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THE UNIVERSITY OF NEW SOUTH WALES

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Manly Vale N.S.W. Australia

HYDRAULIC INVESTIGATIONS INTO DECANTING FROM IEA WASTEWATER TREATMENT PLANTS

PART 2: FURTHER INVESTIGATIONS

by

G.M. Witheridge and D.L. Wilkinson

for
Public Works Department, NSW

Research Report No. 175
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HYDRAULIC INVESTIGATIONS INTO DECANTING FROM IEA WASTEWATER TREATMENT PLANTS PART 2: FURTHER INVESTIGATIONS

Author (s)

G.M. Witheridge and D.L. Wilkinson

Sponsoring Organisation

Public Works Department, NSW

Supplementary Notes

The work reported was carried out and published under the direction of the Director of the Water Research Laboratory.

Abstract

This report describes an investigation into the mechanisms responsible for sludge carry-over during decant from an intermittent aeration tank. Several mechanisms were identified which may cause sludge carry-over. An 'early failure' mode may occur during the transient phase at the start of decant. This failure mode can be avoided by gradually increasing the rate of decant to a final steady value. The time required for flow establishment is in the order of five minutes in tanks of current size. Following the transient phase, failure can occur when interfacial shear stresses between the supernatant and settled sludge exceed some critical value. This failure mode is considered to be a 'scour failure' analogous to the onset of erosion of a cohesive sediment. Experiments conducted in a variety of different types of extended aeration tanks indicated that the critical parameters governing failure are the upstream velocity of the supernatant, the settlement time, and the Stirred Sludge Volume Index (SSVI).

Appreciation of the failure mechanisms has indicated certain design improvements which could be made to existing aeration tanks, in particular to the rate of change of weir loading and the design of scum barriers. The significance of tank depth is also discussed.

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PREFACE

The work reported herein was carried out and is published under the direction of the Director of the Water Research Laboratory, acting with partial funding and assistance from the Public Works Department of NSW.

This report supersedes Research Report 172 and it should be noted that an errata sheet has been produced for Research Report 172.

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The author gratefully acknowledges the receipt of a research grant from the Public Works Department Waste Water Branch for the field work at Port Macquarie during 1988.

