Hydraulics Research
Wallingford

GRANGEMOUTH MUD PROPERTIES

Report SR 197
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CONTRACT

This report describes work funded by Hydraulics Research and by the Department of the Environment under Research Contract PECD 7/6/110 for which the 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 Department of the Environment. The laboratory tests were conducted by Mr I Hale of Liverpool University and by Ms M C Ockenden and Mr R J Jones in Dr E A Delo's section in the Tidal Engineering Department, under the management of Mr M F C Thorn.

ABSTRACT

Hydraulics Research (HR) and the Department of the Environment (DoE) have jointly funded research with the objective of collaborating with University and Polytechnic researchers in the field of cohesive sediments. One such collaboration was undertaken with the Department of Civil Engineering at Liverpool University, which received a two year grant from the Science and Engineering Council commencing October 1988, to study mud process modelling. Hydraulics Research had committed to provide support for this research by assisting in the testing of mud from the site at which the mud process modelling was to be investigated. Assistance was also to be given in the execution of a field survey at the site. The site chosen for the study was Grangemouth on the Firth of Forth, Scotland.

An investigation of the properties of Grangemouth mud was undertaken at Hydraulics Research by HR staff and a visiting research assistant from Liverpool University. The study comprised standard mud tests to measure the consolidation and erosion properties and new investigative techniques to determine the likely importance of other cohesive sediment transport processes.

New techniques were used to study the settling of cohesive sediment on slopes and the entrainment of fluid mud by flowing water. Both of these processes were postulated as being important in the transport mechanisms at Grangemouth. An attempt will be made to observe these processes in the field during the forthcoming survey exercise at Grangemouth. The results of the laboratory studies described in this report and the field measurements will be used in the development of a three dimensional mud transport numerical model at Liverpool University.

Sedimentology tests were undertaken to determine particle size distribution, organic content, bulk density and cation exchange capacity of the mud. Standard laboratory tests were run to determine the consolidation and erosion properties of the mud. Six consolidation tests were conducted in settling columns and empirical relationships between effective stress and dry density and between permeability and dry density were determined. Three erosion tests were conducted in the carousel flume from which an empirical relationship between erosion shear strength and dry density was found and an estimated value of the erosion constant.

New laboratory techniques were employed to study the process of deposition of sediment on slopes and the entrainment of fluid mud in flowing water. A researcher from Liverpool University conducted tests in a small tilting flume at Hydraulics Research to investigate the deposition of mud on slopes. Two mechanisms for movement of the mud down the slope were identified. The first was "density flow", which was thought to be dependent on the occurrence of hindered settling (for which the near-bed concentration needed to exceed approximately 10 gl^{-1}). The second mechanism was "bed slump", which occurred if a weak matrix of flocculated sediment, forming on the bed, exceeded a critical thickness. The critical thickness was found to be dependent on the bed slope. Re-entrainment of the moving bed layer into the overlying suspension and erosion of the underlying mud bed, by the moving bed layer, were not observed in the experiments. Bed slump was considered to be the main mechanism for down the slope transport of mud.

Tests were conducted in the carousel flume to investigate the entrainment of fluid mud by flowing water. It was intended to examine the importance of the bulk Richardson number in determining the critical conditions for entrainment. However, it was found to be generally difficult to generate in the carousel the desired initial conditions of a fluid mud layer beneath an overlying less concentrated suspension. Nevertheless, instabilities were seen in the form of interfacial waves between the fluid mud and overlying flowing suspension in some of the tests.

Grangemouth Mud Properties SR197 25.9.89

ERRATA

p5 Equation (8) $m_e = 0.0002\text{-}0.0006 kgN^{-1}s^{-1}$ should read
$m_e = 0.0005\text{-}0.0014 kgN^{-1}s^{-1}$

p5 The individual runs...lower end of this range ($m_e \approx 0.0002 kgN^{-1}s^{-1}$)
should read
The individual runs...lower end of this range ($m_e \approx 0.0005 kgN^{-1}s^{-1}$)

p9 Equation (8) $m_e = 0.0002\text{-}0.0006 kgN^{-1}s^{-1}$ should read
$m_e = 0.0005\text{-}0.0014 kgN^{-1}s^{-1}$

Fig 8 Vertical scale (previously 0.0-2.0) should cover range 0.0 - 4.6

Fig 8 Labels on lines: m = 0.0006 should read m = 0.0014
m = 0.0003 should read m = 0.0008
m = 0.0001 should read m = 0.0002

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1 INTRODUCTION

Hydraulics Research (HR) and the Department of the Environment (DoE) have jointly funded research with the objective of collaborating with University and Polytechnic researchers in the field of cohesive sediments. One such collaboration was undertaken with the Department of Civil Engineering at Liverpool University, which received a two year grant from the Science and Engineering Council commencing October 1988, to study mud transport modelling. Hydraulics Research provided support for this research by assisting in the testing of mud from the site at which the mud transport modelling was to be investigated. Assistance was also given in the execution of a field survey at the site. The site chosen for the study was Grangemouth on the Firth of Forth, Scotland.

The investigation of the properties of Grangemouth mud was undertaken at Hydraulics Research by HR staff and a visiting research assistant from Liverpool University. The study involved sedimentology tests to determine particle size distribution, organic content, bulk density and cation exchange capacity of the mud. Standard laboratory tests were run to determine the consolidation and erosion properties of the mud. In addition, other laboratory tests were conducted to study the process of deposition of sediment on slopes (Liverpool University researcher) and the entrainment of fluid mud in flowing water.

Forth Ports Authority collected six drums of mud samples by a dredger from the entrance to Grangemouth Docks on 10 November 1988 (Fig 1). The drums were transported by courier to Hydraulics Research. The laboratory test were conducted between November 1988 and January 1989.

2 CHARACTERISATION OF THE MUD

Bulk densities were determined on mud samples from each of the six drums. The densities were 1440, 1360, 1350, 1370, 1350 and 1350kgm^{-3} for drums 1 to 6 respectively. The average value of 1370kgm^{-3} represents a dry density of approximately 600kgm^{-3}.

The particle size distribution for all six drums is shown in Figure 2. This shows that the percentage by weight of silt (ie $\leq$ 63 microns in diameter) in each drum is between 80 - 90%, with the remainder being fine sand.

The organic content of samples from the six drums was obtained by the acid digestion method. This gave an organic content in the range 4.7 - 5.5% for all six drums.

The cation exchange capacity was measured on the sub 20 micron fraction, which contains the clay minerals. This was in the range 18.8 - 20.3meq/100g for all six drums.

3 CONSOLIDATION TESTS

Laboratory tests were conducted in settling columns to investigate the consolidation properties of the mud (see Ref 1 for a detailed description of the procedure). Each test involved the continuous deposition of a mud bed from a suspension with a constant mud concentration. This suspension was injected into a column over a period of some hours. Bed thickness, excess pore pressures and density profiles were recorded frequently over a number of days until bed consolidation was nearly complete. The mud used throughout the deposition tests came from drum 6. Table 1 summarises the input conditions of the six consolidation tests.

In each test the thickness of the bed reached a peak soon after the end of the input phase, when virtually all the material had settled out of suspension. The bed thickness then decreased with time, quickly at first but tailing off to a constant value which corresponded to near complete consolidation (Fig 3).

Figure 4 shows the final observed densities for each test against depth from the bed surface. The points show some scatter but indicate a trend of increasing density with depth.

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. The percentage mass points were 20% (ie the point in the bed with 20% of the total mass beneath it), 40%, 60%, 80% and 100%. The effective stress at each of these points (total stress minus excess pore pressure) is then calculated. Figure 5 shows the relationship between effective stress and dry density for these percentage mass points. A line of best fit by eye was drawn through the points and had the equation:

$$\sigma' = 5 - 0.05\rho_d + 0.00055\rho_d^2 \qquad (1)$$

in the range $50 \le \rho_d \le 350\text{kgm}^{-3}$

where

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

The density of the upper layer during formation of the bed was approximately $50kgm^{-3}$.

A relationship between permeability and dry density was also determined (Fig 6). The same percentage mass points (20% mass below, 40%, 60%, 80% and 100%) were used, with permeability and density calculated for these points. A line of best fit by eye through the points had the equation:

$$\log(k) = -0.01\rho_d - 5.00 \qquad (2)$$

where

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

4 EROSION TESTS

Three erosion tests were conducted in the carousel, on mud from drum 6. The mud was first mixed homogeneously in a mixing tank and then pumped into the carousel. Before each test the mud was mixed into suspension by hand and then allowed to deposit and consolidate. Two tests were run with 2.7 days consolidation and one with 7 days consolidation.

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 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 at first increases rapidly (indicating strong erosion), then the rate of increase tails off until the concentration remains nearly constant (no further 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 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.

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 method of analysis of the data is documented in detail in Ref 1. The shear strength of the exposed bed surface against density is plotted for the three tests in Figure 7. A best fit line through the data gives a relationship of

$$\tau_e = 0.0045\rho_d^{0.9} \qquad (3)$$

where

τ_e = shear strength of mud (Nm^{-2})
ρ_d = dry density of mud (kgm^{-2})

The most common representation of erosion is

$$dm/dt = Am_e(\tau-\tau_e) \qquad \text{for } \tau \geq \tau_e \qquad (4)$$

where

dm/dt = rate of erosion ($kgm^{-2}s^{-1}$)
m_e = erosion constant ($kgN^{-1}s^{-1}$)
τ = applied shear stress (Nm^{-2})

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 2). The constant of proportionality for a run is given by

$$\alpha = (\tau_b-\tau_o) / (c_e-c_o) \qquad (5)$$

where

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

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

If it is further assumed that the erosion rate for the exposed mud surface area is given by equation (4) we obtain, using (5) and replacing m by cV

$$dc/dt = Am_e\alpha(c_e-c_o)/V \qquad (6)$$

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

$$(c_e-c_o) = (c_e-c_o)\ \exp\ (-Am_e\alpha t/V) \qquad (7)$$

This solution exhibits the expected behaviour of concentrations, tending to equilibrium values for large times. Based on the analytic form of this theoretical solution, the carousel erosion flume results for a test can be normalised and plotted using linear 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.

Figure 8 shows the normalised results of erosion rate for the three tests together. The erosion constant, m_e, was in the range

$$m_e = 0.0002\text{-}0.0006kgN^{-1}s^{-1} \qquad (8)$$

The individual runs in each test varied within this range, with the runs in test 3 (7 days settling) being in the lower end of this range ($m_e \approx 0.0002kgN^{-1}s^{-1}$), and the runs in tests 1 and 2 in the higher end of the range.

5 DEPOSITION ON SLOPES

The researcher from Liverpool University conducted tests to investigate the deposition of mud on slopes. Full details of the tests, with results and discussion, are given in Appendix A and are only summarised here.

The tests were run at HR in a tilting flume, 2.30m long, 0.15m wide and 0.40m deep. The flume could be jacked up at one end to give the desired bed slope. A range of bed slopes from 1:10 to 1:50 was covered. The concentration of suspended sediment was chosen to cover a range of likely field concentrations. Bed thicknesses with time were recorded at six stations along the slope.

Settling column tests, with the same suspension concentrations, were run parallel to the flume tests to determine resulting bed thicknesses where no lateral movement was involved.

Two mechanisms for movement of the mud down the slope were identified. The first was "Density Flow", a horizontal density gradient which caused settling particles to be deflected in the downslope direction. This was thought to be dependent on the occurrence of hindered settling, for which the near-bed concentration needs to exceed approximately $10gl^{-1}$. This mechanism was considered to be of minimal significance in typical field conditions.

The second mechanism was "Bed Slump", which occurs if a weak matrix of flocculated sediment, forming on the bed, exceeds a critical thickness. This weak matrix (a Bingham fluid), usually called "fluid mud", may form if the sediment is settling at a rate which exceeds the formation of the bed (ie faster than the water is being expelled from the bed). The critical thickness is dependent on the bed slope (Fig 18 in Appendix). Bed slump was thought to be the main mechanism for the downslope transport of mud.

Re-entrainment of mud particles from the moving bed and erosion of the bed below the moving layer were not observed in the experiments but are discussed in Appendix A, along with suggestions for further work.

6 ENTRAINMENT TESTS

6.1 Objectives

The aim of the work was to look at the conditions for the formation of fluid mud and the parameters determining its re-erosion or entrainment. In particular, from HR report SR 147 (Ref 3), two relationships are suggested and the laboratory tests attempted to investigate these relationships. They were:

"The overlying water will entrain mud from the fluid mud layer if the bulk Richardson number Ri_B is less than 10, where

$$Ri_B = \frac{\Delta\rho \; g \; d_m}{(\Delta U)^2} \qquad (9)$$

and

$\Delta\rho$ = density difference between fluid mud and suspension (kgm^{-2})
g = acceleration due to gravity (ms^{-2})
d_m = thickness of fluid mud layer (m)
ΔU = velocity difference between fluid mud and suspension (ms^{-1})

"The vertical flux of mud entrained from the mud layer is assumed to be similar to that for salt in a saline wedge:

$$\frac{dm}{dt} = -V_e C_o \quad (kgm^{-2}s^{-1}) \quad \text{when } Ri_B < 10 \qquad (10)$$

where

$$V_e = \Delta U \frac{0.1}{(1 + 63\, Ri_B^2)^{3/4}} \qquad (11)$$

C_o = constant concentration in fluid mud layer

6.2 Details of tests

Using the mud suspension which was already in the carousel, tests were run in which the mud was allowed to settle from suspension for short periods (10mins to 1 hour) and then the roof speed (and hence shear stress) was increased gradually to see when the mud started to erode/be entrained. Irrespective of how long the mud had settled or the rate of increase of shear stress, at a roof speed corresponding to 1.4V (1.0rpm, approx. $0.05Nm^{-2}$) the mud began to be entrained and the concentration in suspension rose. Just prior to this, the interface between the fluid mud (or bed) and the overlying suspension began to become unstable, with waves passing along the surface, increasing in size, and finally breaking the surface. From previous measurements of velocity made with a laser, the horizontal velocity of the overlying suspension at this time on the outside edge of the carousel was approximately $0.13ms^{-1}$ at the interface between the fluid mud and overlying suspension.

The concentration continued to rise as long as the roof speed was increasing. Tests in which the roof speed was held constant (with an applied voltage greater than 1.4V) also showed an initial rise in concentration as the mud started to erode, but this reached a peak after about 10 minutes and then started to drop again. The interface also appeared to stabilise again, with waves no longer visible. The drop in concentration may be due to the material being swept to the inside of the carousel by the secondary flow, or it could be due to some other process.

An attempt was then made to create conditions with different Richardson numbers, by trying to change $\Delta\rho$ and d_m. This was done in a settling column, as changing these parameters in the carousel is a major operation, and it was necessary to be sure that it was going to work before going ahead with this. Starting with a column filled to the same depth as the carousel (0.110m) and with the same concentration ($\approx$40kgm^{-3} mud), the density of the forming bed was measured both just above and just below the interface, and at several points in the bed.

Tests were then run in an attempt to change the density profile by adding a small amount of very concentrated suspension. The concentration in this suspension was calculated to increase the thickness of the bed by 5mm after one hour, whilst leaving the depth of suspension above the bed as close to 0.1m as possible. The resulting density profiles from these tests indicated that the bed was forming with a definite density profile, rather than a layer of nearly constant density as previously suggested (see Refs 3 and 4). The density difference between the top of the "bed" and the overlying suspension was not easy to determine, because of the changing profile down the bed and down the water column. No obvious change in $\Delta\rho$ could be picked out from these tests. In addition, the depth of the fluid mud layer remained unclear, as the density profile showed that no layer of constant density was being formed in these conditions.

These tests suggest that the conditions in the carousel are not particularly good for creating fluid mud. Disadvantages may be the shallow settling depth, or the range of concentrations investigated. Dewatering of the fluid mud (if it exists) appears to happen too quickly in the carousel.

6.3 Recommendations

It would be useful to run further tests with the mud settling from a greater depth than that in the carousel. These would show if it is possible to create a situation where a layer of constant density is formed, which dewaters more slowly than for the tests in the carousel. The critical value of the Richardson number has still not been checked because the carousel is not suitable for determining either the thickness of the "fluid" mud or the density difference between the mud and the overlying suspension.

7 CONCLUSIONS

1. An investigation of the properties of Grangemouth mud was undertaken at Hydraulics Research. The mud was collected by the Forth Ports Authority (Fig 1). The study involved sedimentology tests to determine particle size distribution, organic content, bulk density and cation exchange capacity of the mud. Standard laboratory tests were run to determine the consolidation and erosion properties of the mud. In addition, other laboratory tests were conducted to study the process of deposition of sediment on slopes (Liverpool University researcher) and the entrainment of fluid mud in flowing water.

2. The average bulk density of the mud in the six drums was $1370kgm^{-3}$. Between 80-90% of the mud was silt sized particles and the remainder was fine sand (Fig 2). The organic content was approximately 5% and the cation exchange capacity was approximately 20meq/100g.

