). The organic matter was 10.1 - 11.1% and the cation exchange capacity 17.6 - 18.1meq/100g.

3. Four settling column tests on the dredged material investigated the consolidation of mud beds formed by continuous deposition of a suspension pumped into the column. A constant rate of input over a period of 2 or 4 hours was chosen for each test. Each bed reached a maximum thickness soon after the end of the input period. After this point, consolidation was rapid at first, with a reduction in bed thickness (Fig 4) and a corresponding increase in mean dry density of the bed. Consolidation was virtually complete after about 7 days. The relationship between the effective stress, σ', and dry density, ρ_d, appeared to be affected by the rate of creation of the bed. For tests TC1 and TC2 (beds 30-35mm final thickness) this relationship (Fig 7a) was

$$\sigma' = 0.00045\rho_d{}^2 - 0.018\rho_d + 0.18 \qquad (7.1)$$

For tests TC3 and TC4 (final bed thickness 7080mm) the relationship (Fig 7b) was

$$\sigma' = 0.0008\rho_d{}^2 - 0.016\rho_d + 0.08 \qquad (7.2)$$

Similarly, the permeability was affected by the manner of creation of the bed. The tests indicated a relationship between permeability, k, and dry density, ρ_d, (Fig 8) of

$$\log k = -0.017\rho_d - 5.0 \tag{7.3}$$

for tests TC1 and TC2 (beds 30-35mm), and

$$\log k = -0.011\rho_d - 5.0 \tag{7.4}$$

for tests TC3 and TC4 (beds 70-80mm).

4. Five uni-directional current erosion tests were carried out in the carousel flume on deposited mud beds, three on Seal Sands mud, two on dredged material. For each series of tests the beds were deposited from the same initial suspension and allowed to consolidate for 2.7 or 7 days. The results of the three Seal Sands tests together gave a relationship between the erosion shear strength, τ_e, and the dry density of the exposed mud surface, ρ_h, (Fig 12a). This was

$$\tau_e = 0.0025\rho_h^{1.0} \tag{7.5}$$

The corresponding relationship for the dredged material (Fig 12b) was

$$\tau_e = 0.00014\rho_d^{1.7} \tag{7.6}$$

The erosion constant m_e was evaluated from all the runs in the erosion tests (Fig 13). The mean value was approximately $0.0009 kgN^{-1}s^{-1}$.

5. Four tests on the dredged material were run in a wave flume - one on a placed bed (dry density $560 kgm^{-3}$) and three on high density slurries (dry

density 375kgm^{-3}). The beds were tested with appropriate conditions of wave height and water depth to give peak bottom orbital velocities in the range 0.05ms^{-1} to 0.30ms^{-1} and corresponding peak bed shear stresses in the range 0.1Nm^{-2} to 0.5Nm^{-2}. The rate of erosion under waves was found to increase with applied shear stress (Fig 15). At a density of 560kgm^{-3}, the critical shear stress for erosion was higher than 0.45Nm^{-2}. At a density of 375kgm^{-3}, the critical shear stress for erosion was between 0.2Nm^{-2} and 0.4Nm^{-2}.

6. In comparison with other muds tested by HR, the dredged material from the River Tees has a lower than average percentage of silt, a higher than average percentage of organic material, low cation exchange capacity and average bulk density. The erosion constant is about average compared with the other muds. It is not possible to compare the consolidation properties directly due to developments in the testing procedure.

8. REFERENCES

1. Burt, T N and Game, A C. "The carousel: commissioning of a circular flume for sediment transport research", Hydraulics Research, Wallingford, England. Report SR 33, January 1985.

2. Delo, E A. "The behaviour of estuarine muds during tidal cycles: An experimental study and mathematical model", Hydraulics Research, Wallingford, England. Report SR 138, February 1988.

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TABLES

TABLE 1 : Description of suspensions and resulting beds in consolidation tests

TEST NO.	CONCENTRATION OF MUD IN INPUT SUSPENSION (kgm^{-3})	RATE OF INPUT (m^3h^{-1})	DURATION OF INPUT (hours)	DEPOSITION RATE ($kgm^{-2}h^{-1}$)	BED THICKNESS AT END OF TEST (mm)
TC1	5.61	0.0022	2	1.87	30
TC2	10.63	0.0011	4	1.77	34
TC3	19.65	0.0029	2	8.72	72
TC4	18.99	0.0015	4	4.21	83

TABLE 2 : Description of beds in erosion tests

TE1, TE2, TE3 (Seal Sands mud)

Depth of suspension in Seal Sands tests	0.106m
Concentration of mud in suspension, Seal Sands tests	34.9kgm^{-3}
Concentration of salt in suspension, Seal Sands tests	28.8kgm^{-3}

TE4, TE5 (Dredged material)

Depth of suspension in Dredged material tests	0.109m
Concentration of mud in suspension, Dredged material tests	44.7kgm^{-3}
Concentration of salt in suspension, Dredged material tests	27.7kgm^{-3}

Roof speed of successive runs, all tests:

Run 1	2.22 rpm
Run 2	2.58 rpm
Run 3	2.95 rpm
Run 4	3.31 rpm

TEST NO	CONSOLIDATION PERIOD (days)	BED THICKNESS (mm)	MEAN DRY DENSITY (kgm^{-3})	TEMPERATURE OF SUSPENSION DURING TEST (°C)
TE1	2.7	9.2	400	15.5
TE2	2.7	9.0	411	14.5
TE3	2.7	9.8	377	14.1
TE4	2.7	17.2	283	14.5
TE5	7	14.7	331	14.8

TABLE 3 : Comparison of muds recently tested at HR

MUD TYPE	% SILT ($\leq$ 63 microns)	ORGANICS (%)	CATION EXCHANGE (meq/100g)	MINERALOGY	BULK DENSITY (kgm^{-3})	EROSION CONSTANT (m_e) ($kgN^{-1}s^{-1}$)	EROSION SHEAR STRENGTH (τ_e Nm^{-2})	PERMEABILITY (k ms^{-1})	EFFECTIVE STRESS (σ' Nm^{-2})	SETTLING VELOCITY (w_{50} ms^{-1})
CARDIFF TAFF/ELY	80–100	12.6–14.9			1300–1850		$\tau e=0.00022p^{1.5}$	$k=10^{-9}e^2$	$\sigma'=3000e^{-2}-4.5$	$w_{50}=0.0003C^{1.0}$
CARDIFF RHYMNEY	> 90	10.6–12.8			1300–1850		$\tau e=0.0042p^{0.9}$	$k=10^{-9}e^2$	$\sigma'=4000e^{-2}-4.0$	$w_{50}=0.0003C^{1.0}$
FAWLEY	95	2.2–2.4	23.6–24.2	quartz 26% clays 74%	1220–1650		$\tau e=0.0005p^{1.43}$	$\log(k)=-0.014p-4.9$	$\sigma'=0.004p^2+0.058p+7.6$	$w_{50}=0.0075C^{1.9}$
GRANGEMOUTH	80–90	4.7–5.5	18.8–20.3	quartz 18% clays 82%	1370	0.0005–0.0014	$\tau e=0.0045p^{0.9}$	$\log(k)=-0.01p-5.5$	$\sigma'=0.0005p2-0.01p+0.05$	
HARWICH	88–95	2.2–2.7	21.5–23.6	quartz 24% clays 76%	1250	0.0007	$\tau e=0.00035p^{1.43}$	$\log(k)=-0.0115p-5.3$	$\sigma'=0.0011p^2-0.15p+15.0$	$w_{50}=0.002C^{2.0}$
HONGKONG	65–80	6.9–9.6	14	quartz 20% clays 80%		0.0006–0.0015	$\tau e=0.0013p^{1.2}$			
IPSWICH				quartz 17% clays 83%	1320	0.0009–0.0030	$\tau e=0.00028p^{1.55}$			$w_{50}=0.0012C^{1.4}$
KELANG	65–80			quartz 17% clays 83%		0.0002–0.0009	$\tau e=0.0005p^{1.4}$			
KINGSNORTH	64	4.8	26.0	quartz 17% clays 83%	1375	0.0007	$\tau e=0.005p^{0.9}$	$\log(k)=-0.017p-4.75$	$\sigma'=0.0009p^2-0.09p+2.25$	$w_{50}=0.0014C^{1.0}$
MEDWAY	80	2.7–2.9	20.9–22.9	quartz 21% clays 79%	1220	0.0007	$\tau e=0.0007p^{1.3}$	$k=10^{-10}e^3$	$\sigma'=1600e^{-1.8}-2.3$	
POOLE	80–85	2.2–2.3	20.6–20.7	quartz 30% clays 70%	1500	0.0007–0.0014	$\tau e=0.0003p^{1.5}$		$\sigma'=9000e^{-3}-0.204$	
TEES SEAL SANDS	75	4.0–4.5	15.1–15.7	quartz 19% clays 81%	1550	0.0002–0.0014	$\tau e=0.0025p^{1.0}$			
TEES DREDGED	75	10.1–11.1	17.6–18.1	quartz 22% clays 78%	1430	0.0005–0.0018	$\tau e=0.00014p^{1.7}$	** $\log k=-0.011p-5.0$	** $\sigma'=0.0008p^2-0.016p+0.08$	

NB p = dry density, e = voids ratio (e = 2650/p − 1), C = concentration
(** = relationship is for beds 70-80mm final thickness)

TABLE 4 : Details of wave tests

TEST NO	DRY DENSITY	WATER DEPTH	WAVE HEIGHT	MAX.BOTTOM ORB.VEL.	PEAK BED SHEAR STRESS
	kgm^{-3}	m	m	ms^{-1}	Nm^{-2}
1	560	0.30	0.054	0.29	0.45
2	375	0.30	0.021	0.11	0.18
3	375	0.55	0.021	0.08	0.12
4	375	0.40	0.054	0.25	0.38