3. Six consolidation tests were conducted in settling columns. An empirical relationship (Fig 5) between effective stress (σ') and dry density (ρ_d) was found to be:

   $$\sigma' = 5 - 0.05\rho_d + 0.00055\rho_d{}^2 \qquad (1)$$

   The formation density of the upper layer was found to be approximately $50kgm^{-3}$. An empirical relationship (Fig 6) between permeability (k) and dry density (ρ_d) was found to be:

   $$\log (k) = -0.01\rho_d - 5.00 \qquad (2)$$

4. Three erosion tests were conducted in the carousel flume. An empirical relationship between erosion shear strength (τ_e) and dry density (ρ_d) (Fig 7) was found to be:

   $$\tau_e = 0.0045\rho_d{}^{0.9} \qquad (3)$$

   The erosion constant (m_e) was calculated (Fig 8) to be in range:

   $$m_e = 0.0002\text{-}0.0006kgN^{-1}s^{-1} \qquad (8)$$

5. The researcher from Liverpool University conducted tests in a tilting flume to investigate the deposition of mud on slopes. Two mechanisms for movement of the mud down the slope were identified. The first was "Density Flow", which

was thought to be dependent on the occurrence of hindered settling (for which the near-bed concentration needs to exceed approximately $10gl^{-1}$). The second mechanism was "Bed Slump", which occurs if a weak matrix of flocculated sediment, forming on the bed, exceeds a critical thickness. The critical thickness is dependent on the bed slope (Fig 18 in Appendix). Bed slump was considered to be the main mechanism for the downslope transport of mud.

6. Tests were conducted in the carousel flume to investigate the entrainment of fluid mud by flowing water. It was found that the carousel was not particularly good for generating fluid mud. It was recommended that greater depths of flow than those in the carousel could be investigated.

8 ACKNOWLEDGEMENT

The assistance of the Forth Ports Authority in the collection of the mud samples is gratefully acknowledged.

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TABLES

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

Test No.	Concentration of mud input suspension	Rate of input	Duration of input	Deposition rate	Bed thickness at end of test
	(kgm^{-3})	(m^3h^{-1})	(hours)	(kgm^{-2})	(mm)
GC1	12.93	0.0026	2	5.02	42
GC2	12.11	0.0031	2	5.73	44
GC3	11.98	0.0038	2	6.80	47
GC4	15.78	0.0013	4	3.07	44
GC5	12.26	0.0044	2	8.13	50
GC6	11.42	0.0025	4	4.33	69

FIGURES

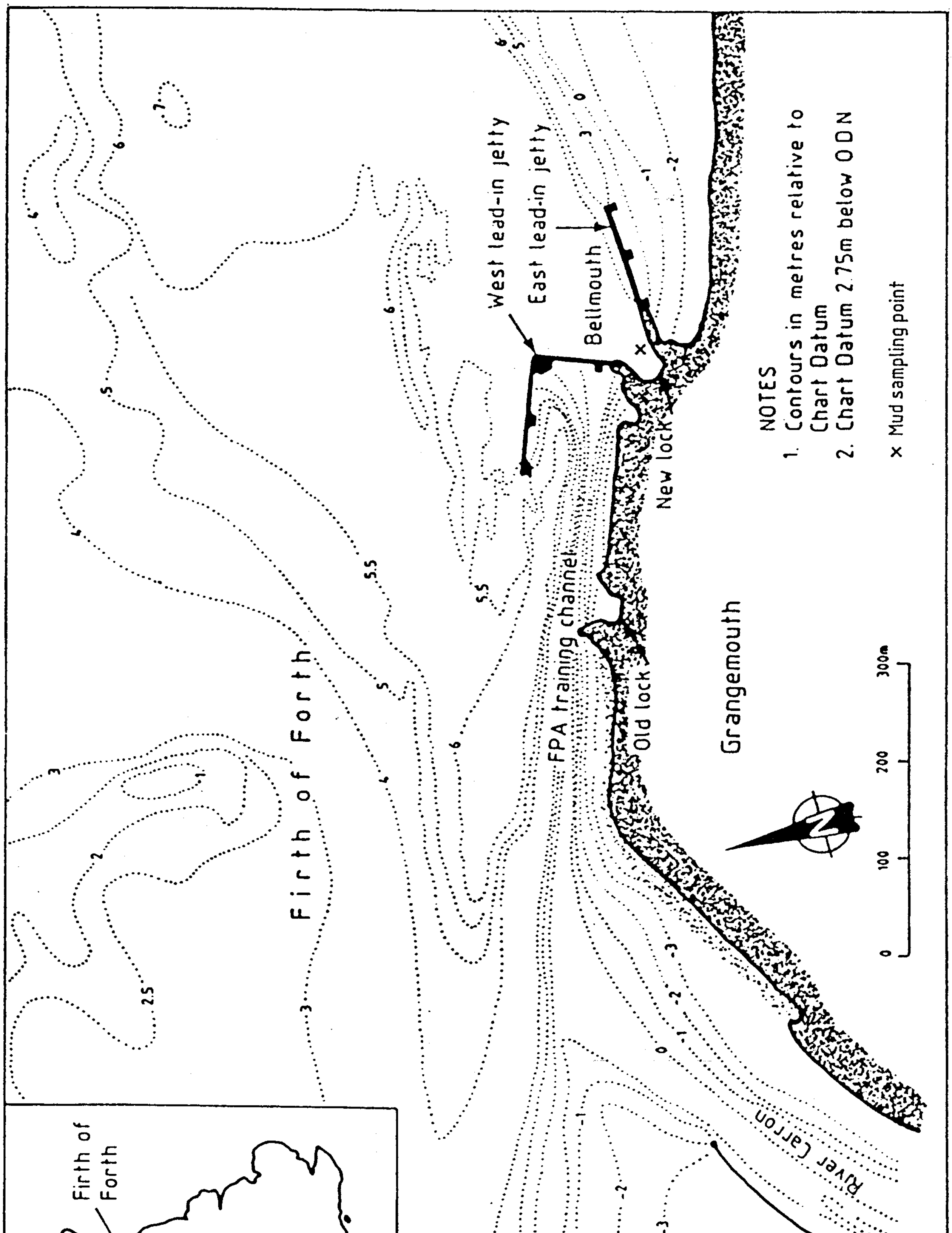

Fig 1 Location map of Grangemouth Docks and mud sampling point

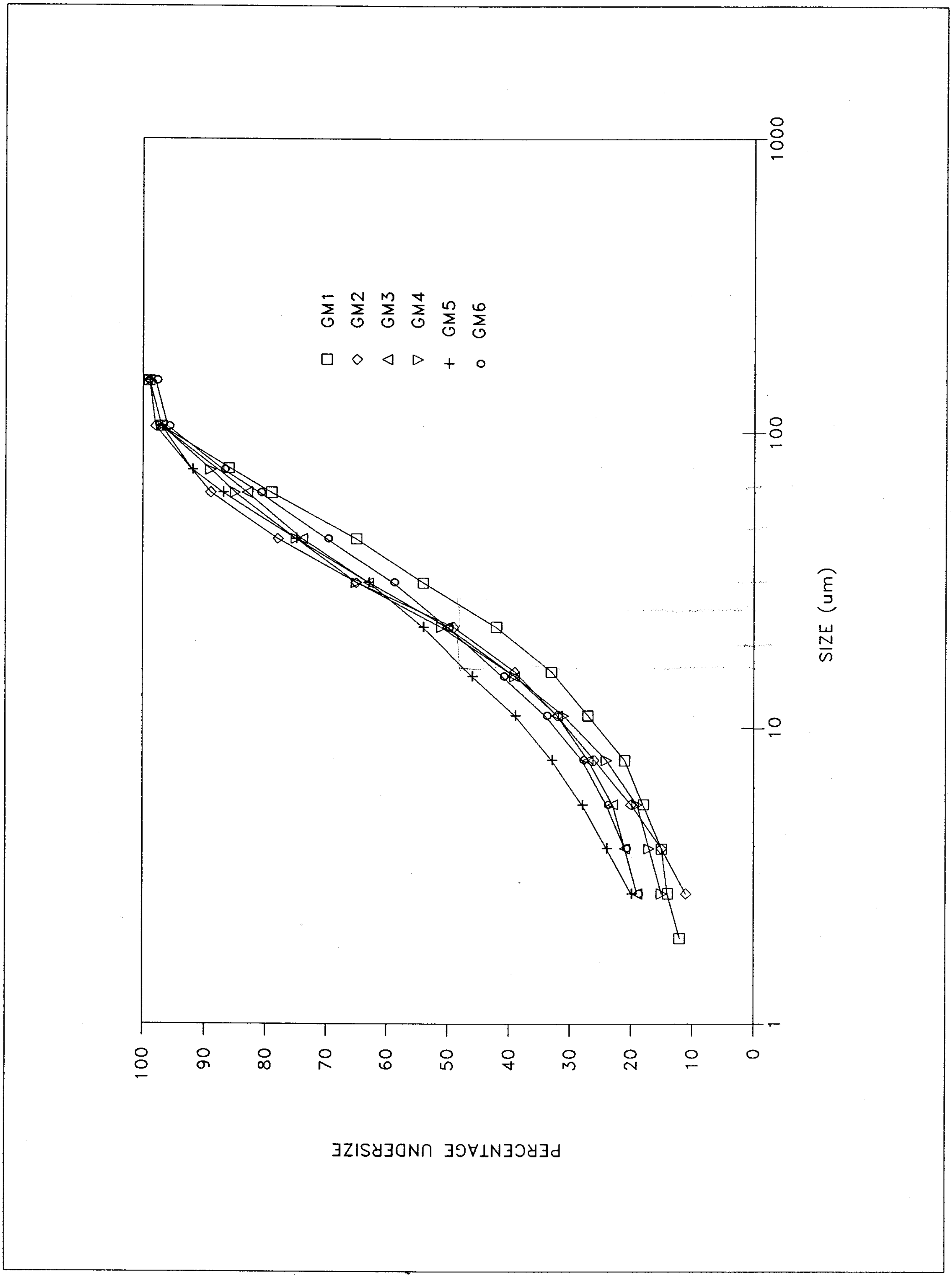

Fig 2 Particle size grading

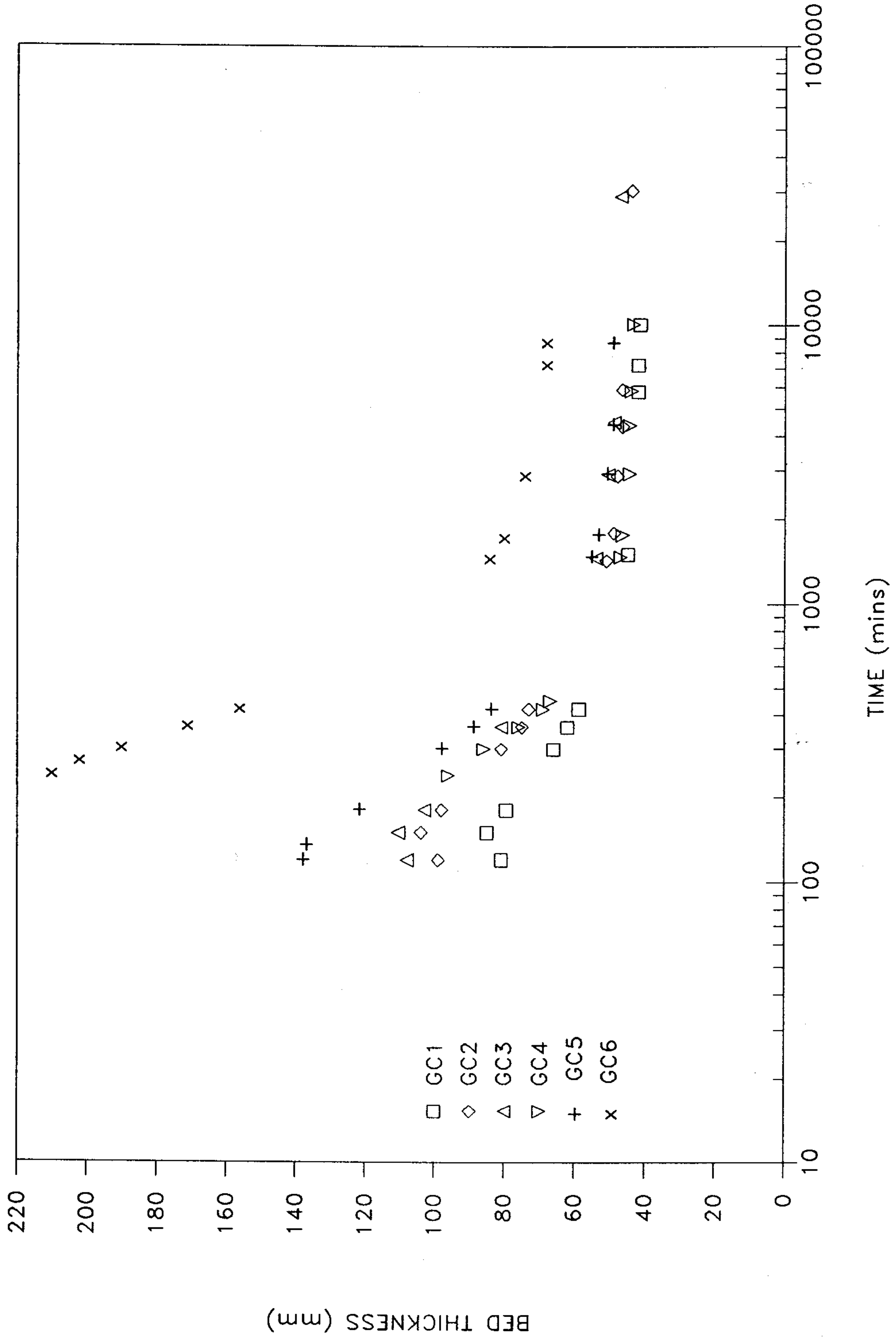

Fig 3   Variation of bed thickness with time
All tests

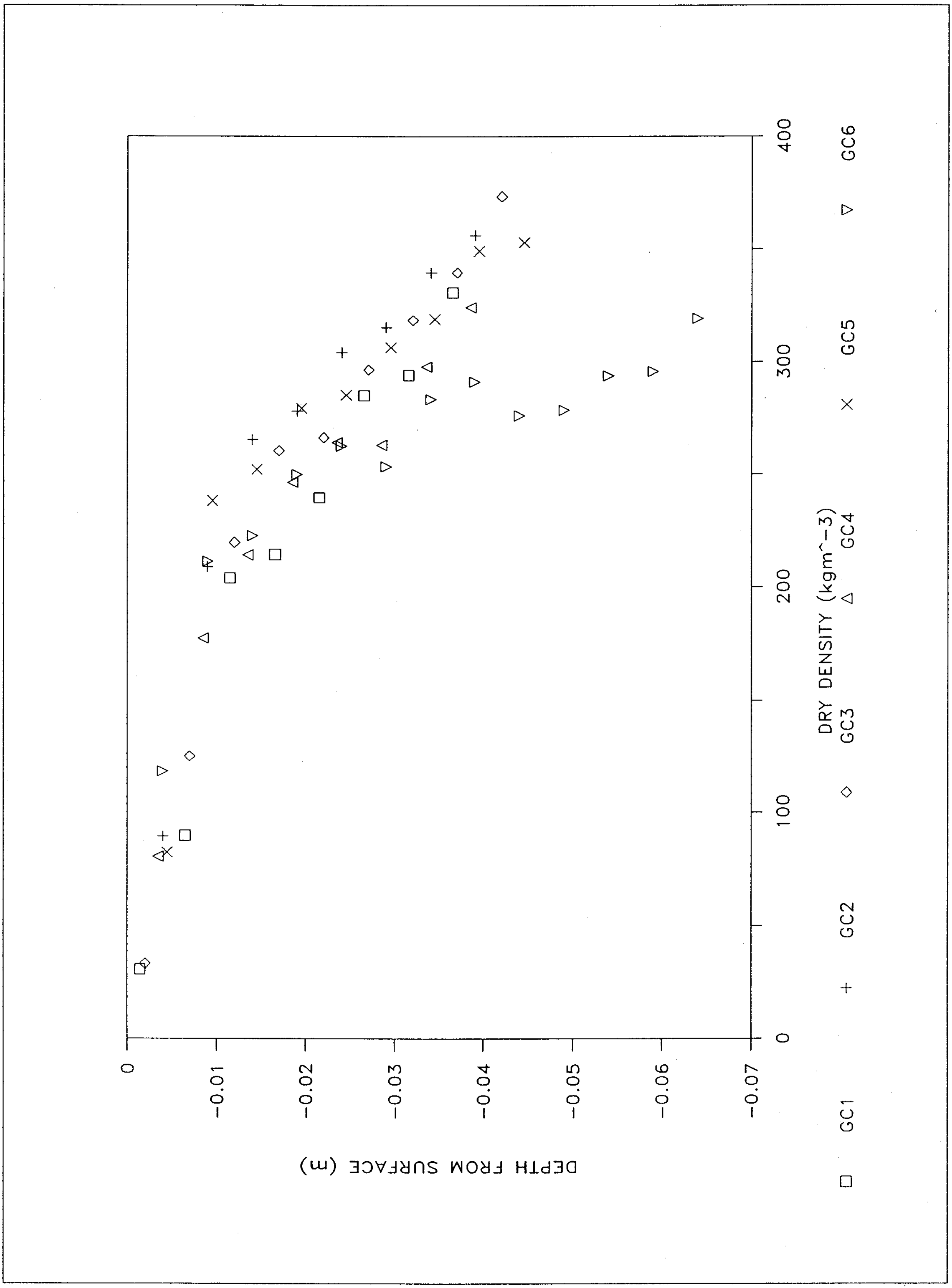

Fig 4 Final density against depth from surface
All tests

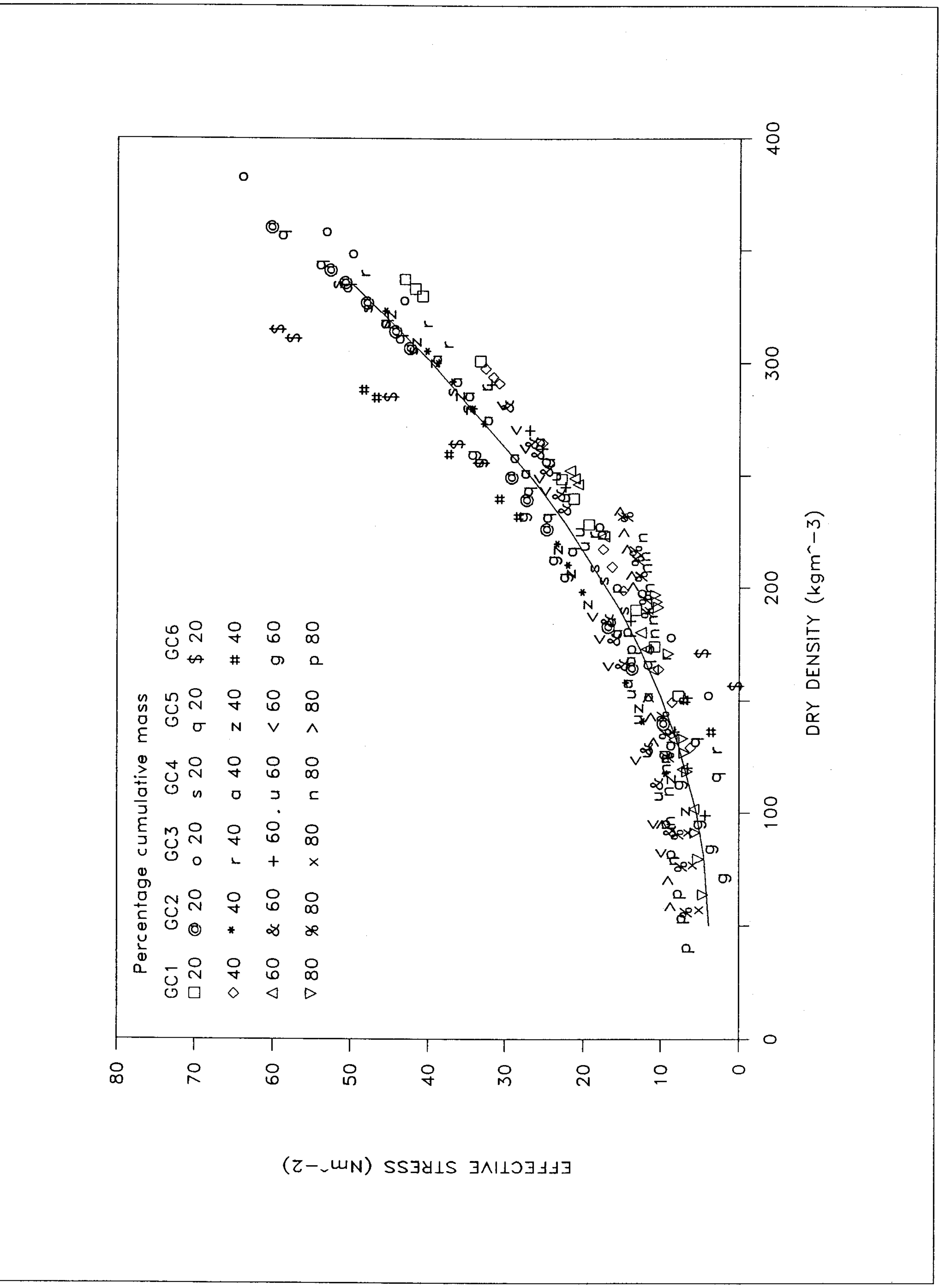

Fig 5 Effective stress with density relationship

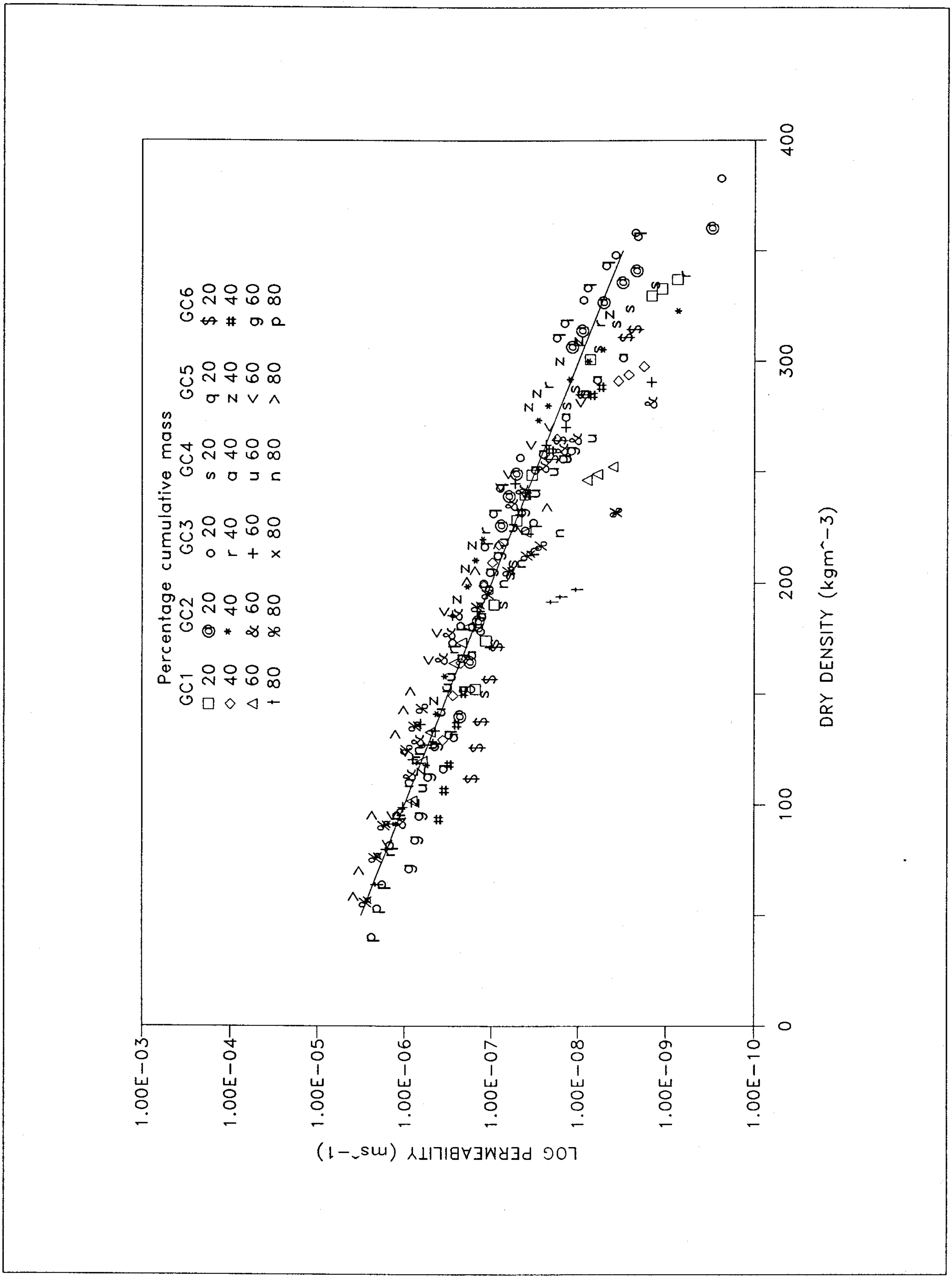

Fig 6   Permeability with density relationship

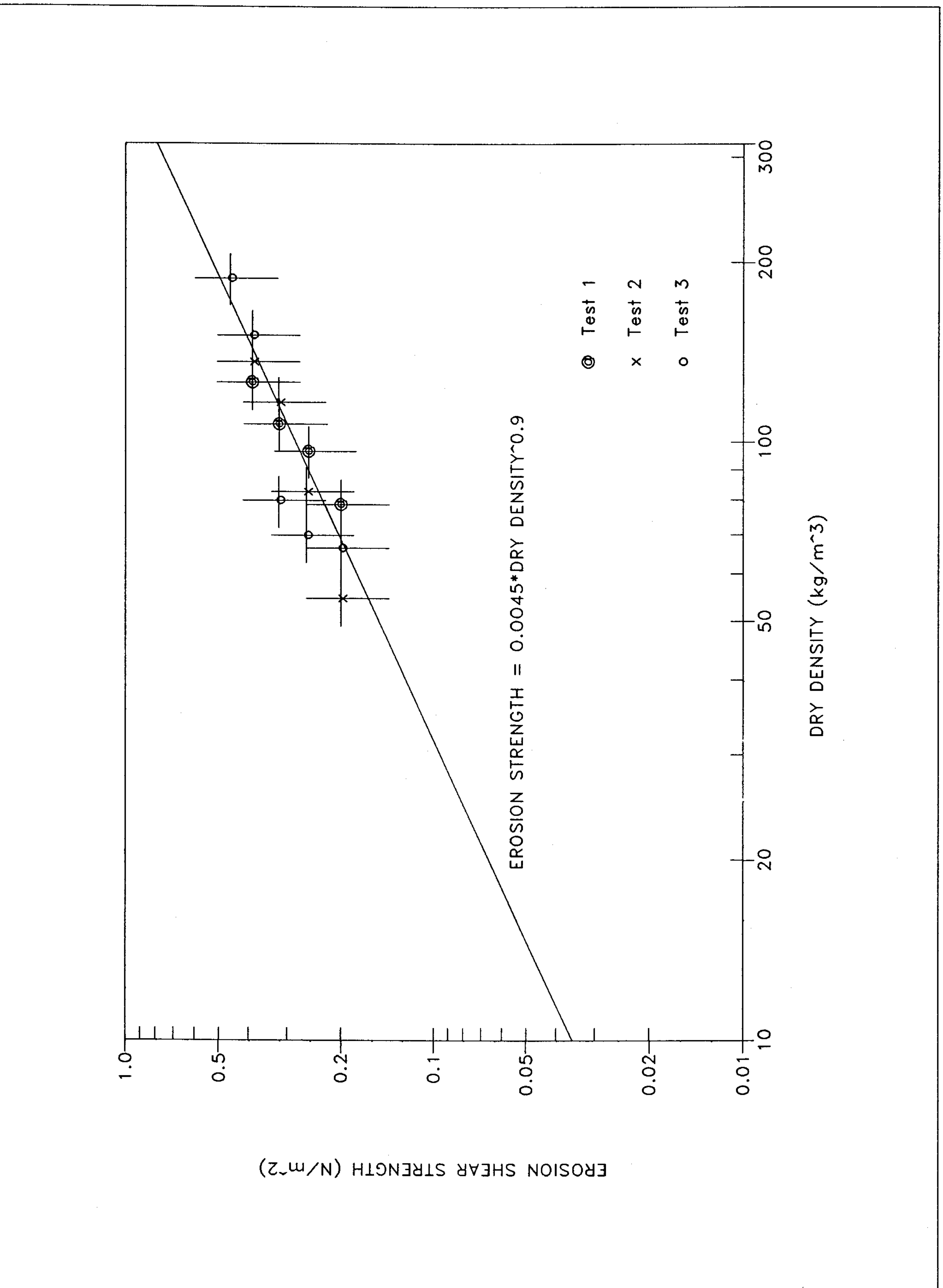

Fig 7 Shear strength with density
Erosion tests 1, 2 and 3

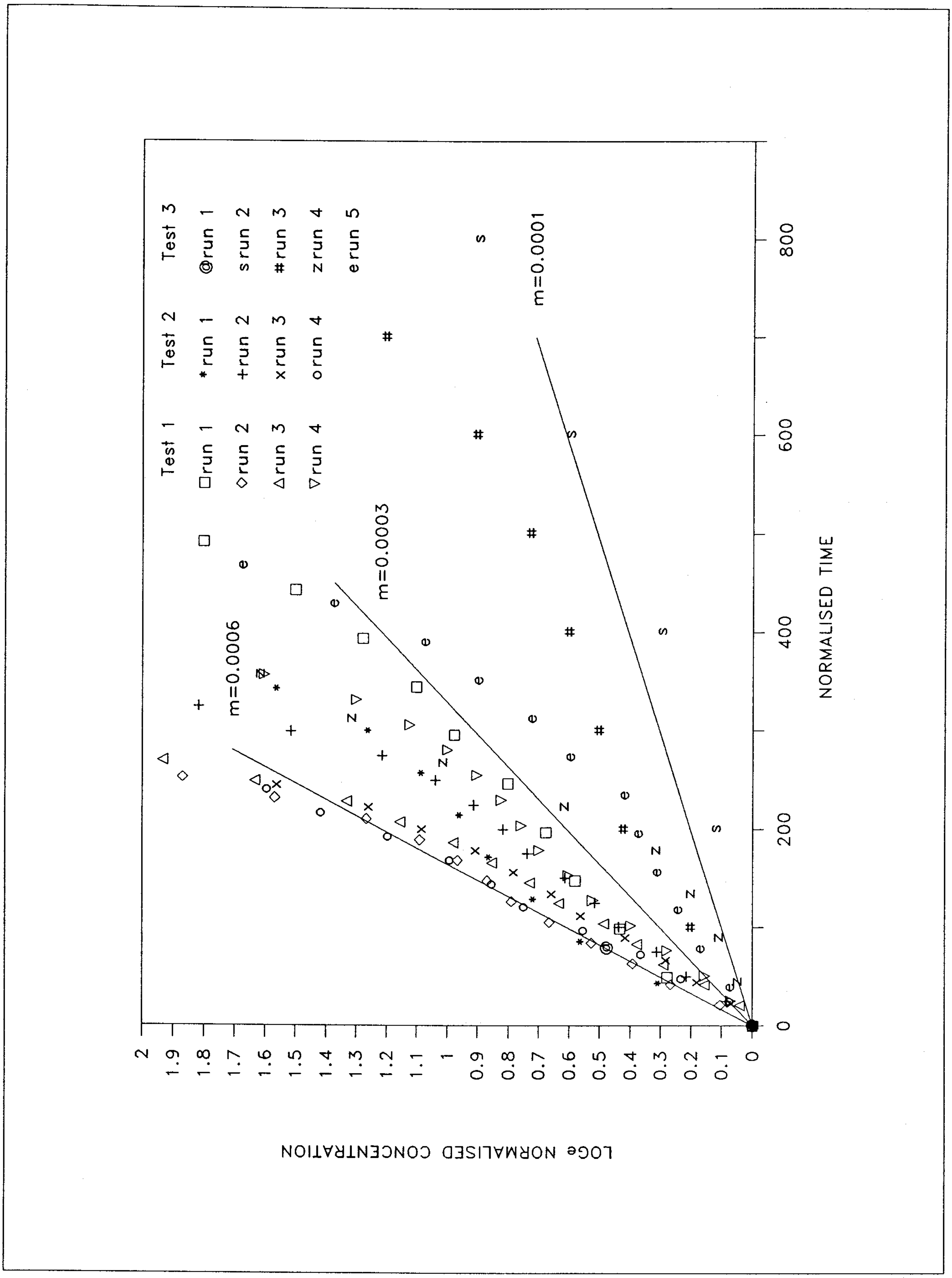

Fig 8 Normalised results of erosion rate
Erosion tests 1, 2 and 3

APPENDIX

'The behaviour of mud suspensions as they settle on to a sloping bed: an experimental investigation'.

by

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1. Introduction

Over recent years, interest has been shown into what happens as mud settles out of suspension on to a sloping bed. Does the mud remain where it falls on the bed or does it move down the slope, in a similar way that rain drains from a catchment? The effect of mud moving down slopes of an estuary bed could be quite significant; filling up low points in the estuary, e.g. dredge berths, approach channels, etc., much quicker than if only vertical settling occurs.

Numerical models which simulate the movement of mud in the estuary, and which are used to predict the dredging requirements for port and harbour developments, thus need to incorporate any downslope movement of mud that is likely to occur. To be able to predict the occurrence of any downslope movement of mud and quantify it, an appreciation of the mechanism which causes the phenomenon is required.

To this end, a series of experiments was conducted at Hydraulics Research Ltd. (H.R.), from 21st November to 23rd December 1988, in their laboratories. The following report describes the experiments that were conducted and the observations which were made. Discussion of the observation, the presentation of conclusions and recommendations for future work are also included.