TABLE 5 : Results of wave tests

TEST NO	EROSION RATE FROM DEPTH OF EROSION	EROSION RATE FROM MASS IN SUSPENSION	PEAK BED SHEAR STRESS
	$kgm^{-2}s^{-1}$	$kgm^{-2}s^{-1}$	Nm^{-2}
1	1.9E-05	7.9E-04	0.45
2	9.1E-05	4.4E-05	0.18
3	5.4E-05	2.6E-05	0.12
4	1.5E-03	6.7E-04	0.38

FIGURES

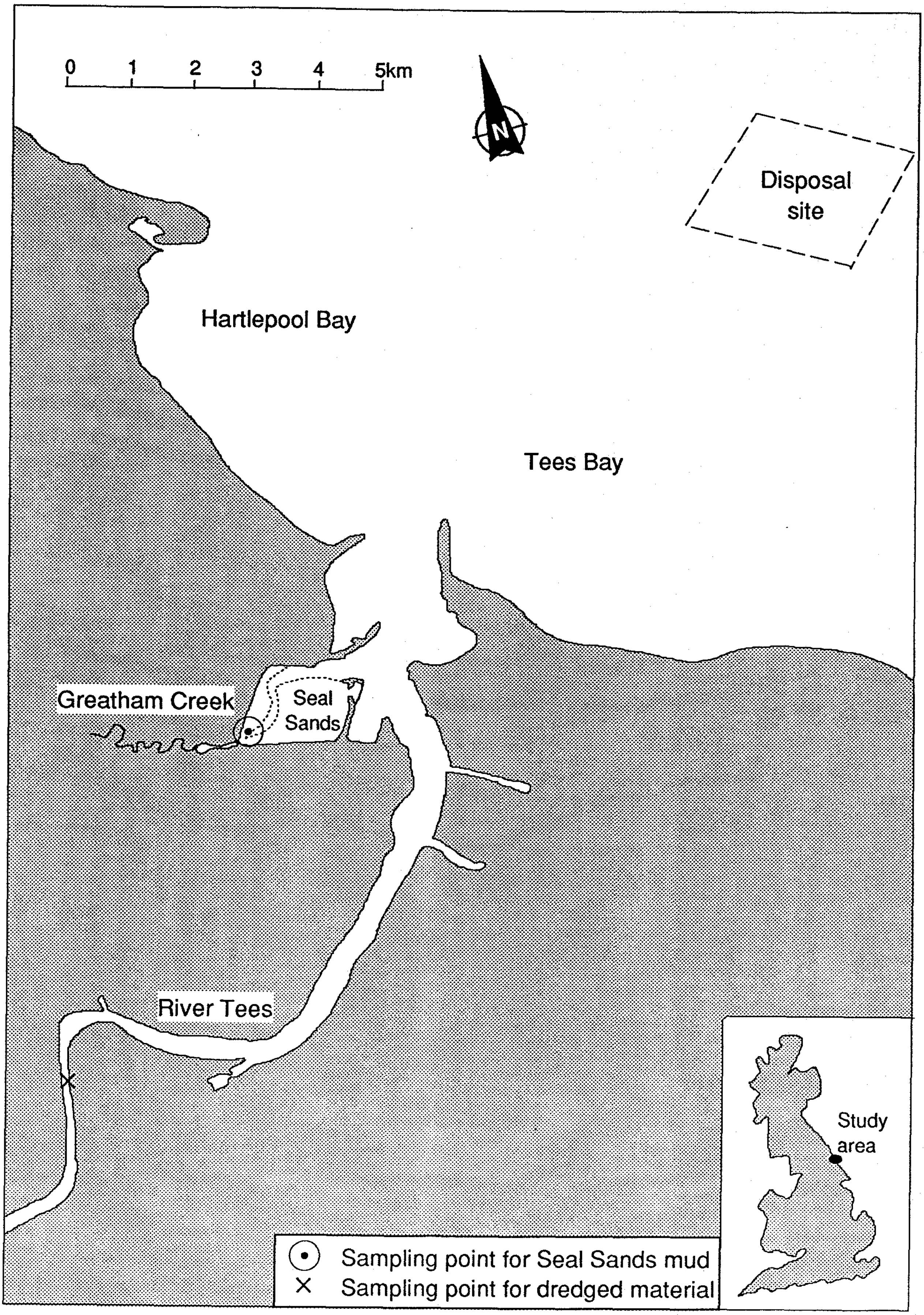

Fig 1 Location map of River Tees and mud sampling points

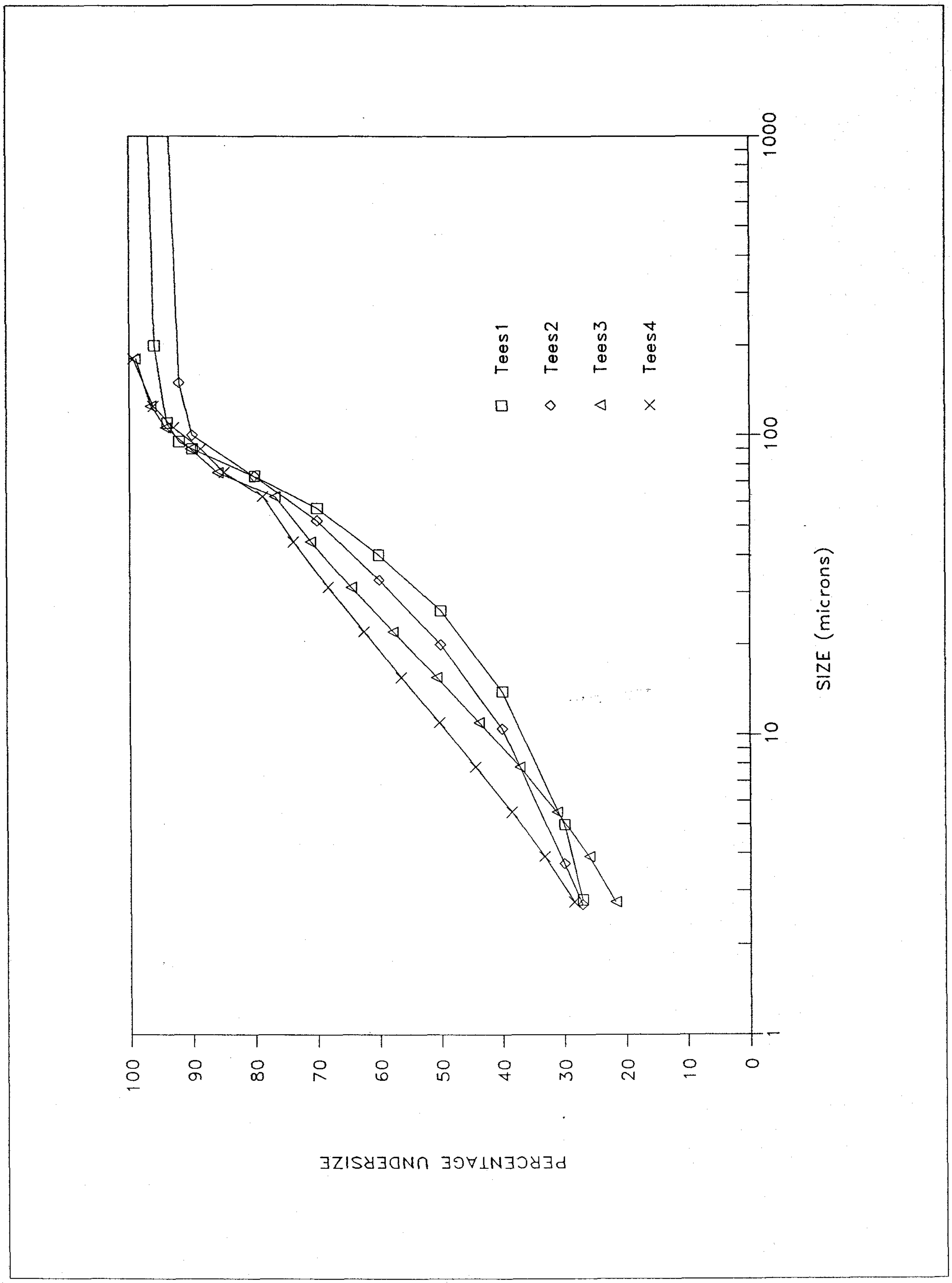

Fig 2 Particle size grading

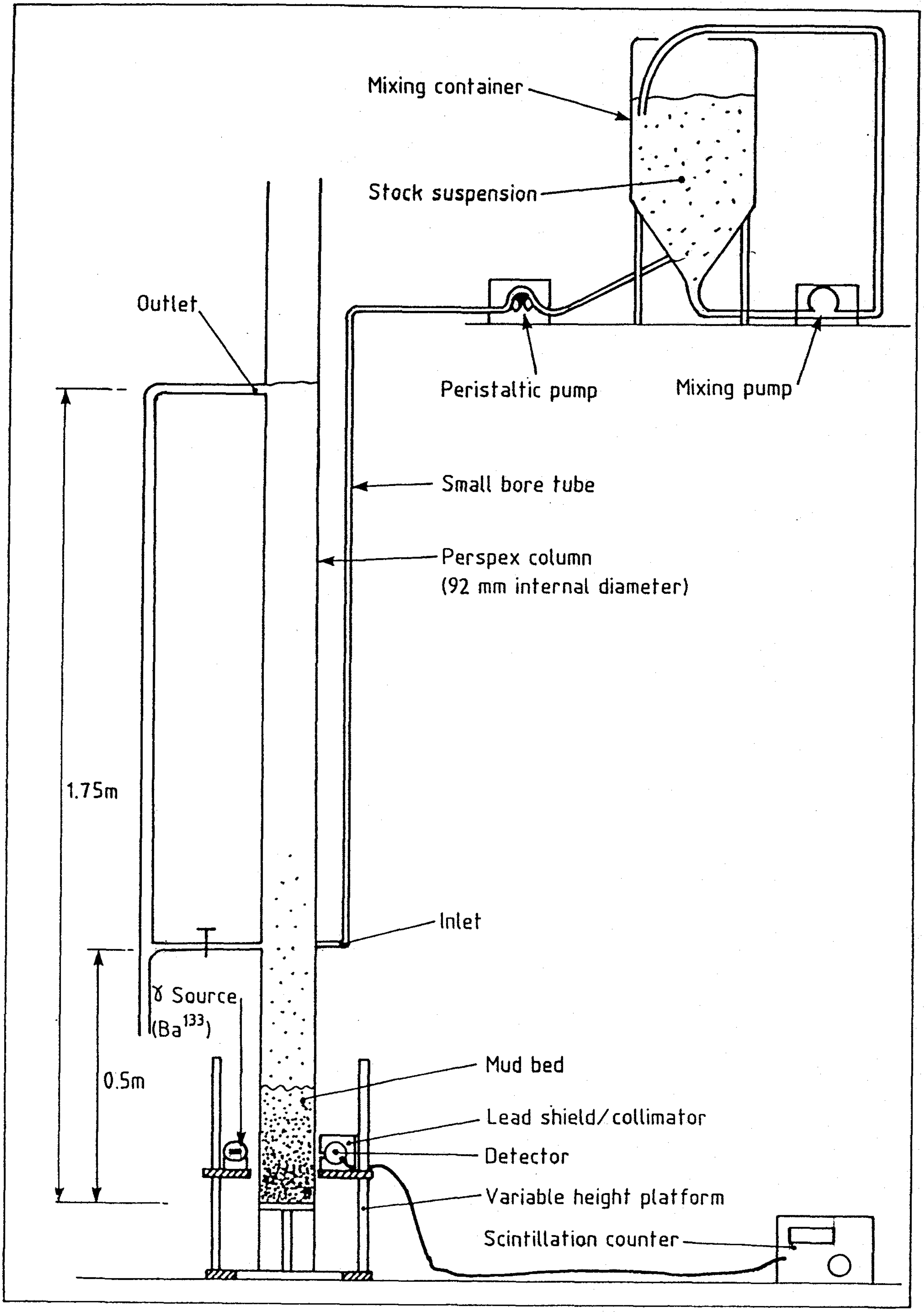

Fig 3 Settling column apparatus

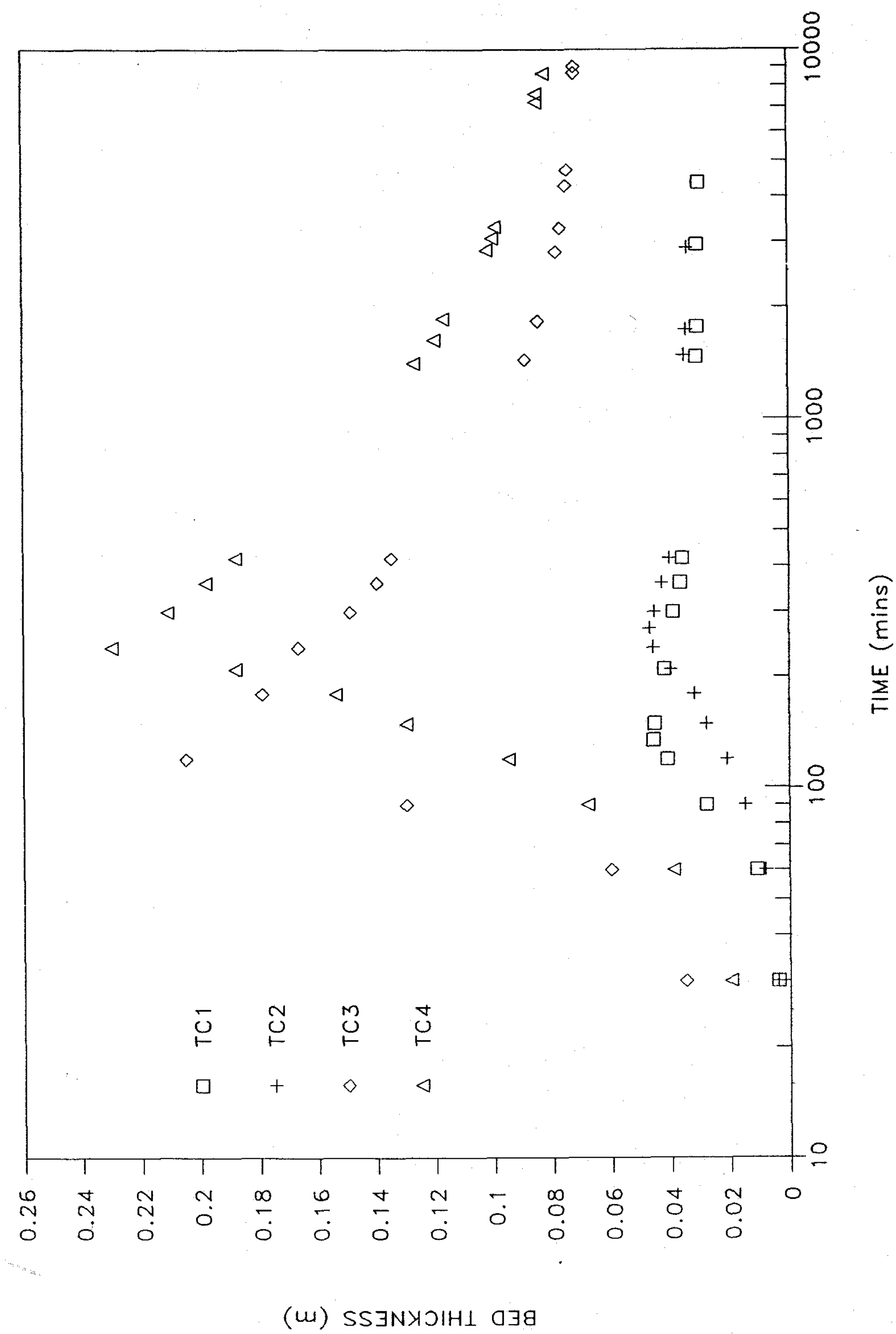