2. Experimental Work

2.1 Apparatus and Test Procedure

The tests were conducted in a tilting tank which is shown in Figure 1. The tank was pivoted at one end and by using a jack, positioned at the other end of the tank, the required bed slope could readily be achieved. At six locations along the length of the tank, measurement scales were fitted, perpendicularly to the floor of the tank, so water depths and settled bed thicknesses could be easily measured. In some tests, a concentration measuring probe, a nephelometer, was positioned just above the bed, approximately half way along the length of the tank, to measure the near-bed concentration.

For a typical test, saline water was mixed with a mud slurry to produce a uniform concentration suspension throughout the tank. Samples of the suspension were taken so that the starting concentration and salinity could be determined for each mixture tested. After uniform conditions had been achieved, the mixing was stopped and the suspension allowed to settle. Measurements of the settled bed thickness and the near-bed concentration were made at regular intervals throughout the test and recorded.

Another series of tests was also conducted in parallel with the tilting tank tests described above. These tests were conducted in a standard settling column and were used to determine:-

a) How the settled bed thickness varied with time for different concentrations and different depths of suspensions, where no lateral movement occurred.

b) What densities occurred at different points throughout the bed thickness.

The bed thickness was measured using a tape attached to the side of the settling column while a radioactive densimeter was used to determine the bed densities.

2.2 30 g/l Harwich Mud Test

This initial test was used to try and demonstrate the occurrence of mud movement down a slope. To this end, no measurements of settled bed thickness or near-bed concentrations were made. A video tape recording was, however, made of the settling mechanism.

The tilting tank was filled with slurry of approximately 30 g/l concentration and tilted to give a bed slope of 1:10, approximately. The mud used to make the slurry originated from Harwich Harbour, Essex. The following observations were made during the course of the experiment:-

1) Following the mixing, the slurry was of a uniform concentration throughout the tank. Flocs formed only slowly as the residual turbulence, from the mixing process, dissipated.

2) Once flocculation and the settling process became established, four distinct bands formed through the depth of the suspension, as shown in Figure 2.

Band 1: This near-surface layer had a relatively low sediment concentration, containing mainly unflocculated particles. This layer was formed by the mud particles flocculating and settling, faster than the unflocculated particles, into the lower parts of the tank.

Band 2: In this layer, hindered settling was the predominant feature. Hindered settling is where the settling velocity of particles is reduced by water, displaced by the movement of these particles, flowing in the opposite direction. Flocs of different sizes settle at different rates and the concentration of this type of suspension is such that there is considerable interaction between particles as they settle. This causes particles to collide, resulting in flocs continually increasing and decreasing in size. The mean movement of all the particles in this layer was in the vertical direction.

Band 3: This layer was located at the base of Band 2 and above the settled bed. In this layer, hindered settling was still present but the particles were observed to move laterally down the slope, as well as by the vertical settling. The interface between Band 2 and Band 3 was broadly parallel to the settled bed and the floor of the tank, as shown in Figure 2. This phenomenon of lateral movement of sediment as it settled in the vicinity of the bed was designated as "density flow".

Band 4: This consisted of the settled bed layer, made from deposited flocculated particles. The settled bed thickness varied in a different manner than if no lateral movement of mud particles had taken place along the length of the tank, as shown in Figure 3.

The thickness of each of these layers changed with time. Band 3 grew in thickness to a maximum value of about 3cm then gradually reduced to zero as the conditions necessary for its existence varied.

2.3 5 g/l Grangemouth Mud Test

Based on the observation of the 30 g/l Harwich Mud test, described in Section 2.2, it was decided to perform a series tests, in the same tilting tank, where conditions were much closer to those experienced in typical field situations. It was decided to examine suspensions having an initial uniform concentration less than 15 g/l of Grangemouth Mud. Bed slopes of 1:10 to 1:50 were to be considered, again to be more representative of field conditions.

The first of this programme of tests used a concentration of 5 g/l of Grangemouth Mud with the tank tilted to give a bed slope of 1:10 approximately. In this test, however, no lateral movement of mud was observed to occur; the four bands described in Section 2.2 were not all present. Although a Band 1 layer formed, the Band 2 was not the same as in the 30 g/l Harwich Mud test. Although the particles in Band 2 had flocculated there was no hindering by displaced water and only minor interaction between the particles as they settled. Band 3 was not present, so, particles settled straight from Band 2 to form the bed, Band 4.

The concentration of the suspension was monitored 1.5cm above the floor of the tank (0.7cm above the final settled bed level) using a nephelometer. The variation of the suspension concentration at this point throughout the duration of the test is shown in Figure 4.

A companion settling column test at the same concentration, approximately, with a depth of 40cm approximately was performed. The depth was equivalent to that experienced in the deep end of the tilting tank. The final settled bed level in the column test was 6.5mm contrasting with 10.5mm which was measured in the tilting tank test, for the same depth. If the settled bed thickness in the settling column test is adjusted to compensate for the difference in the suspension concentrations between the deep end of the tilting tank and the settling column (4.74 g/l to 3.07 g/l), a thickness of 10.0mm is obtained. This thickness, together with the possible measurement errors associated with the experiment, substantiate the observation that no lateral movement of mud occurred.

As no lateral movement of mud was observed at this concentration, on a relatively steep slope, it was decided to cease the 5 g/l series of tests.

2.4 10 g/l Grangemouth Mud tests

A complete series of tests, with different bed slopes, was conducted for an initial 10g/l suspension concentration of Grangemouth Mud. The bed slopes examined were as follows: 1:8.8, 1:10.0, 1:10.2, 1:12.7, 1:15.1, 1:19.7, 1:31.0, 1:38.5 and 1:50.7. The average concentration of the suspension, sampled over the duration of the tests was 8.82 g/l.

During this series of tests, two phenomena were recognised in connection with the lateral movement of mud.

The first phenomenon is thought to be the same mechanism as that observed in the 30 g/l Harwich mud tests, described in Section 2.2 and called "density flow". It was observed that, although this mechanism was present for all the slopes considered, it proved to be somewhat transient. As the mixing turbulence dissipated, the sediment flocculated and settled and the fluid mud flow started. After a period of time, depending on the slope of the bed, the flow reversed; flowing uphill. Soon after this reversal of flow, the fluid mud flow stopped. The reason for this behaviour is thought to be due to internal sloshing of the fluid mud flow against the downhill end of the tank, see Figure 5.

The second phenomenon observed during these tests would appear to be a more traditional failure and was termed 'bed slump'. That is, as the settled bed forms on the sloping floor of the tank, it reaches a critical thickness at which the top-most layer moves downhill under its selfweight. (Internal friction of the settled bed < the downslope weight component of the bed). This mechanism again only lasted temporarily and was only observed to occur on slopes steeper than 1:15.12.

From the measurements made during these tests, the settled bed thickness at the conclusion of each test (60 mins), for a suspension depth of 300mm, was plotted against the bed slope. This graph is shown in Figure 6. A more complete graph is shown in Figure 7, where the final settled bed profile (after 60 mins) is shown for the length of the tank, for each bed slope considered. It should be noted in connection with Figure 7, that apart from at station 3, the depth of suspension at each of the measurement stations varied with bed slope, so the bed thicknesses at these stations for the different slopes are not directly comparable.

It proved difficult to determine the longitudinal settled bed profile, for zero lateral movement of mud, directly from the settling column tests, as it was not possible to obtain a close agreement between the suspension concentrations for the settling column tests and for the tilting tank tests. The average values of concentration in the tilting tank test was 8.82 g/l whereas values of 9.24, 8.20, 8.63 and 8.41 g/l were determined for the settling column tests. This variation arose even after the suspension for the settling column tests was decanted from the tilting tank suspension.

However, the bed thicknesses measured in the settling column tests were adjusted, in Table 1, to account for the discrepancy in the concentration of the suspensions. The bed thicknesses adjusted to a concentration of 8.82 g/l, for a situation where no lateral movement occurs, are plotted against the different depths of suspension in Figure 8. This enabled the measured bed thicknesses from the tilting tank tests to be compared with the situation where no lateral movement had taken place. This comparison is shown in Figures 9 to 16, for the different slopes examined. Figures 9 to 14 indicate that material moved in a downslope direction due to density flow and bed slump. However, in Figures 14 and 15, the picture is confused, probably due to inaccuracites in applying the adjustment for the suspension concentration and sloshing effects.

The near-bed concentration measurements were discontinued in the tilting tank tests after the first test (slope of 1:10), in order to speed up the acquisition of bed thickness measurements. The calibration of the nephelometer, for the concentrations being measured was thought to be unreliable, as it was on the extreme of the instrument operating capabilities.

The radioactive densimeter was also found to be very sensitive for the relatively low concentration which it was used to measure. Measurement of the density in the upper layers of the settled bed did indicate a density of 70 to 80 g/l, for the same conditions under which bed slump occurred. This value of density is typical of 'fluid mud', as defined by HR, see Odd and Rodger (1986).

Tilting Tank Mean Concentration = 8.82 g/l

<u>Settling Column</u>

Depth (mm)	Bed thickness (mm)	Concentration (g/l)	Adjst. Factor	Adjst Depth (mm)
222	8.5	8.197	1.076	9.146
301	12.0	8.407	1.049	12.590
415	19.0	9.238	0.955	18.136
267	10.0	8.633	1.022	10.22

Table 1 : Adjustment of Bed Thicknesses measured in the Settling Column Tests to correspond to the mean slurry density of the tilting tank tests.

3. Discussion of Results

From the experiments described in Section 2, it would appear that there are two mechanisms which are capable of moving sediment down a slope.

3.1 Density Flow

The first mechanism appears to be caused by a density gradient which develops in a region just above the bed. The lateral density gradient is thought to be generated by the near-bed suspension concentration being sufficient to enable a reaction from the bed to be transmitted back into the suspension by the interaction of settling particles or flocs. This reaction from the bed reduces the speed at which particles settle and causes a vertical variation in the concentration of suspension above the bed, see Figure 17. If the bed is horizontal, there will be no lateral density gradient as the concentration of the suspension at any height above a fixed datum would be the same. However, if the bed is sloping, a lateral density gradient will exist, as shown in Figure 17, caused by the relative vertical displacement of the concentration profiles.

As sediment settles through the water column, it is deflected from its vertical path as the lateral density gradient becomes present -Band 3 in Figure 2 - before finally settling on to the bed. The amount of lateral movement, experienced by a settling particle, depends on the ratio of the particle's vertical to its horizontal velocity and the thickness of Band 3. Both the settling velocity and the thickness of Band 3 (Density Flow Layer) depend on the concentration of the suspension. High concentrations result in a slower settling velocity and a greater thickness of Band 3 The horizontal velocity component only varies as a consequence of the relative vertical displacement of the concentration profiles; the steeper the slope, the greater the density gradient.

The significance of this mechanism, with regard to the movement of mud down slopes, is thought to be minimal in typical field situations, because:-

1) Particles settling to the bed are only deflected sideways as they pass through Band 3, on their journey to the bed. Thus for a constant slope, under steady settling conditions the amount of sediment transported off the slope is:-

$$M = \bar{u}_\rho .\ C.\ \delta h.\ T$$

where δh = the thickness of the Density Flow Layer; Band 3.

$\bar{u}_\rho$ = the mean horizontal velocity caused by the density gradient over the thickness of Band 3.

C = the mean concentration of the suspension within Band 3.

T = duration for which the Density Flow occurs.

In the 30 g/l Harwich Mud test the maximum values of δh and $\bar{u}_\rho$ observed were approximately 2.0 cm and 1 cm/s respectively. If these values are considered with a likely maximum field concentration of 20 g/l and T = 2hours (slack water at the turn of the tide), the maximum flux M would be 28 kg per m width of slope.

2) For the density gradient mechanism to exist, it is necessary that the concentration of the slurry is sufficiently high to enable particle interaction and/or hindered settling. This mechanism was not observed to occur in experiments with a mean concentration of 4.42 g/l. This is in agreement with typical conditions which are required for hindered settling, i.e. concentration > 10 g/l or so. A reasonable criterion for the occurrence of Density Flow may be that the near-bed mud concentration should exceed 10 g/l, which will restrict quite significantly the occurrence of the mechanism in field conditions, where typical values are < 5g/l.

The relative insignificance of Density Flow is further well illustrated by the results of the 10 g/l Grangemouth Mud tests, see Section 2.4. In Figure 6, it can be seen that the same bed thickness was observed for a flat bed as for slopes shallower than 1:15, where Density Flow was observed.

3.2 <u>Bed Slump</u>

The second mechanism is a more traditional slope failure, as described in Section 2.4. It can, perhaps, be thought of as a slightly more complicated version of a shallow slope failure studied in soil mechanics. As in soil mechanics failures, there are thought to be critical slope conditions at which the deposited sediment starts to move down the slope. The added complication comes from the manner in which sediment deposited on the bed gains strength.

In the literature, Odd and Rodger (1986), it is postulated that a sediment bed forms at a rate which is controlled by the rate at which water is expelled from between particles. A maximum bed formation rate is referred to and a value of 4 $g/m^2/s$ is assigned to it, but recommendations have been made, Odd and Cooper (1988), that further experiments be conducted to quantify the parameter more precisely. If the rate at which sediment settles on to the bed exceeds this maximum rate of bed formation, a weak interlocking matrix of flocculated sediment forms on top of the bed. Typically this 'matrix', commonly referred to as 'fluid mud', has a dry density of about 75 g/l and can be thought of as a Bingham fluid, having a Bingham yield strength, Y_B, of approximately 0.1 N/m^2, although further quantification bas been requested, by Odd and Copper (1988), for these properties. Should conditions prevail such that the weak matrix forms and it acquires a thickness where the downstream component of self-weight exceeds the Bingham yield strength, then bed slump will occur.

Using a dry density of 75 kg/m^3 and a Bingham yield strength of 0.1 N/m^2 for the weak matrix, the critical thickness required for bed slump to occur, for different slopes, was calculated, and is shown in figure 18. From Figure 18, it can be seen that the predicted critical thickness for bed slump to occur, is the same order of magnitude as the moving bed layers observed in the 10 g/l Grangemouth Mud tests. The reason that the critical condition was not exceeded for all slopes is that the deposition of sediment at a rate greater than the maximum bed formation rate was not sustained for a long enough period to produce the build up of the weak matrix layer to a sufficient thickness.

Consideration is made in the literature (Odd and Rodger, 1986) of re-entrainment of mud from the moving bed layer back into the suspension. In addition, erosion of mud from the underlying bed into the moving bed layer is also taken into account. Neither such mechanism was observed during the 10 g/l Grangemouth Mud Tests. It is believed that neither entrainment mechanism is likely to occur under conditions observed for the 10 g/l Grangemouth Mud tests.

For the re-entrainment of mud particles from the moving bed back into the suspension, the mechanism would have to prevent particles settling on to the bed before any particles could be extracted from it. If a moving bed layer exists where the interfacial shear stress, between it and the overlying suspension, exceeds the erosive threshold and where no or very little settlement takes place, then re-entrainment could be expected to occur.

Concerning the erosion of the underlying mud, if the moving layer is treated as a fluid flowing under the action of gravity, then it is reasonable to expect that the internal velocity gradient could generate a shear stress at the interface with the bed which is large enough to remove material from the latter. Conversely, it can also be argued that the average particle size is reduced by the shear near the bed interface and that the resulting smaller particles provide greater resistance to movement, because of the greater number of collisions and bonds being created and broken. This is consistent with observations of how the bed layer stops moving; by the moving layer reducing in thickness from beneath, i.e. the moving bed layer gains strength to become part of the stationary bed; an apparent growth in the thickness of the stationary bed thus occurs.This phenomenon can be observed in the video recording of bed slump.

The growth or decay of a moving bed layer, therefore, is a balance between re-entrainment into the water column and erosion from or deposition on to the bed. If all the potential energy is not expended on internal resistance the moving bed layer will speed up or if the moving bed velocity exceeds a critical velocity then erosion of the underlying bed may take place. Obviously the changing of particle sizes within the moving bed layer will affect the rate at which sediment will be deposited on the bed. Thus further work needs to be done to quantify the bed formation rate to account for these conditions.

As borne out by Figure 6, once critical conditions are exceeded and a moving bed layer forms, the mass transport is significantly greater than that associated with density flow, mainly due to a greater length of slope contributing to the run off of mud. Therefore, if the rate of deposition exceeds the maximum bed formation rate throughout a period around slack water then greater amounts of sediment will be transported off a slope by bed slump than by density flow.

4. Conclusions

Two mechanisms are identified which cause flocculated mud particles to move down a slope, as they settle from a mud suspension to form part of a deposited bed. They are:-

1) Density Flow - horizontal density gradient causes particles, which are settling vertically from suspension, to be deflected in the downslope direction, see Figure 17. The deflection occurs in a narrow band just above the bed, Band 3 in Figure 2. As this phenomenon is thought to be dependant on the occurrence of hindered settling, the near-bed suspension concentration needs to exceed approximately 10 g/l. As this mechanism merely deflects flocs as they settle, its significance in transporting material down slopes is thought to be minimal in typical field conditions.

2) Bed Slump - the upper layers of a settled bed suffer a traditional slope failure. The upper layers of the bed are thought to be composed of a weak sediment matrix (a Bingham fluid) commonly referred to as "fluid mud". This weak matrix is generated by sediment settling on to the bed at a rate greater than a maximum bed formation rate. Bed Slump only occurs if the thickness of the weak matrix exceeds a critical value, which is dependant on the bed slope, see Figure 18. Bed Slump is though to be responsible for the majority of the downslope transport of mud. Re-entrainment of the moving bed layer into the overlying suspension and erosion of the underlying mud bed, by the moving bed layer were not observed in the experiments.

It is proposed that further work should be undertaken to:-

a) quantify Density Flow and Bed Slump in terms of:-

    i) the concentration of the sediment suspension;

    ii) the depth of the water column;

b) quantify the properties of bed slump material, i.e. the Bingham yield strength, etc.

5. References

1. E.A. Delo and T.N. Burt (1986),

'The Hydraulic Engineering Characteristics of Estuarine Muds'

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2. E.A. Delo (1988),

'The Behaviour of Estuarine Muds during Tidal Cycles: an experimental study and mathematical model'

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3. N.V.M. Odd and J.G. Rodger (1986),

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4. N.V.M. Odd and A.J. Cooper (1988),

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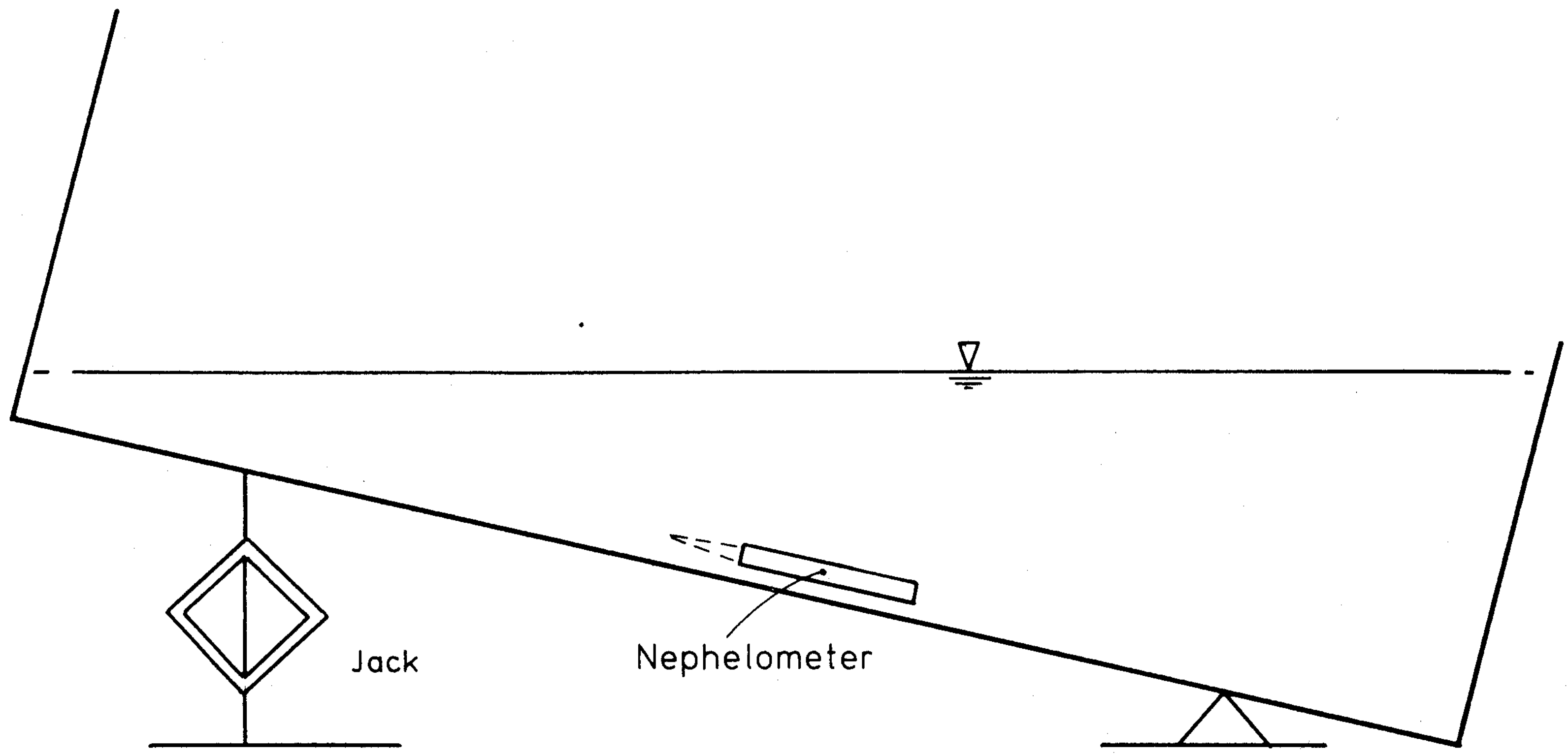


Figure 1. Sloping Tank arrangement. Tank dimensions are 0·15m wide
0·40m deep
2·30m long

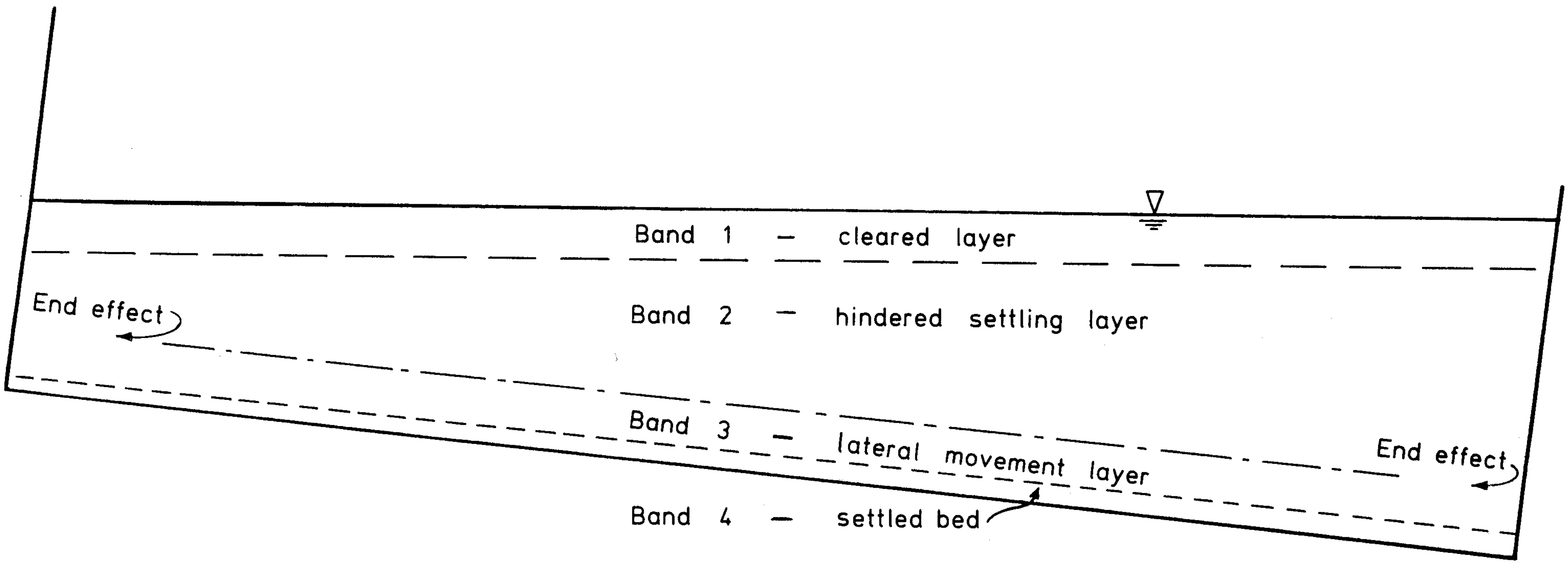


Figure 2. Layering observed in initial settling test.

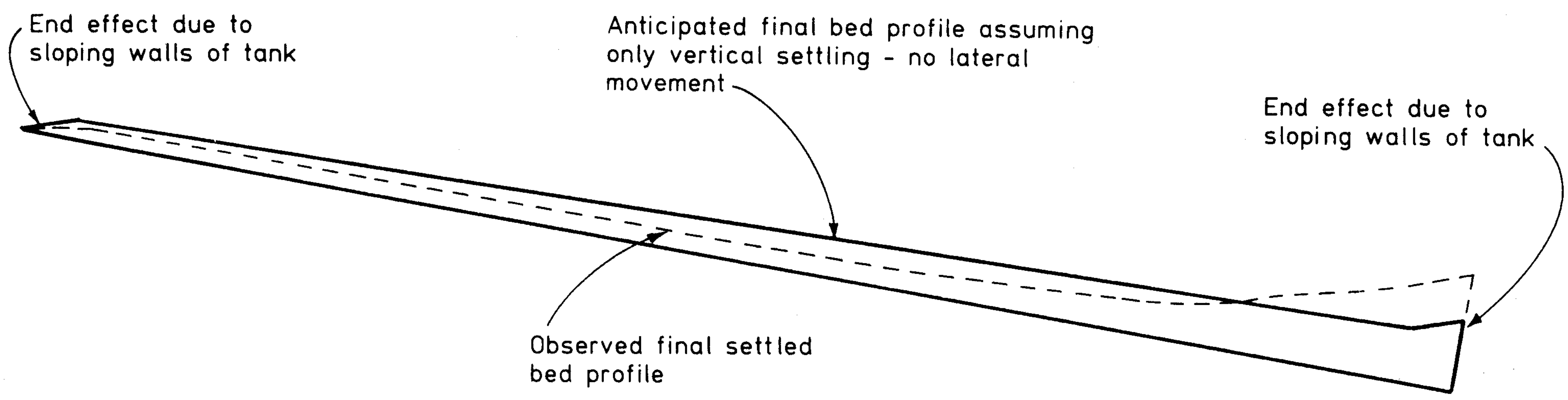


Figure 3. Comparison of final settled bed profiles for initial sloping tank test.

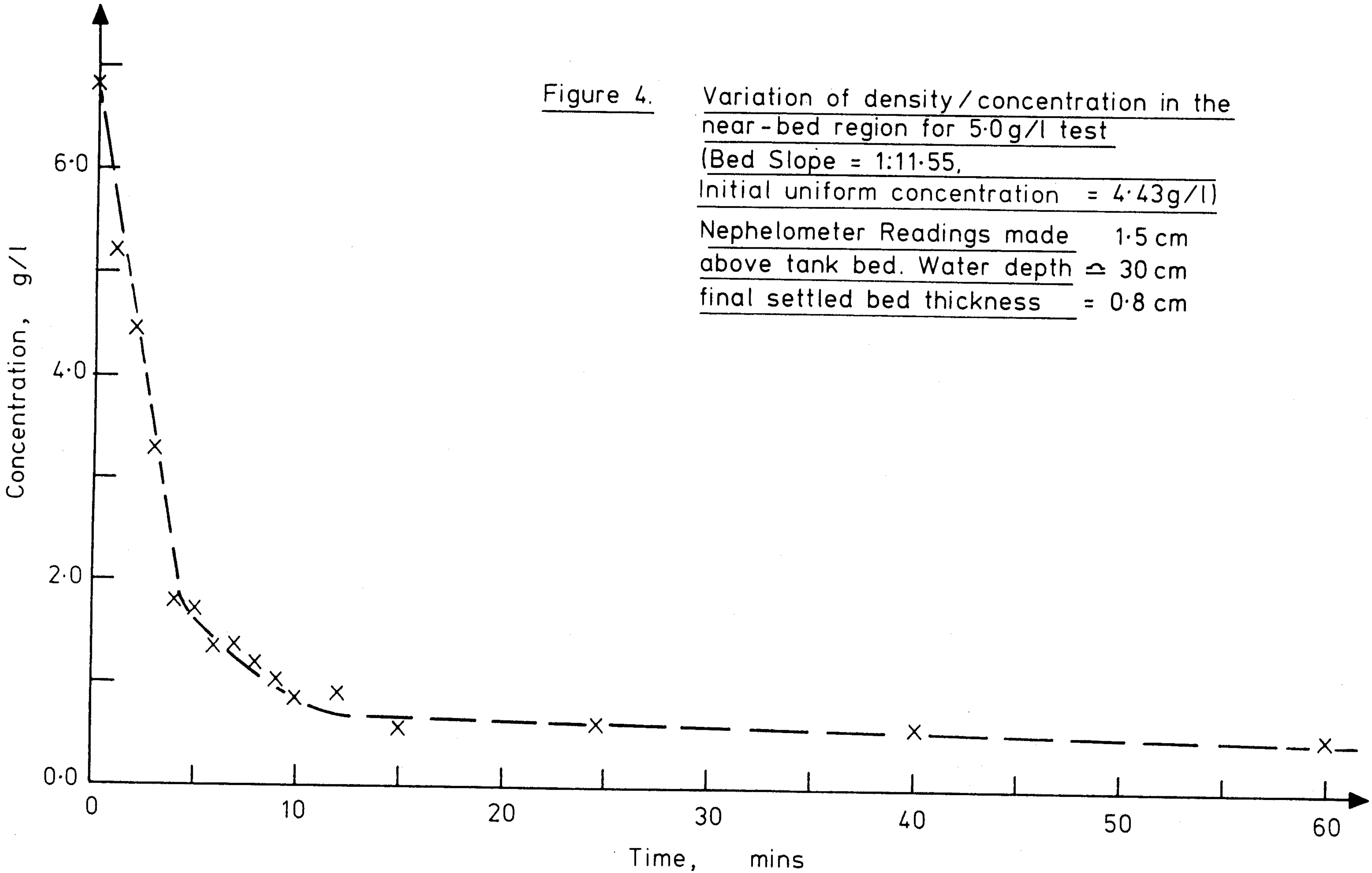


Figure 4. Variation of density / concentration in the near-bed region for 5·0 g/l test (Bed Slope = 1:11·55, Initial uniform concentration = 4·43 g/l)

Nephelometer Readings made 1·5 cm above tank bed. Water depth ≏ 30 cm final settled bed thickness = 0·8 cm

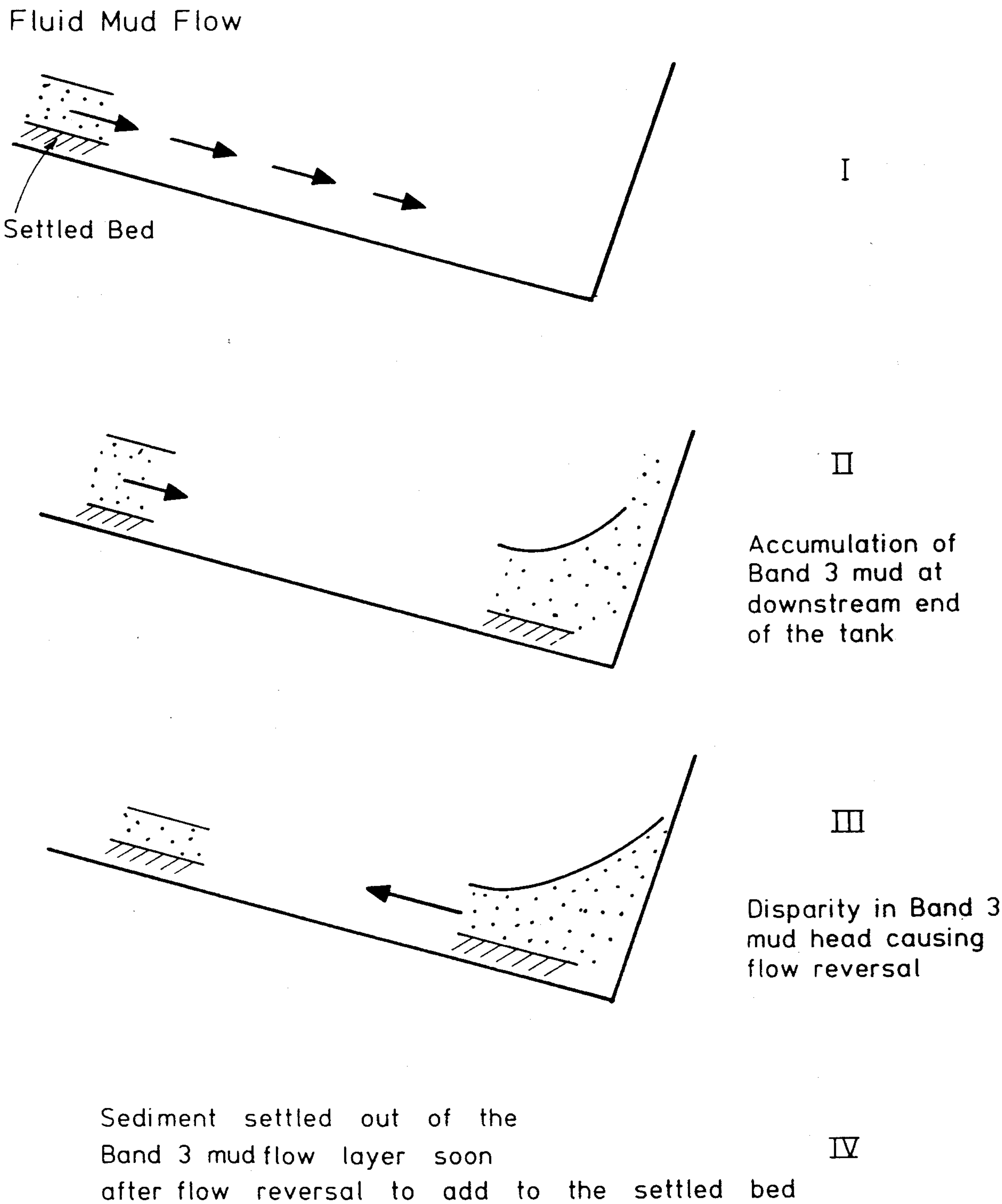


Figure 5. Fluid Mud Sloshing in Tank.