Fig 4 Variation of bed thickness with time, all consolidation tests

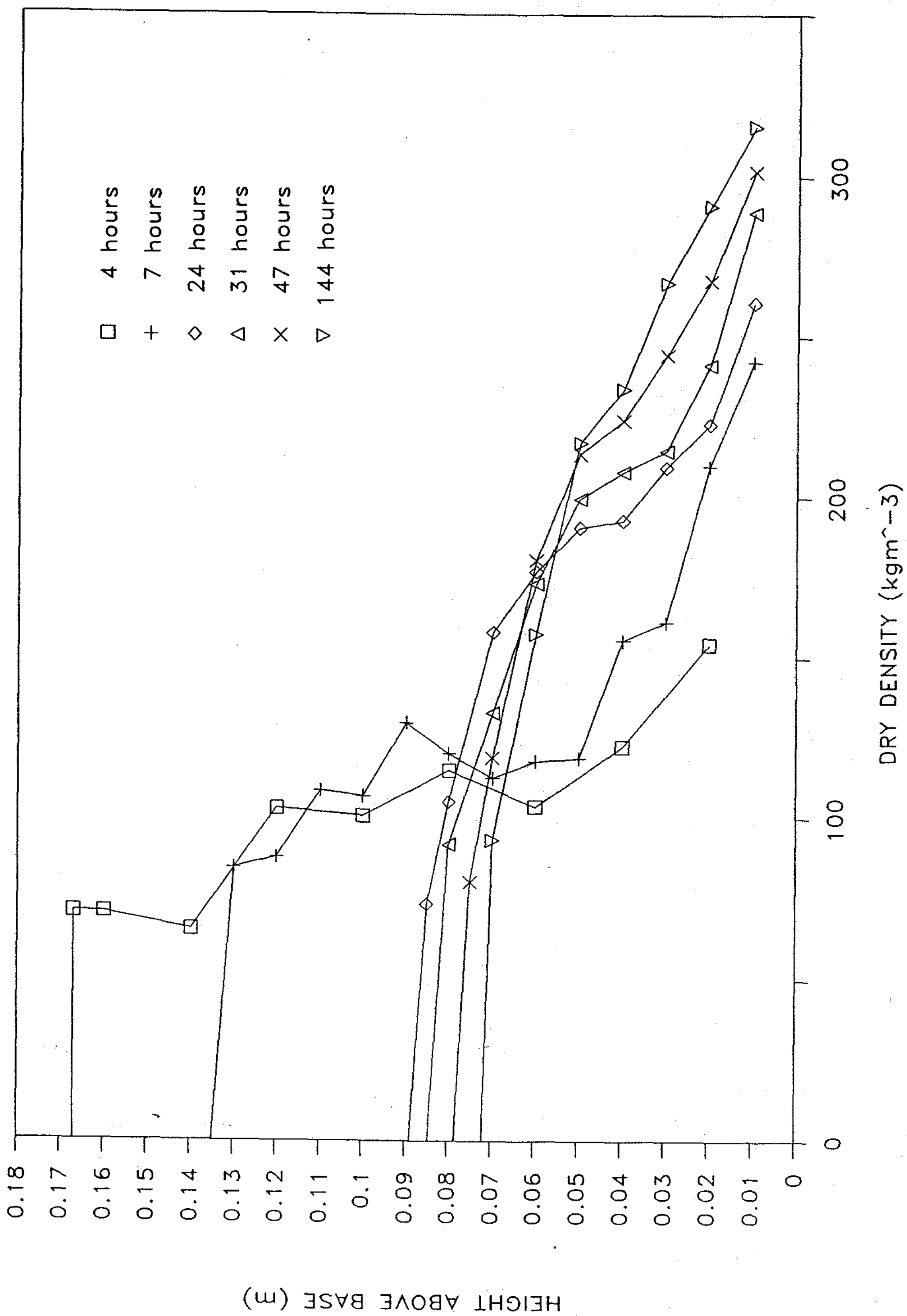

Fig 5 Density profiles with time, test TC3

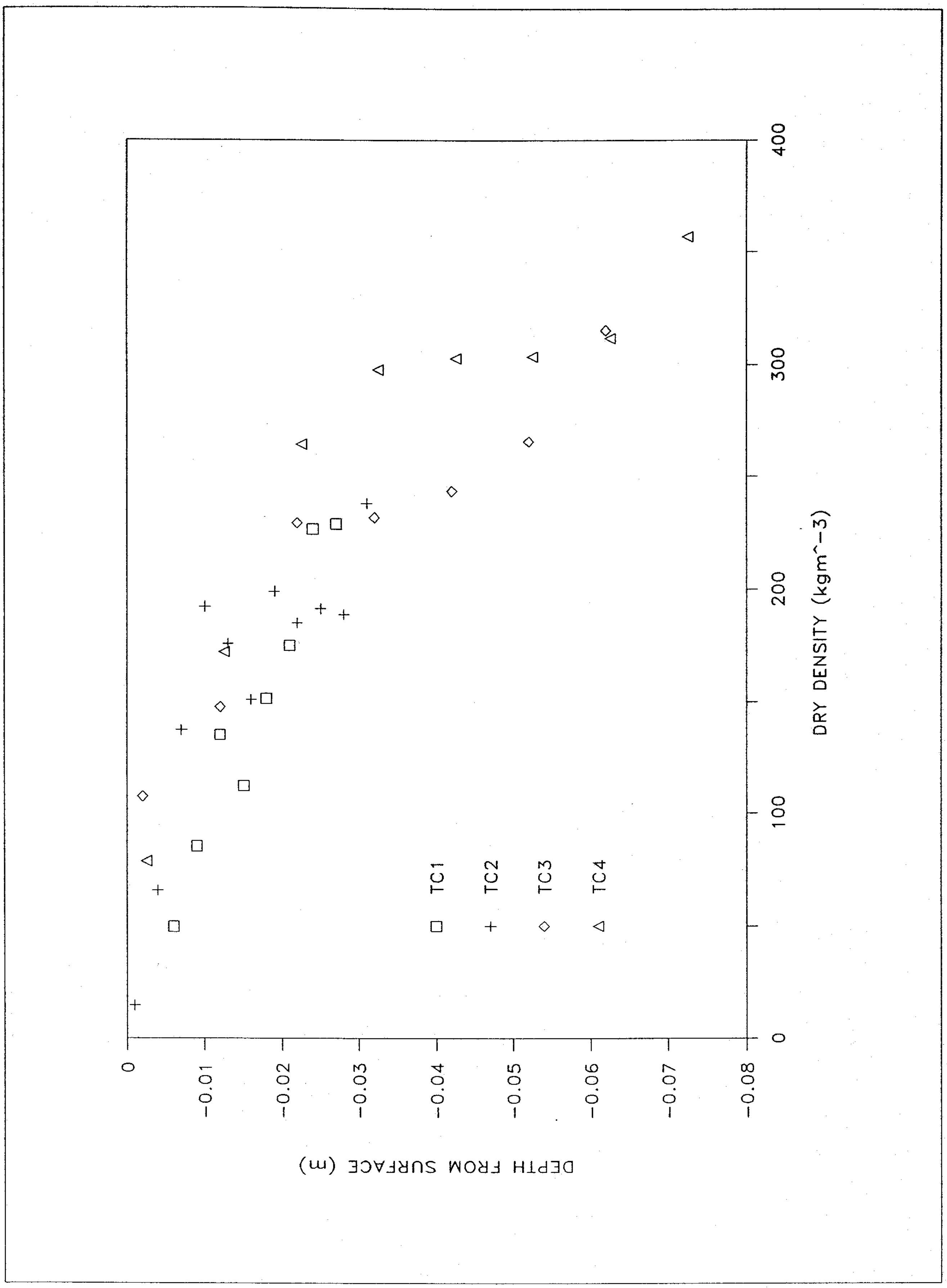

Fig 6 Final density against depth from surface, all consolidation tests