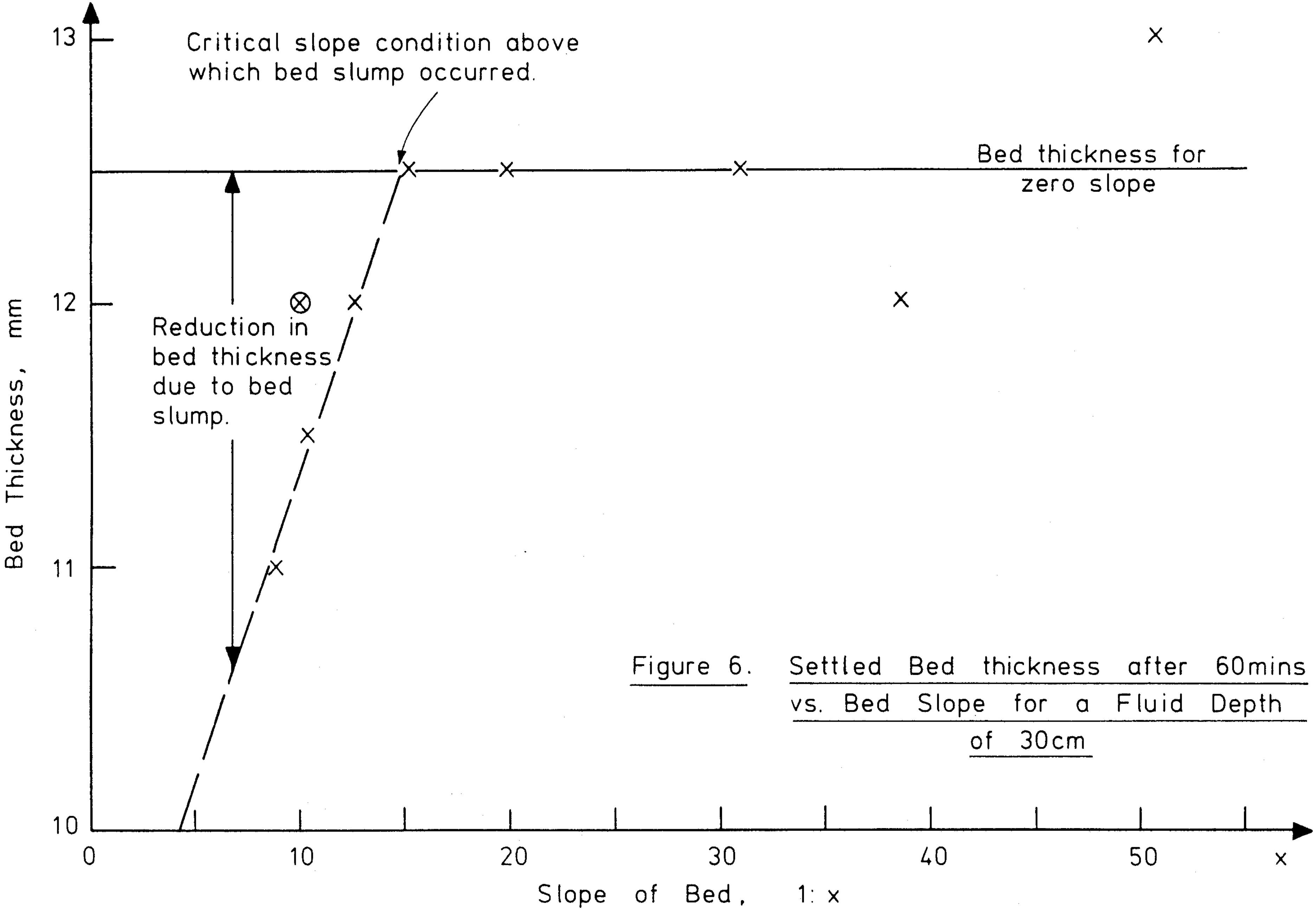
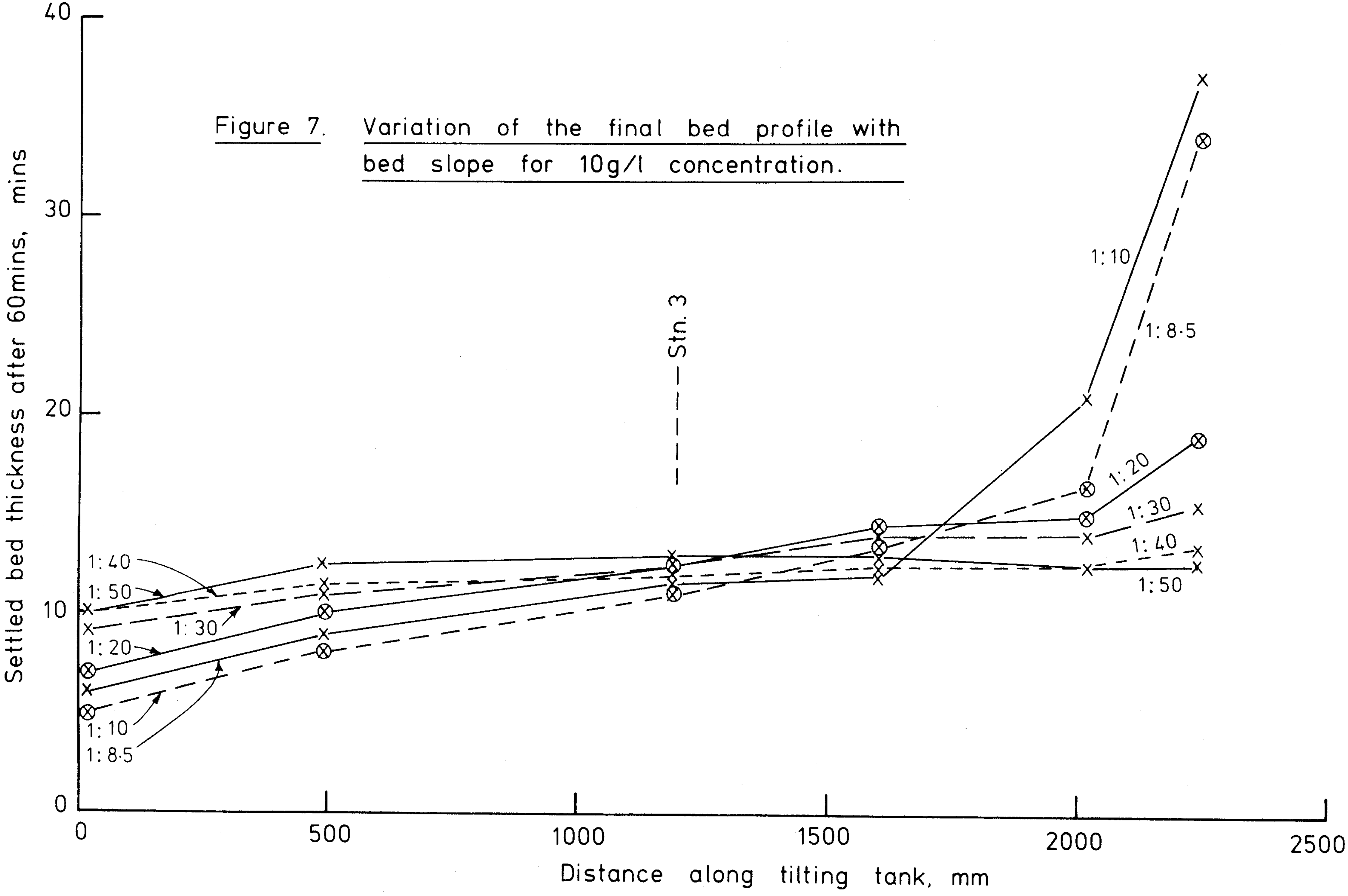


Figure 6. Settled Bed thickness after 60mins vs. Bed Slope for a Fluid Depth of 30cm

Figure 7. Variation of the final bed profile with bed slope for 10g/l concentration.



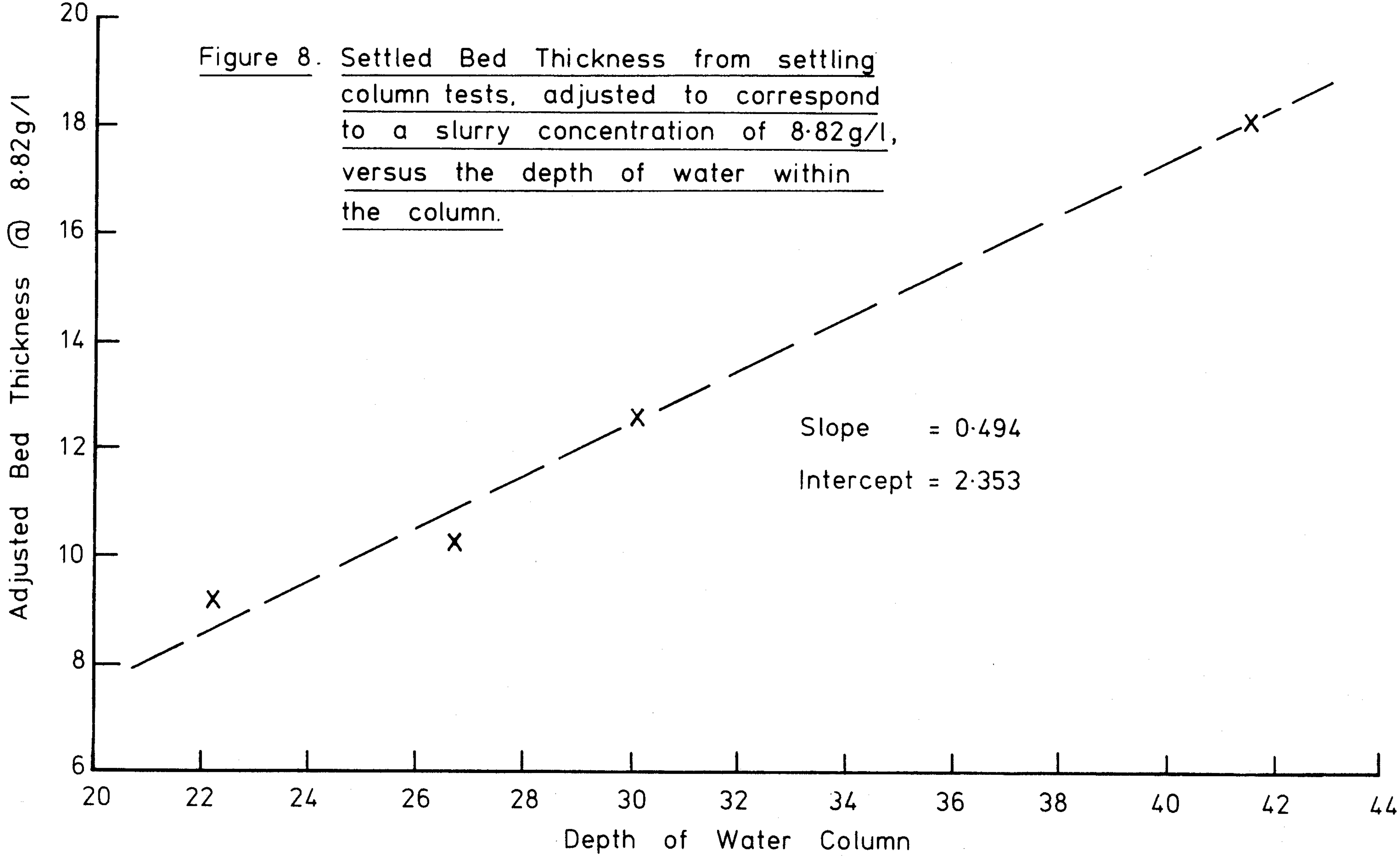


Figure 8. Settled Bed Thickness from settling column tests, adjusted to correspond to a slurry concentration of 8·82g/l, versus the depth of water within the column.

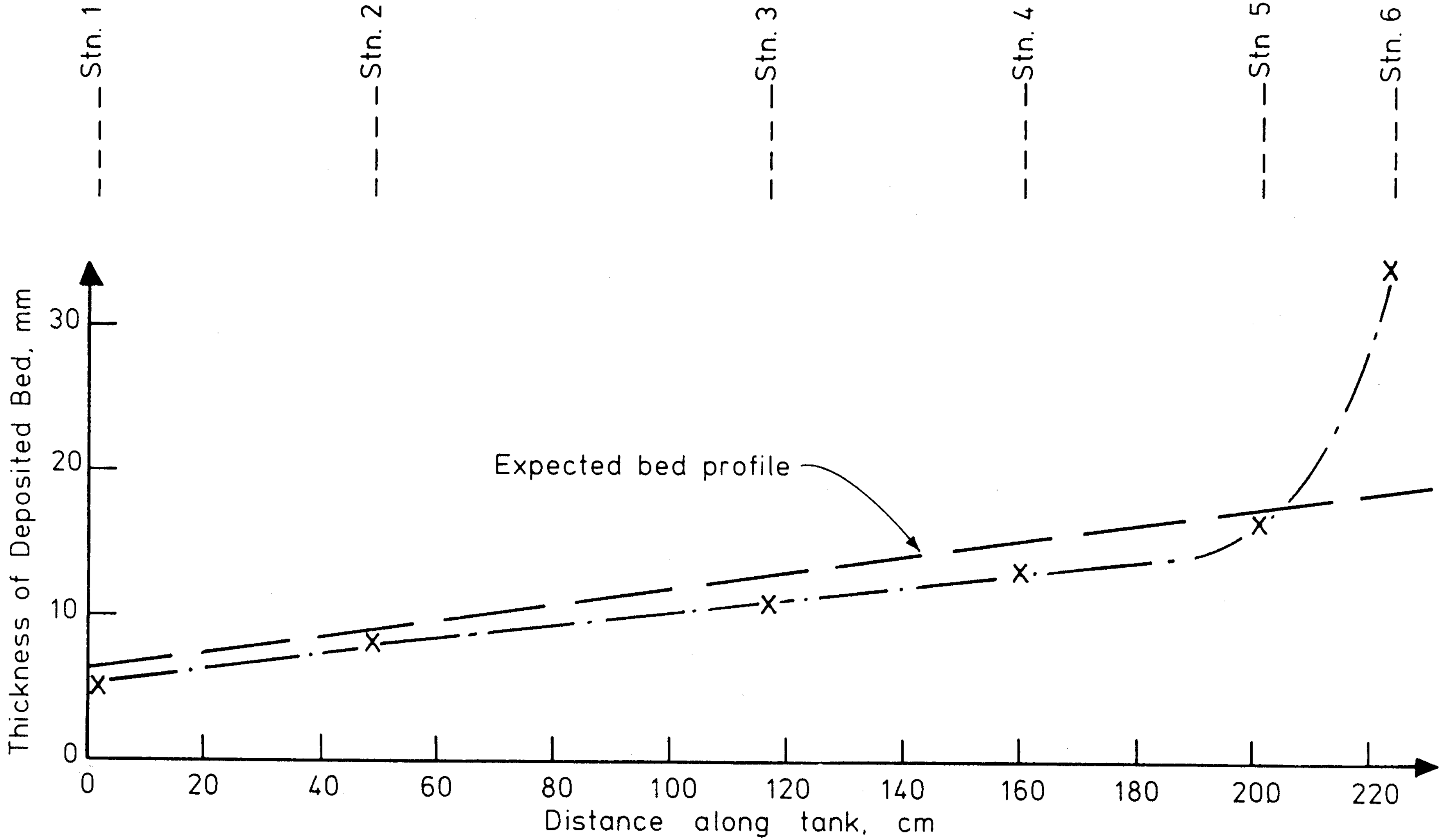


Figure 9. Comparison between the observed and the expected bed thickness

Slope = 1: 8·8

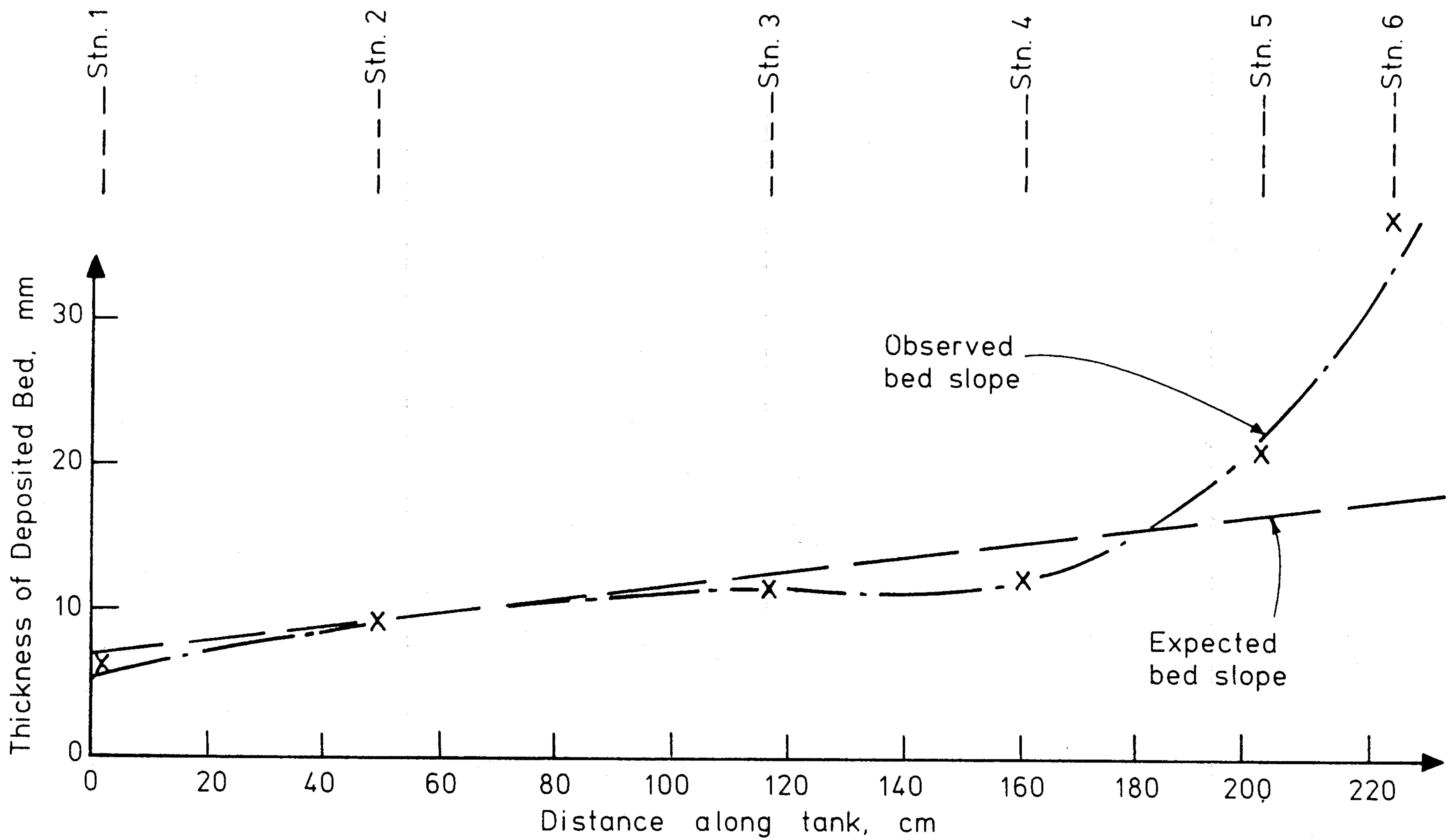


Figure 10. Comparison of the observed with the expected bed profile

Slope 1: 10·2

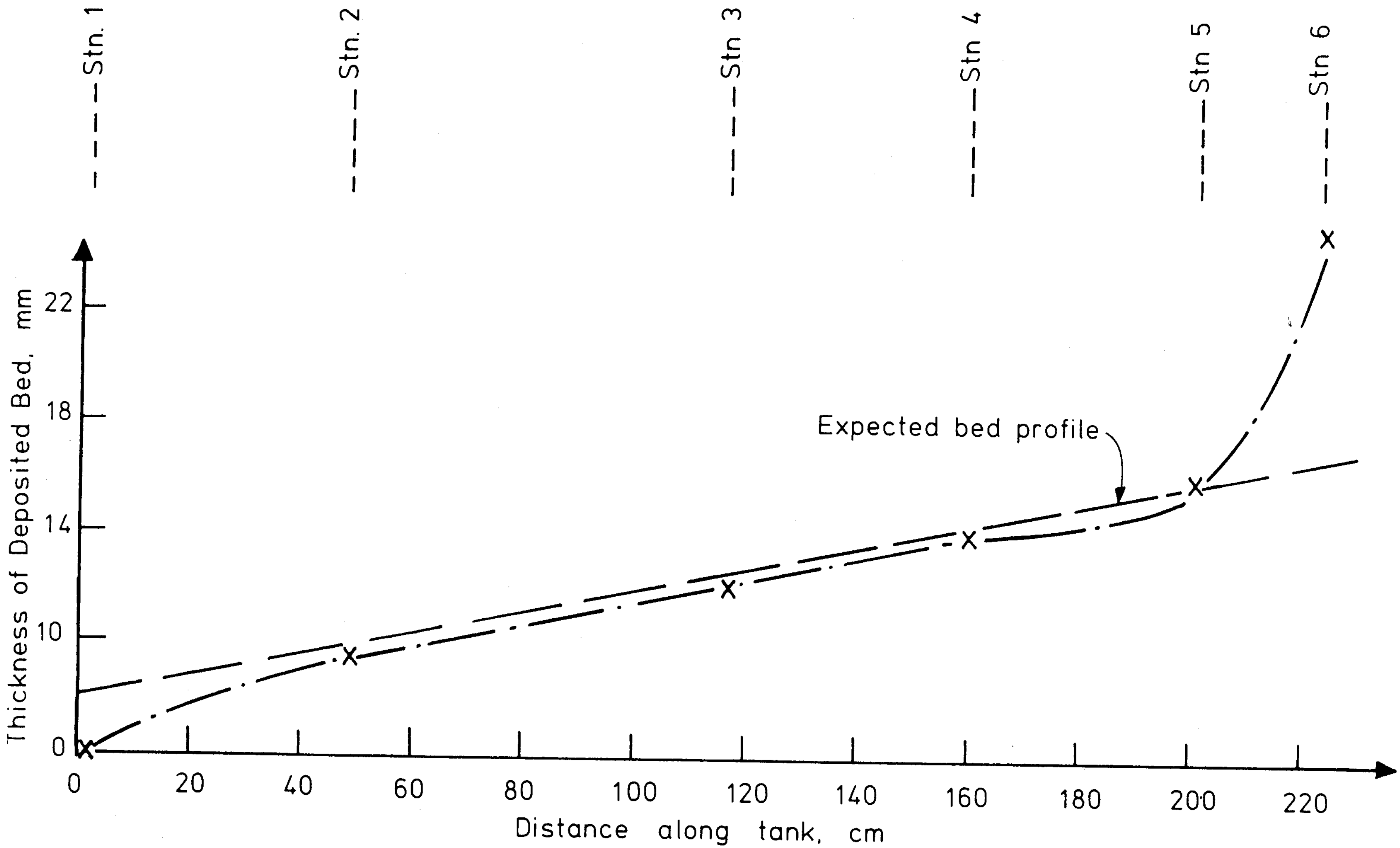


Figure 11. Comparison of the observed with the expected bed thickness

Slope = 1: 12·7

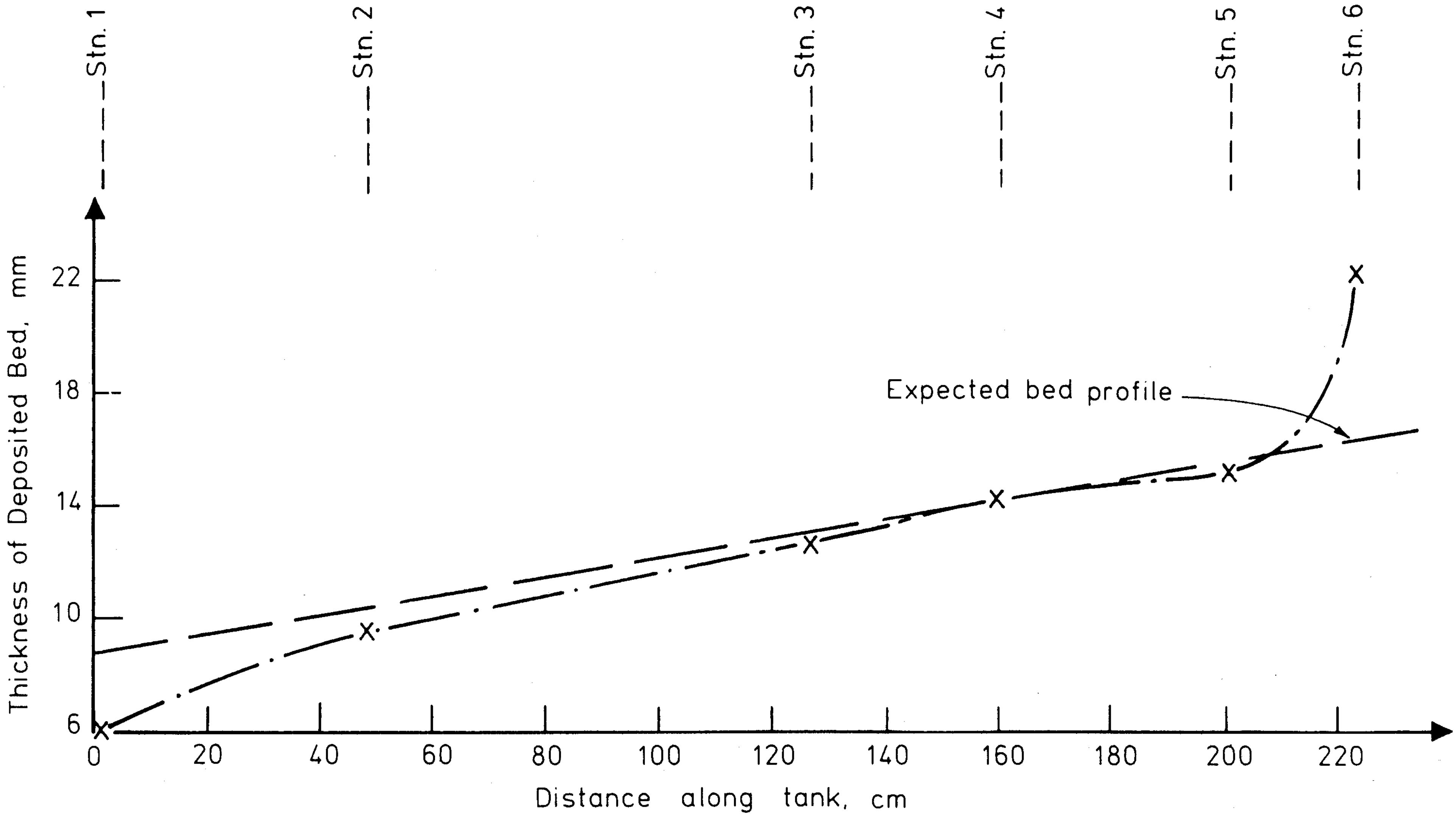


Figure 12. Comparison of the observed with the expected bed thickness.
Slope = 1: 15·1

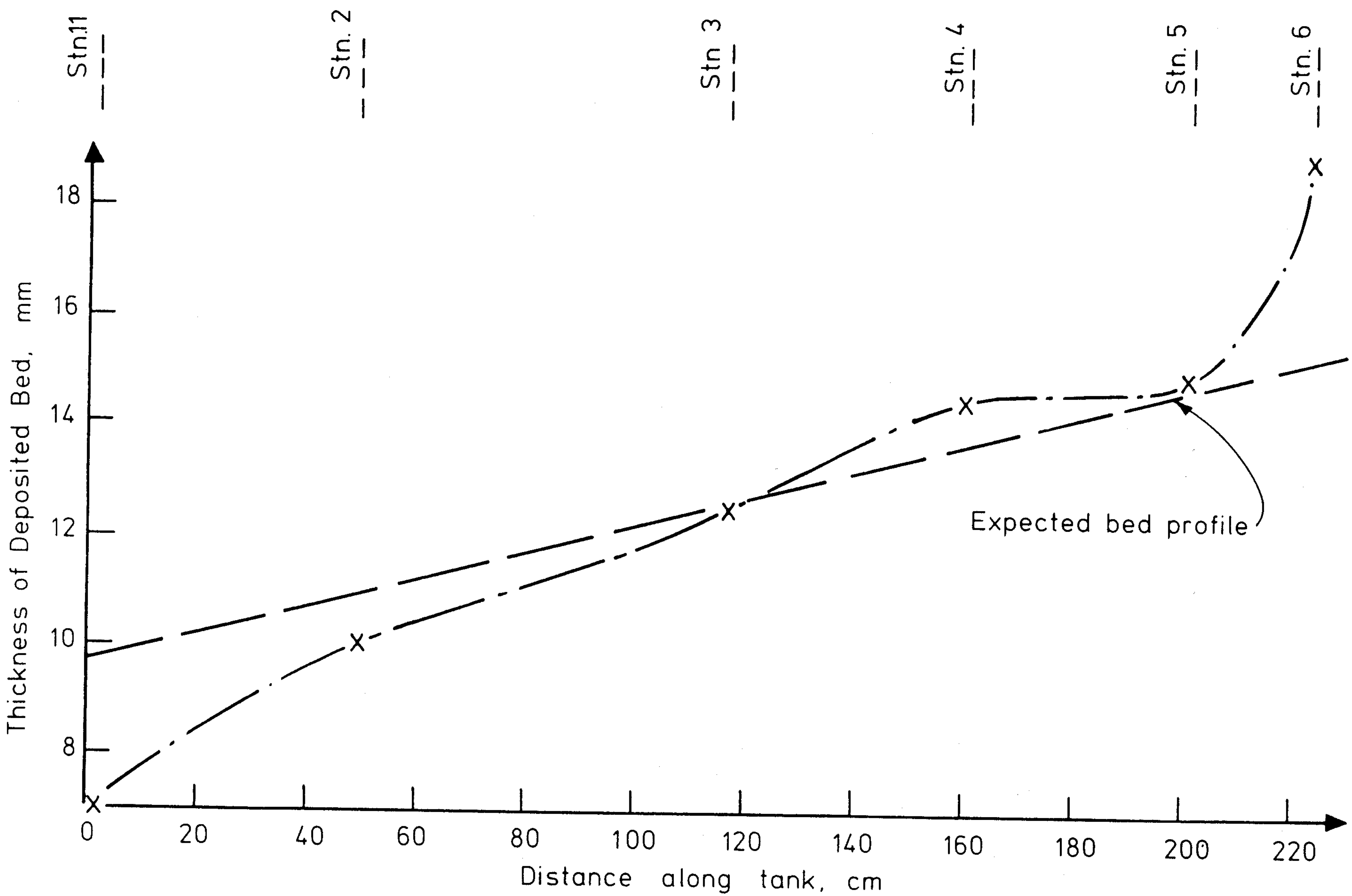


Figure 13. Comparison of the observed with the expected bed thickness.
Slope = 1: 19·7