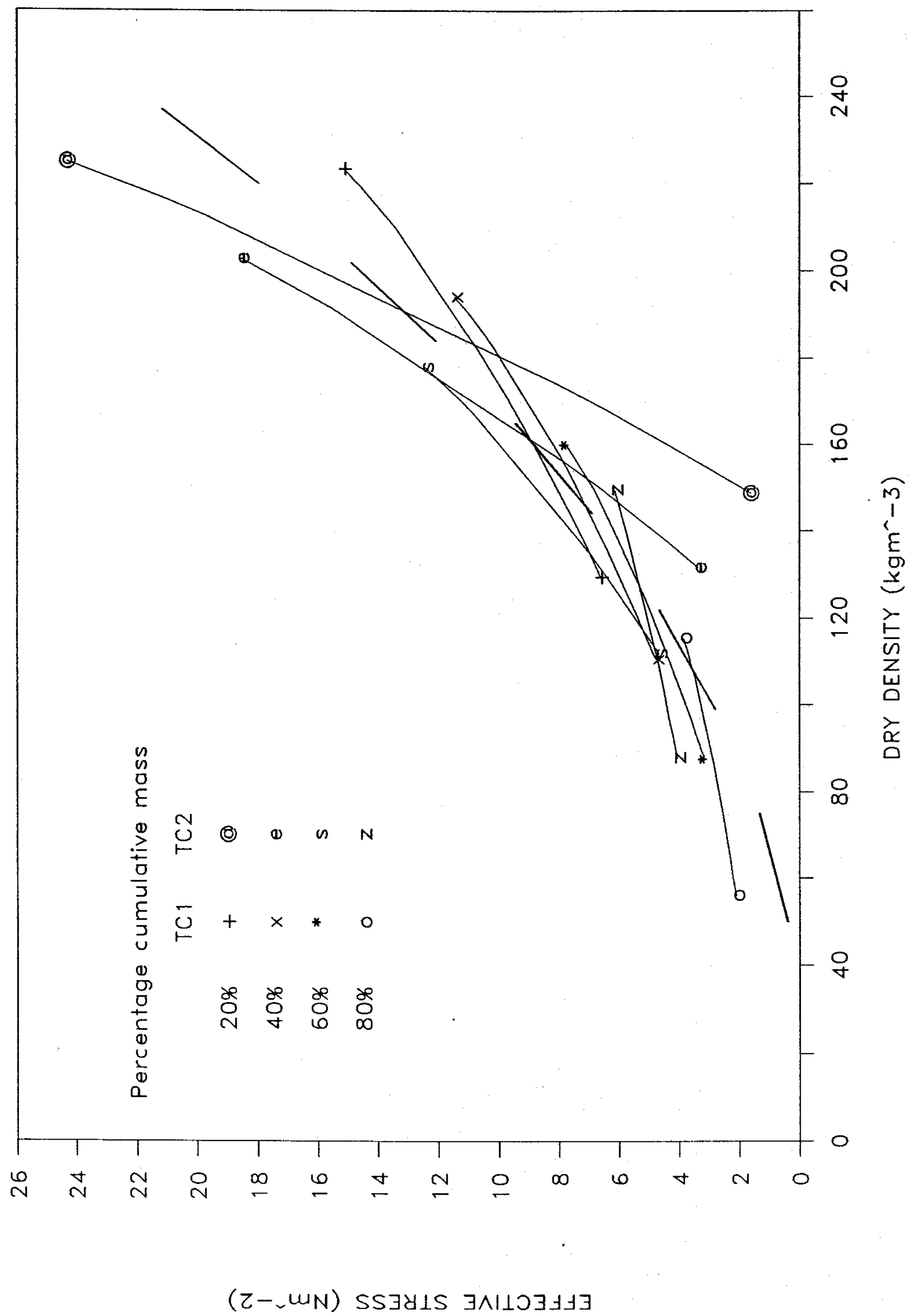

Fig 7a Effective stress with density relationship, tests TC1 and TC2

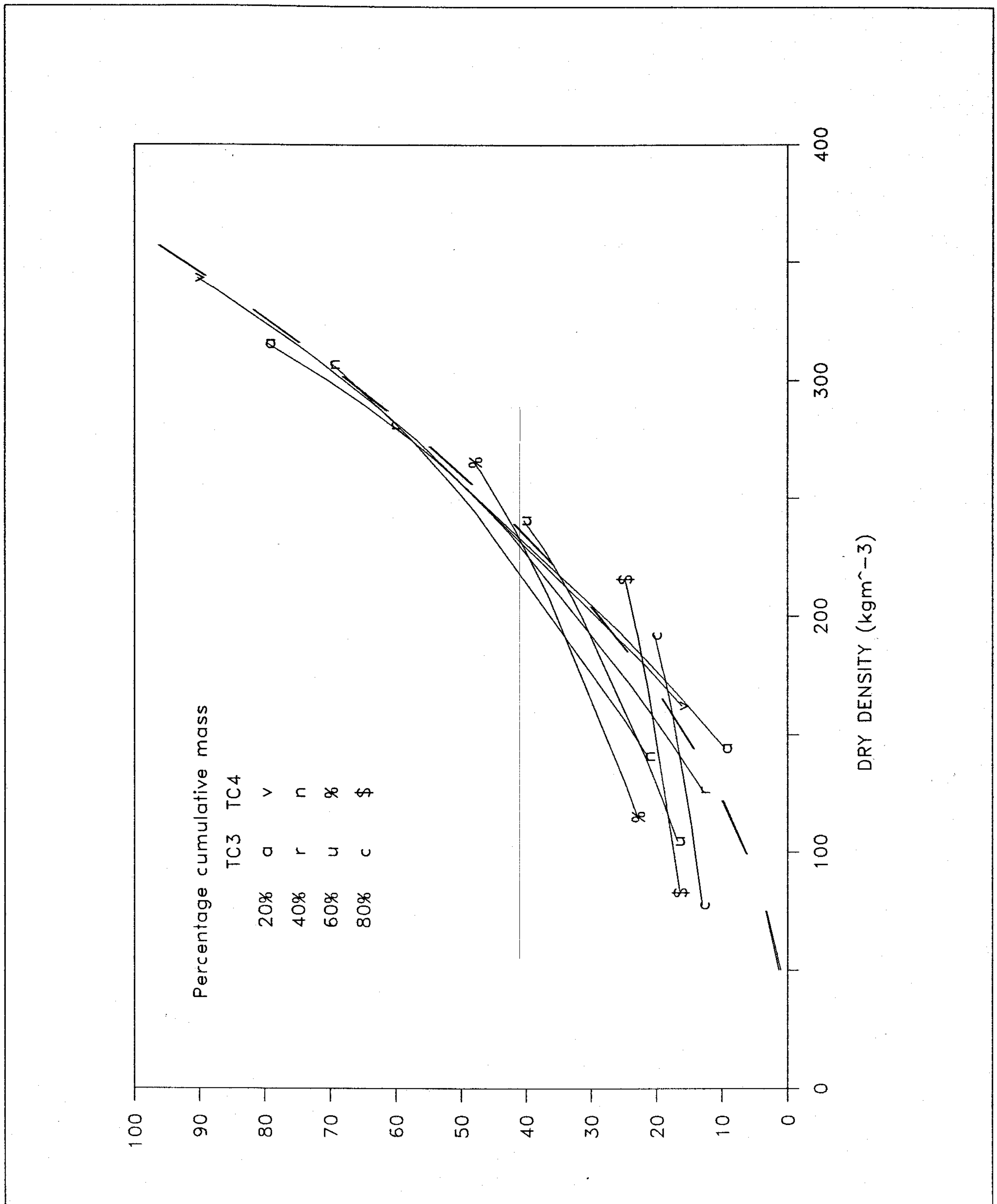

Fig 7b Effective stress with density relationship, tests TC3 and TC4

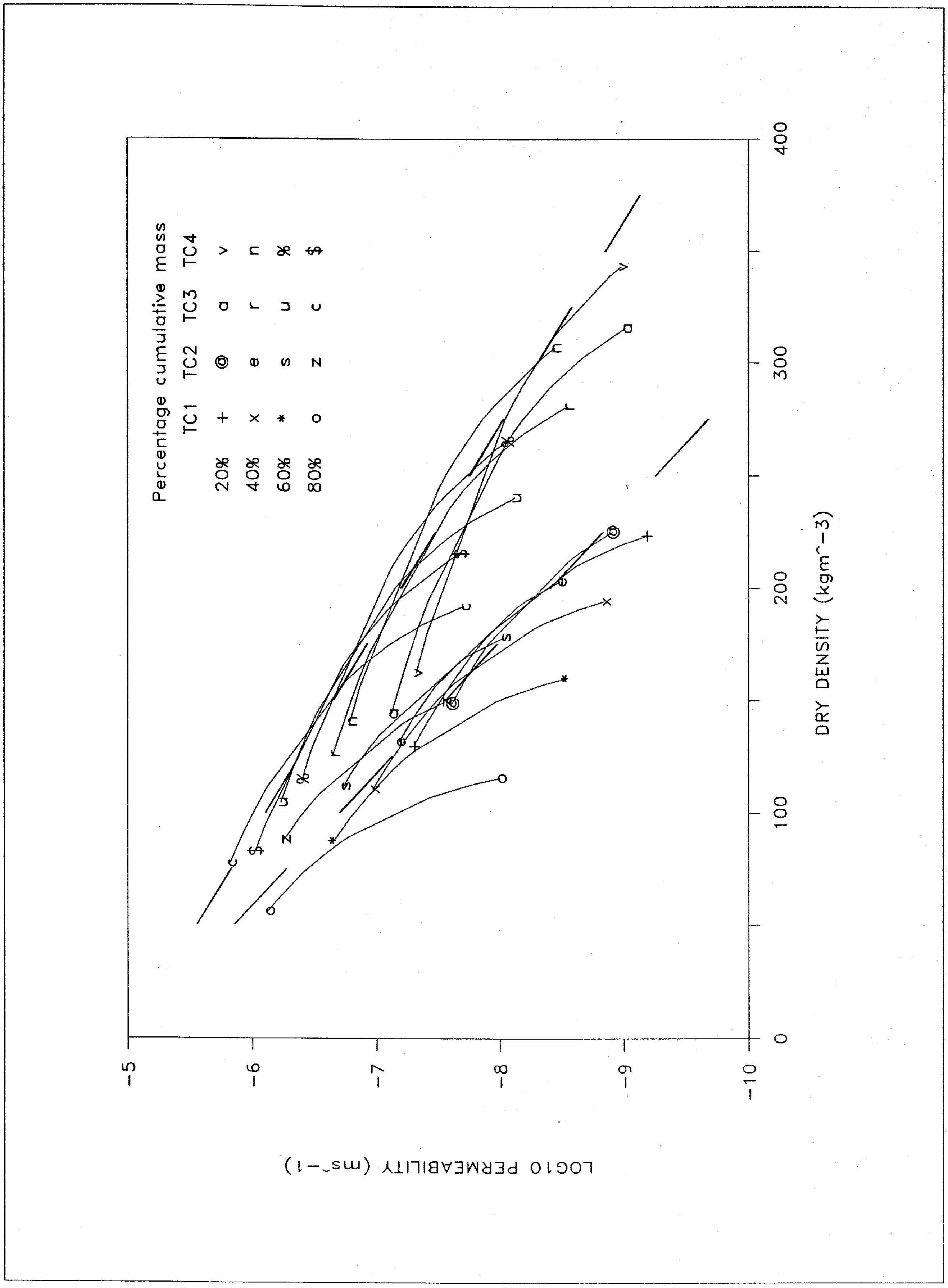

Fig 8 Permeability with density relationship

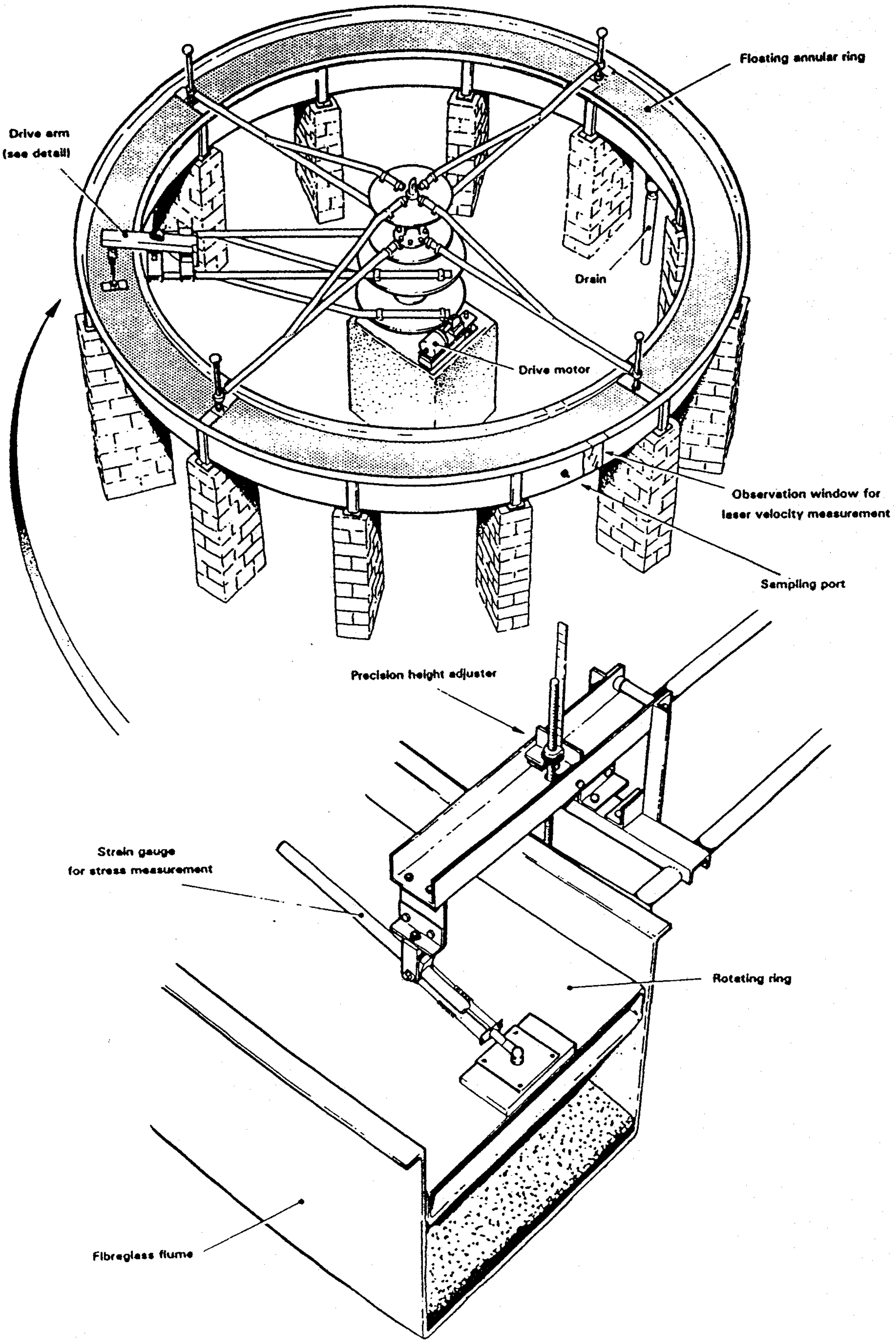

Fig 9 The carousel

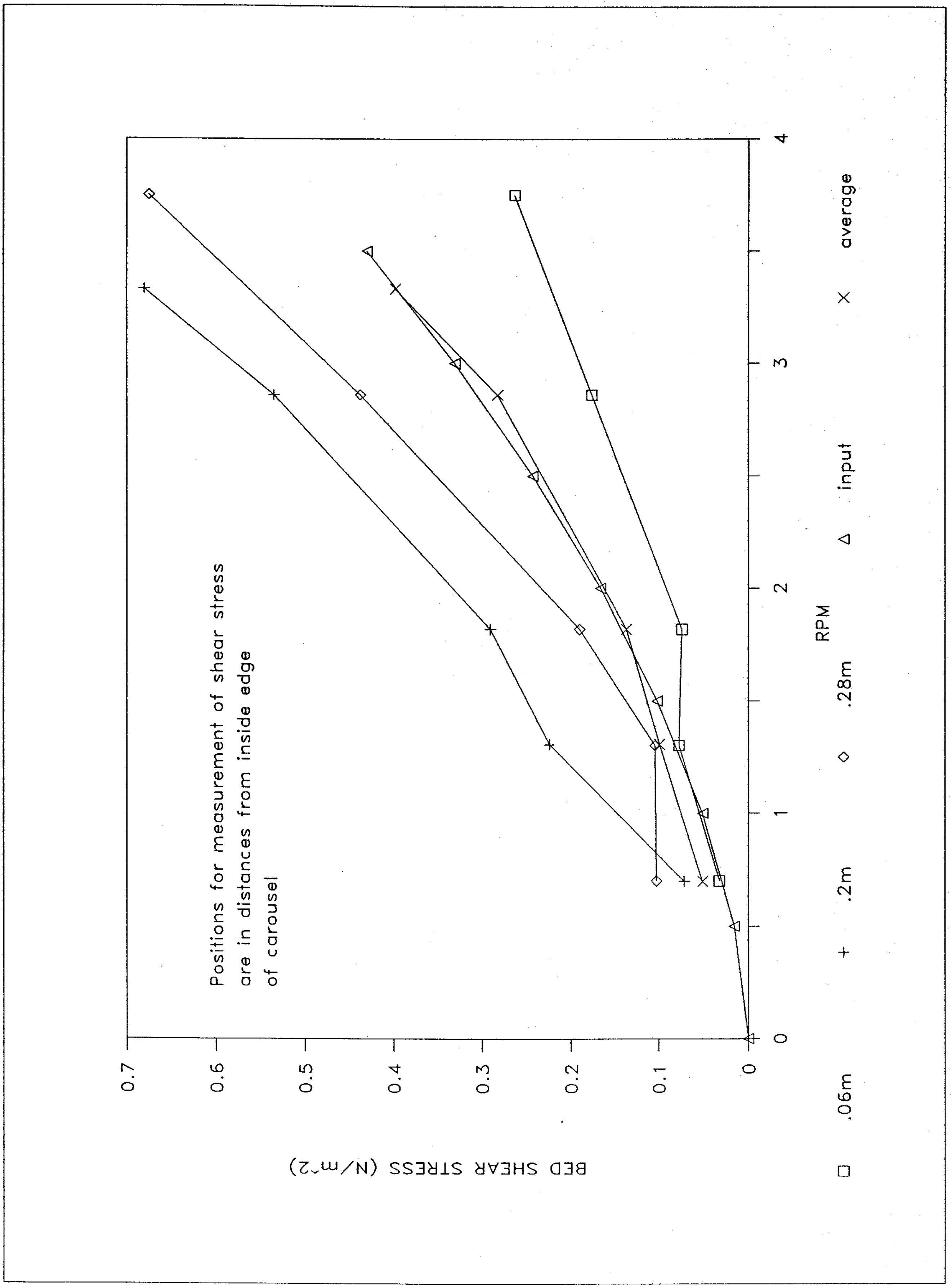

Fig 10 Average bed shear stress against roof speed

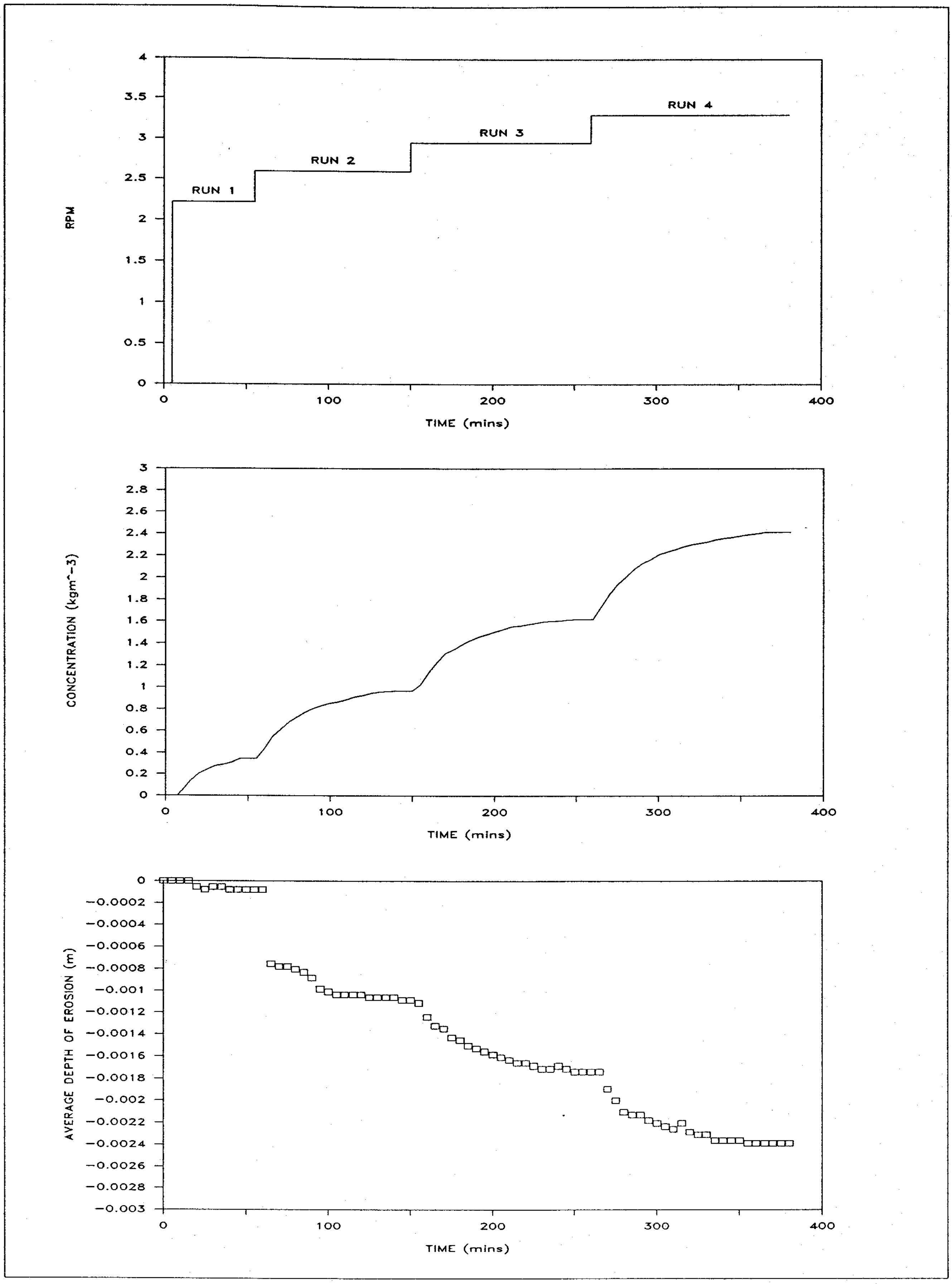

Fig 11 Roof speed Suspended solids concentration and Depth of erosion Test TE5