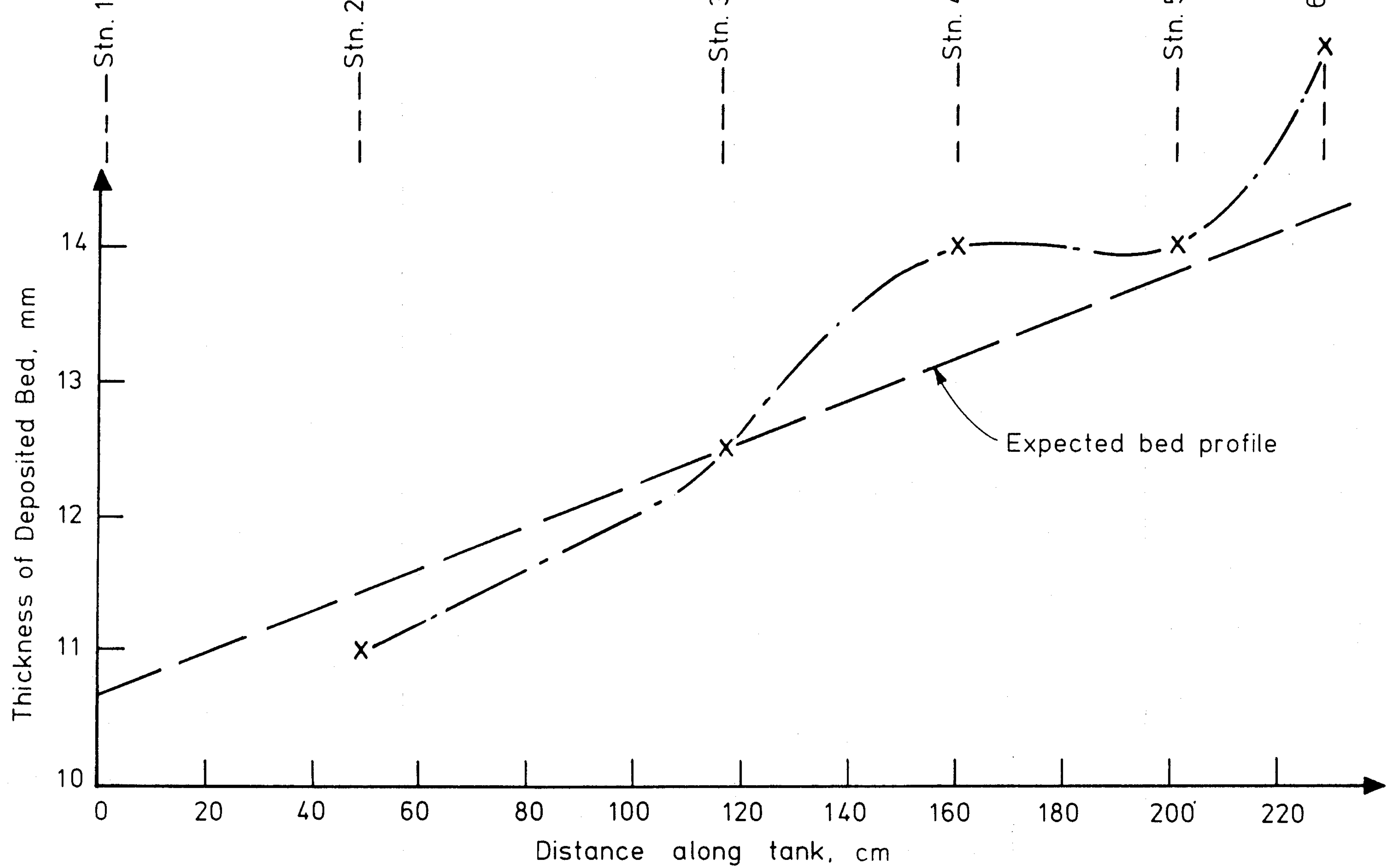


Figure 14. Comparison of the observed with the expected bed thickness

Slope = 1: 30·0

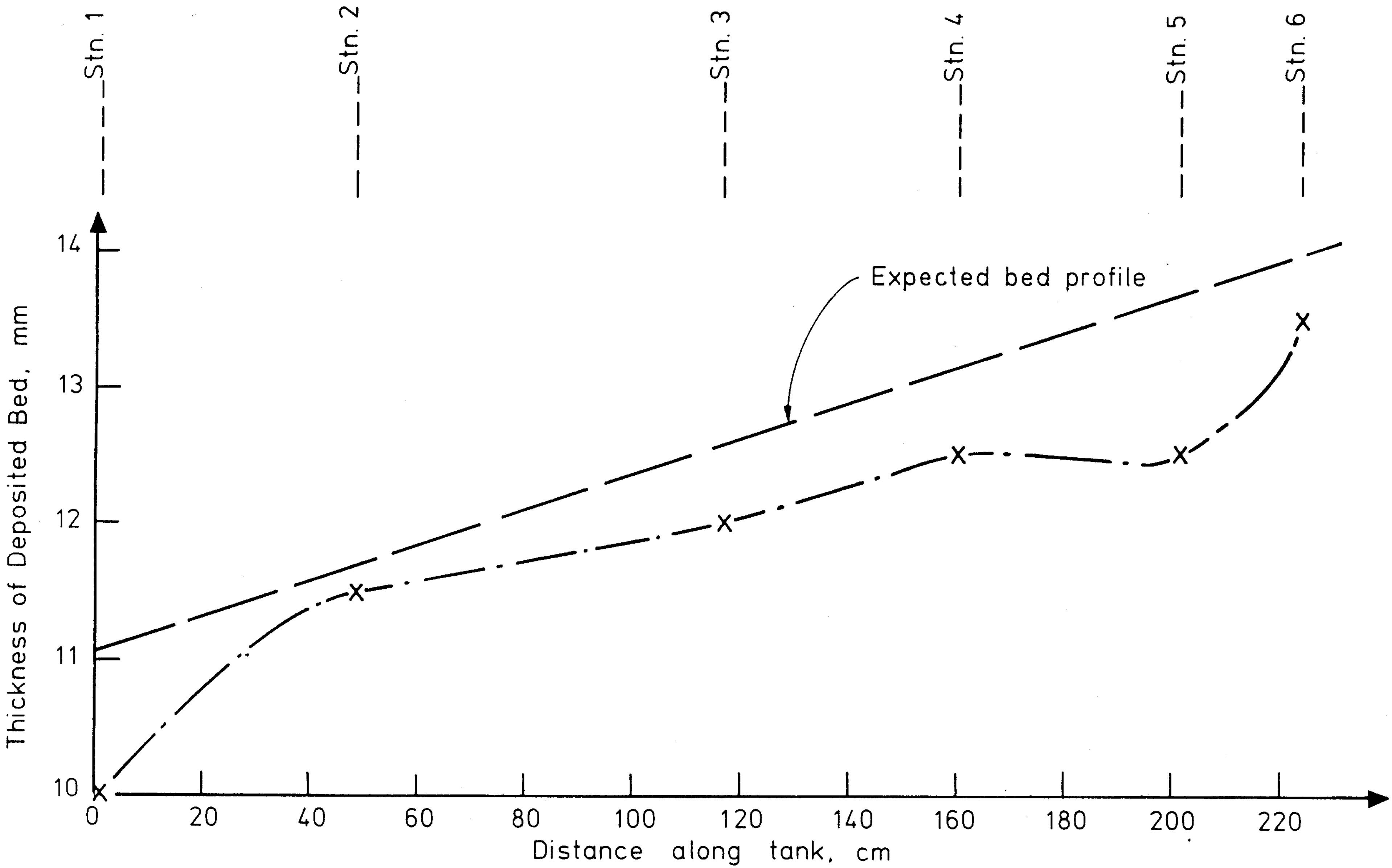


Figure 15. Comparison of the observed with the expected bed thickness

Slope = 1: 38·5

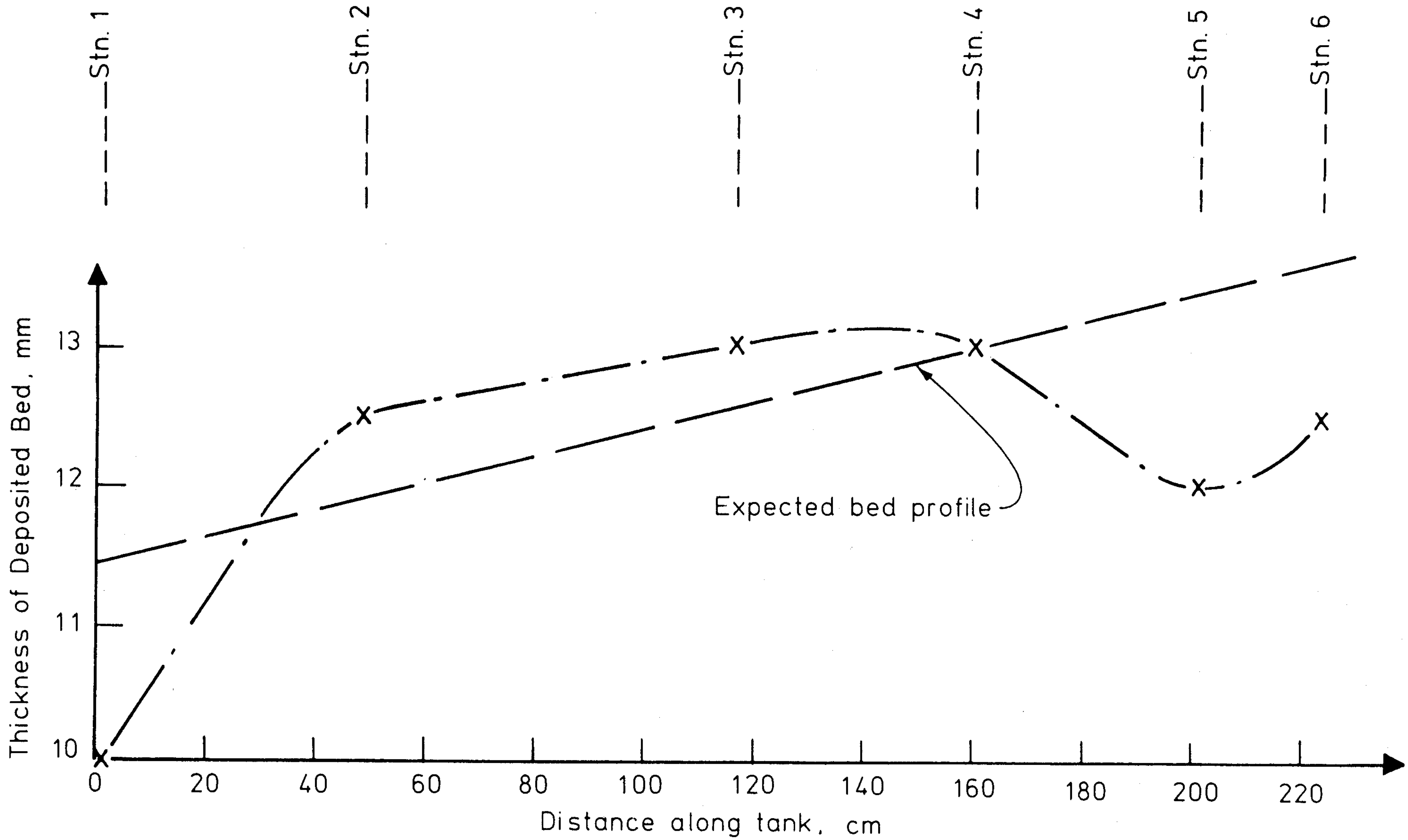
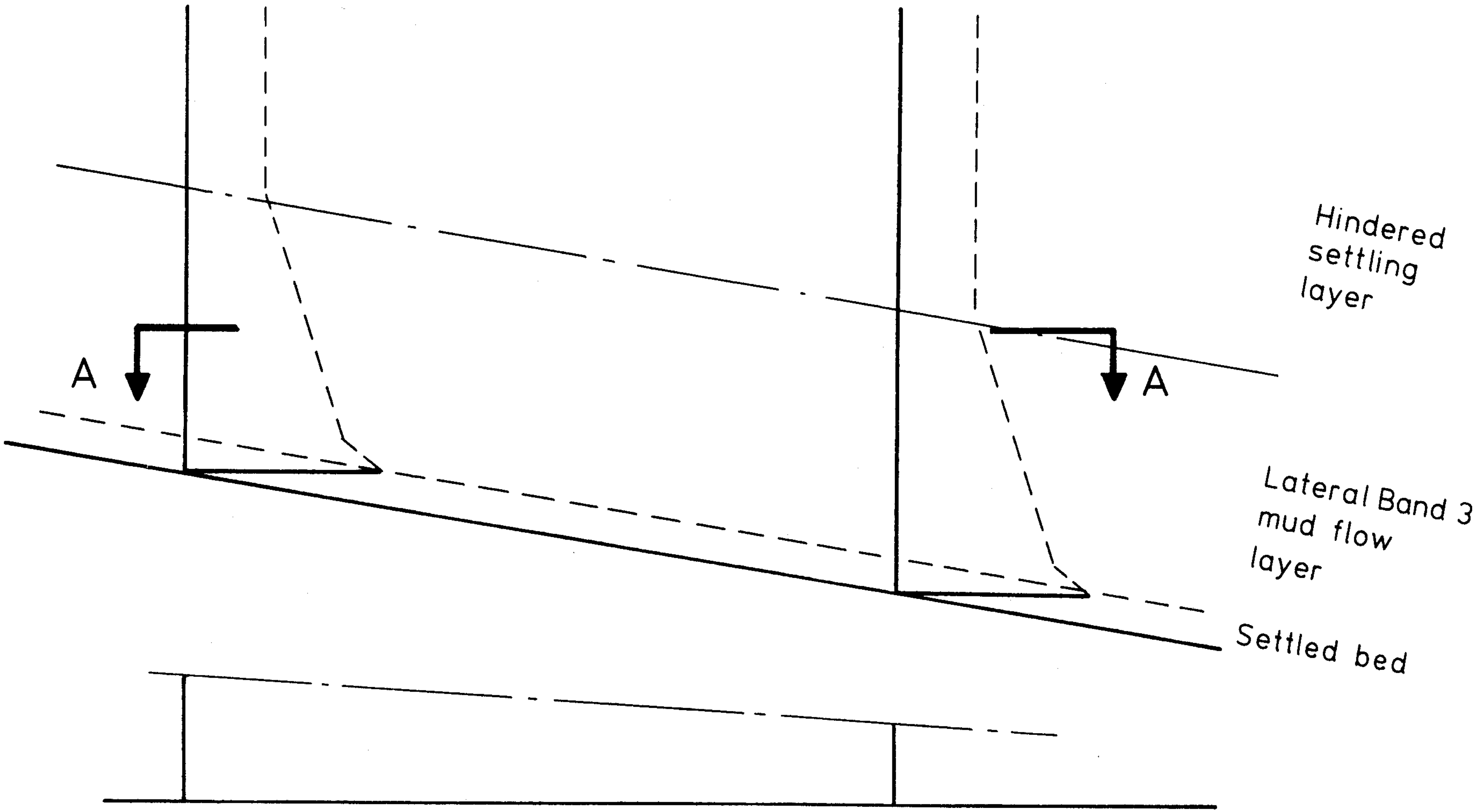


Figure 16. Comparison of the observed with the expected bed thickness

Slope = 1: 50·7



Horizontal density gradient on plane A-A

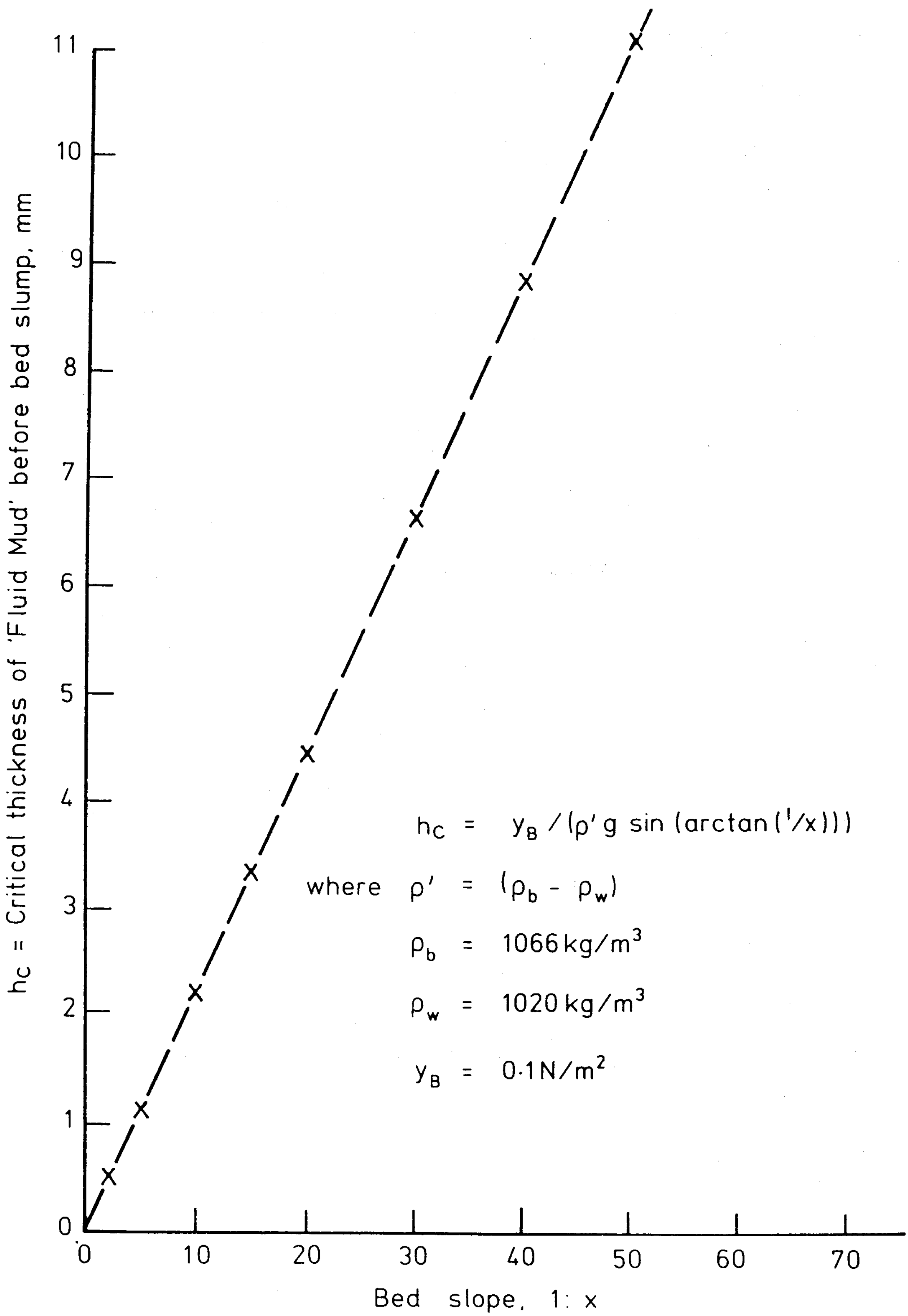


Figure 18. Variation of the critical fluid mud thickness with bed slope.