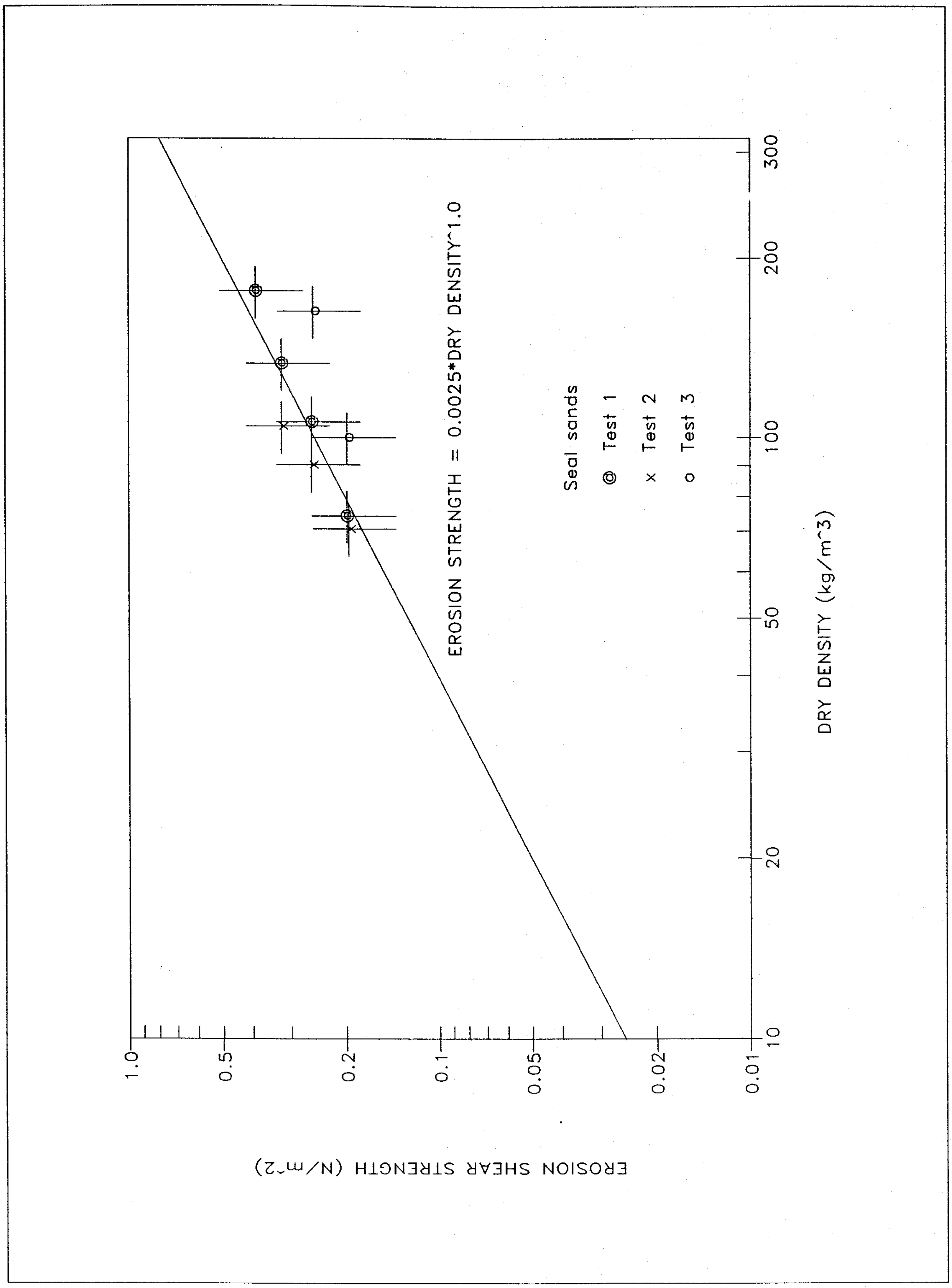

Fig 12a Shear strength with density,
erosion tests TE1, TE2 and TE3

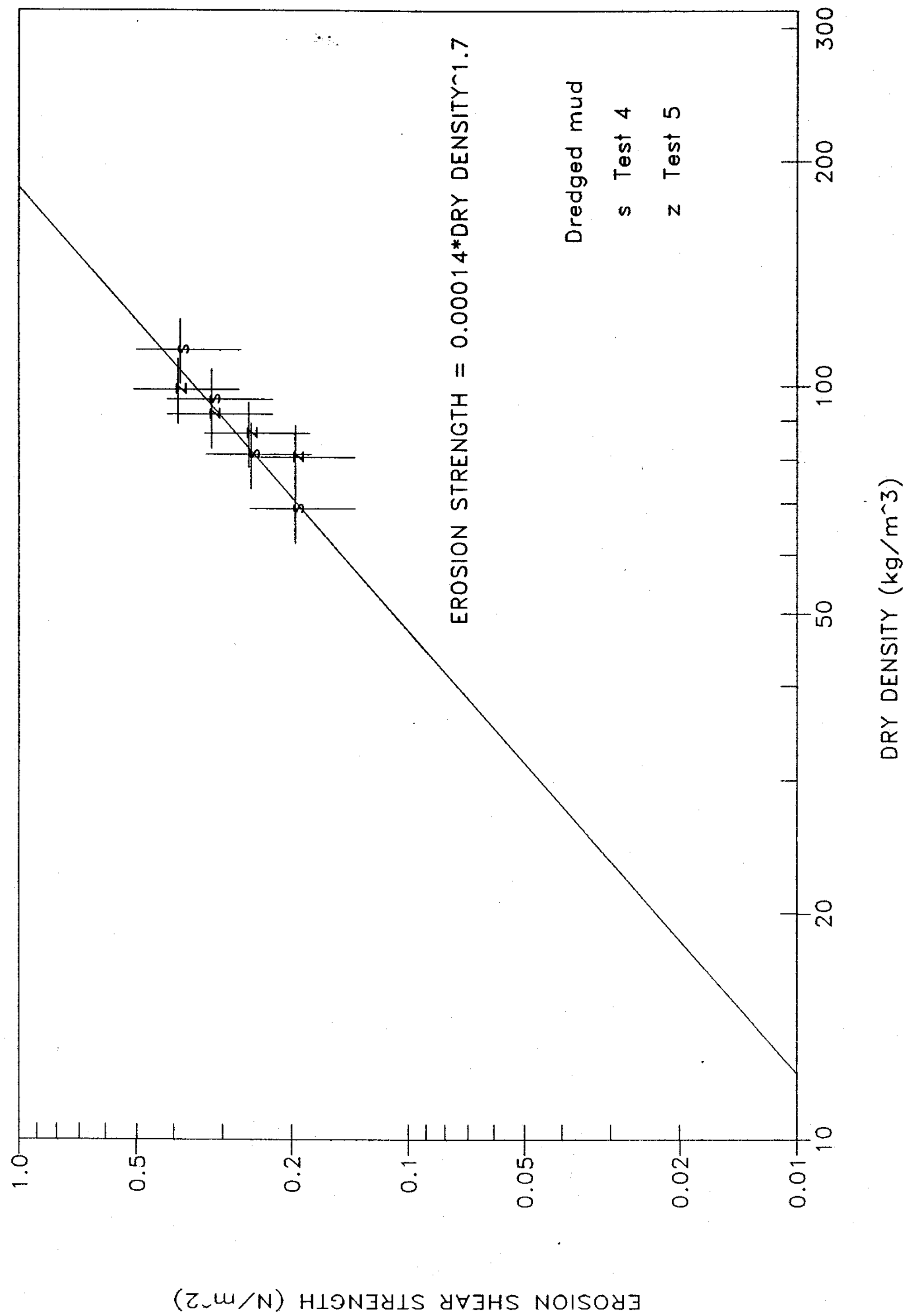

Fig 12b Shear strength with density,
erosion tests TE4 and TE5

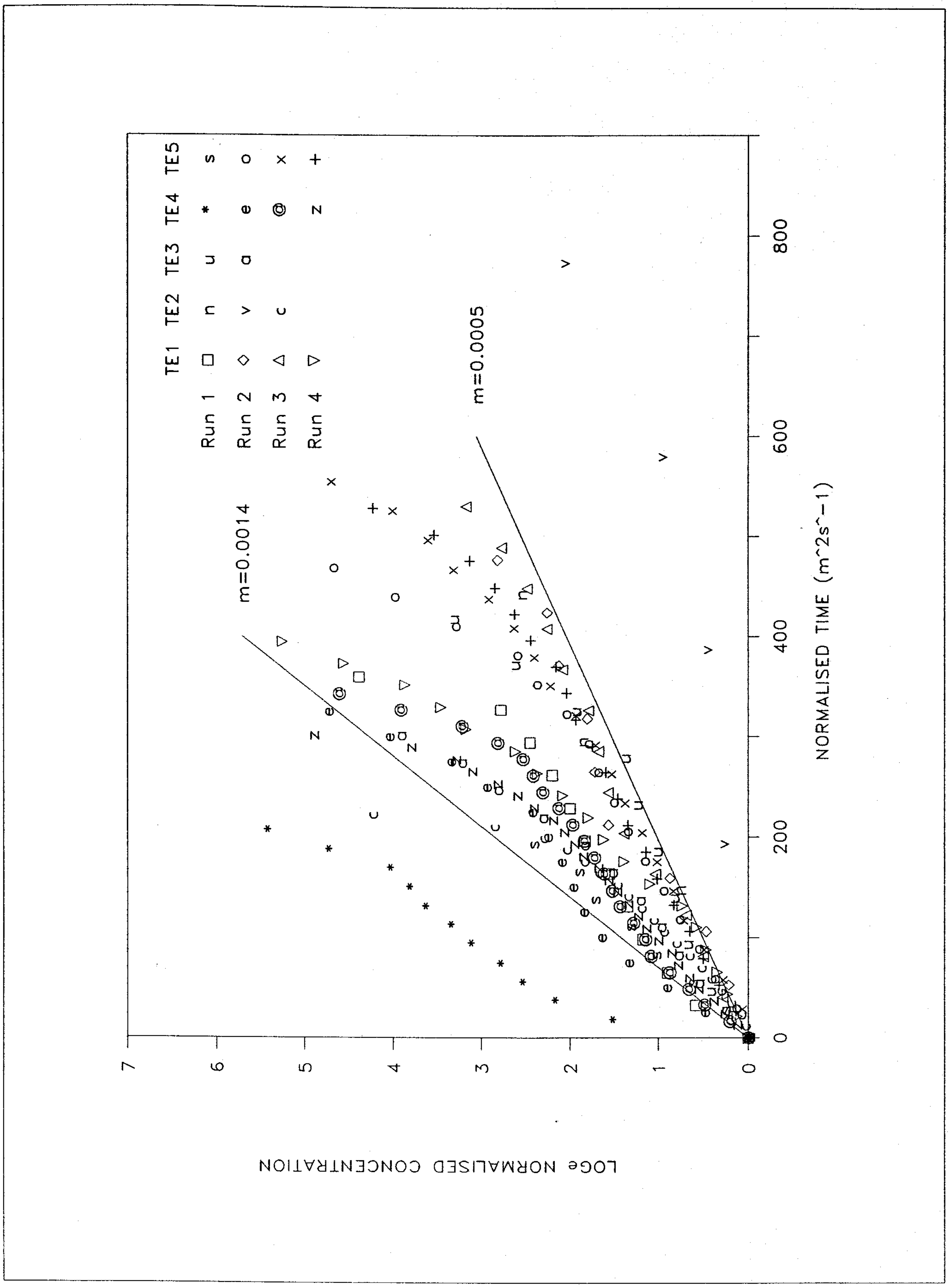

Fig 13 Normalised results of erosion rate, all erosion tests

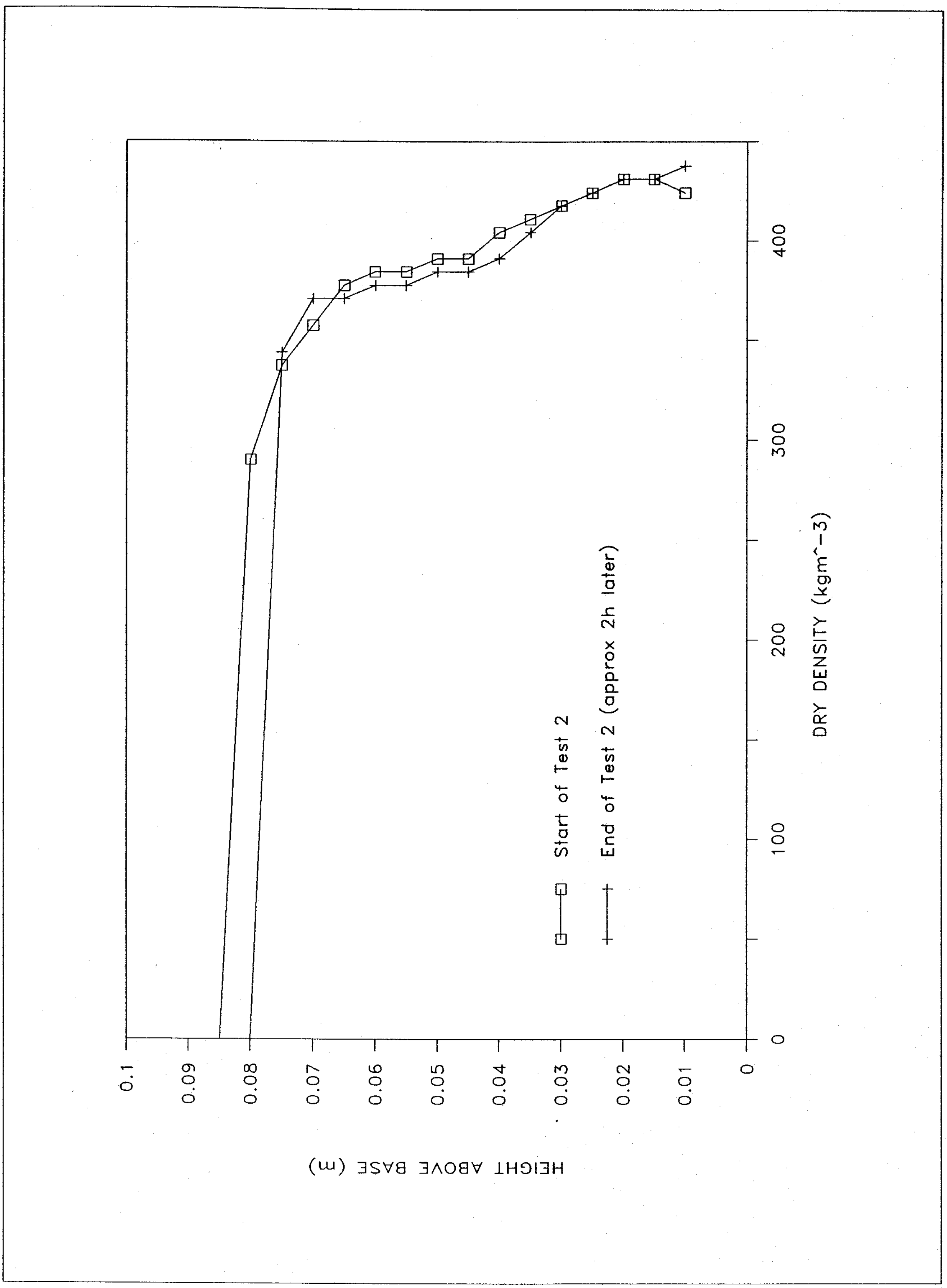

Fig 14 Density profiles of bed during wave Test 2

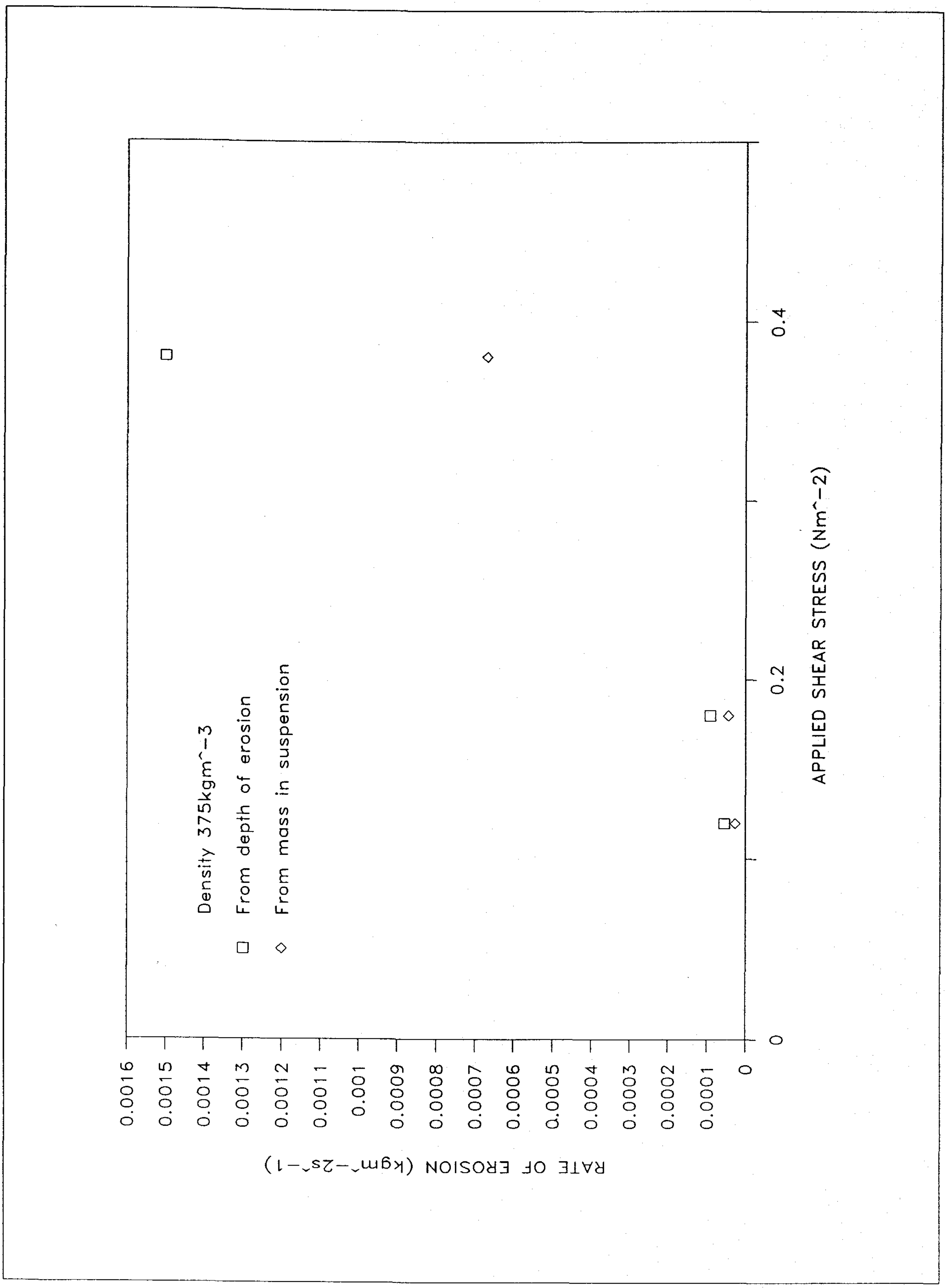

Fig 15 Erosion rate against applied shear stress, wave tests