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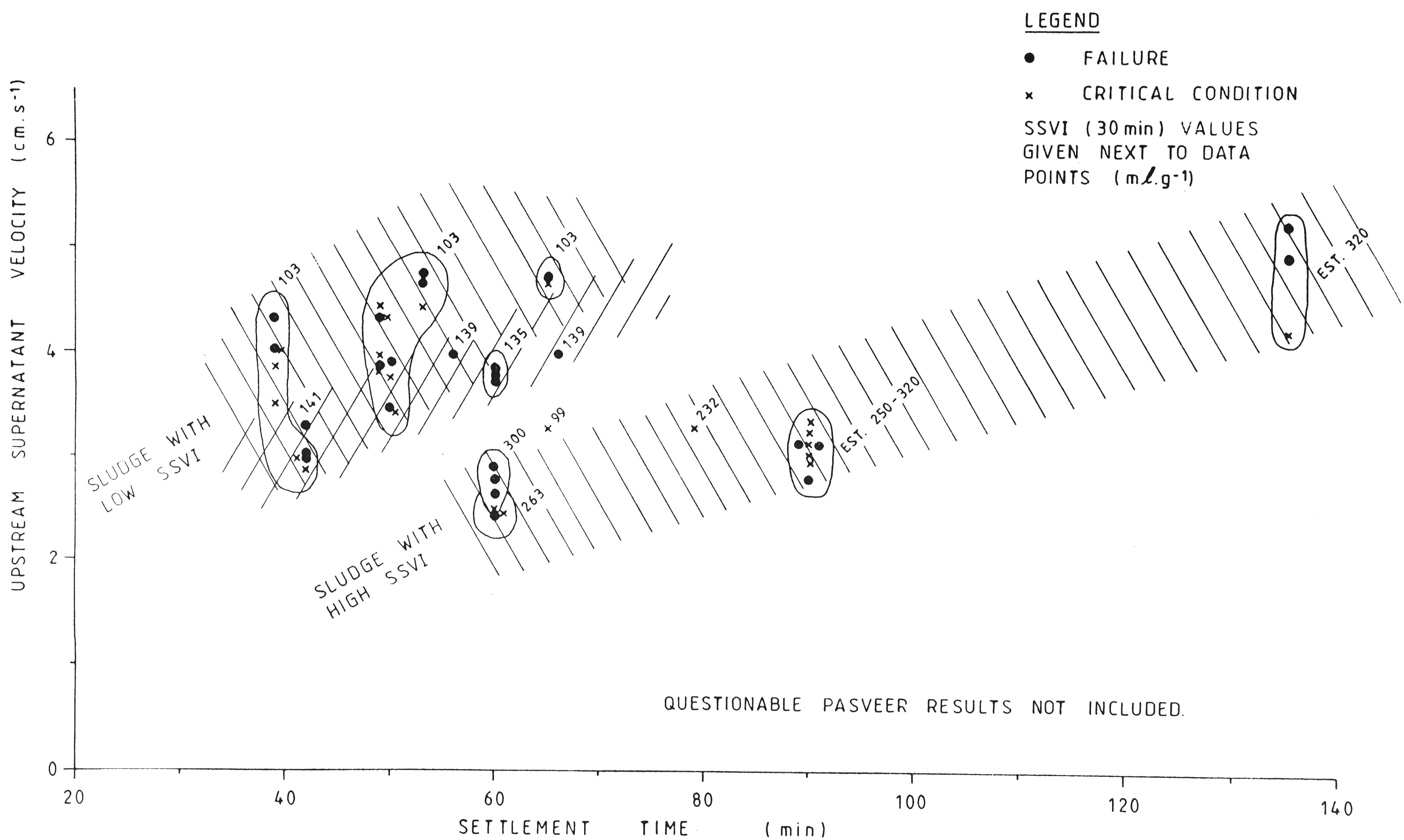
SUMMARY

This report describes an investigation into the mechanisms responsible for sludge carry-over during decant from an intermittent aeration tank. Several mechanisms were identified which may cause sludge carry-over. An 'early failure' mode may occur during the transient phase at the start of decant. This failure mode can be avoided by gradually increasing the rate of decant to a final steady value. The time required for flow establishment is in the order of five minutes in tanks of current size. Following the transient phase, failure can occur when interfacial shear stresses between the supernatant and settled sludge exceed some critical value. This failure mode is considered to be a 'scour failure' analogous to the onset of erosion of a cohesive sediment. Experiments conducted in a variety of different types of extended aeration tanks indicated that the critical parameters governing failure are the upstream velocity of supernatant, the settlement time, and the Stirred Sludge Volume Index (SSVI).

Figure S.1 below, shows the relationship between these three parameters for the range of tested values.

Appreciation of the failure mechanisms has indicated certain design improvements which could be made to existing aeration tanks, in particular to the rate of change of weir loading and the design of scum barriers. The significance of tank depth is also discussed.



DECANT TEST RESULTS

FIGURE S1.

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1. INTRODUCTION

The Public Works Department, NSW, (PWD), widely employs the activated sludge process for the treatment of wastewater. The process functions effectively with low food to micro-organism ratios in the range of 0.01 to 0.1 and is well suited to wastewater which may occasionally be appreciably diluted by stormwater. The Department, through a process of evolutionary design, has sought to improve the performance of its wastewater treatment plants.

The activated sludge process can either operate as a continuous system, allowing for aeration and settlement within separate tanks, or as an intermittent system where aeration and settlement occur cyclically in a single tank. The Pasveer Channel, Bathurst Box and Port Macquarie Tank all operate on the intermittent aeration cycle.

The aeration period is followed by a quiescent period during which the sludge is permitted to settle with the minimum of external disturbance. Following the settlement phase the supernatant liquor is withdrawn and discharged into effluent ponds for tertiary treatment or, in some cases, is disposed of to ocean outfalls.

The Public Works Department and The University of New South Wales, Water Research Laboratory (WRL), have recently investigated means by which the effectiveness of the decant process can be improved. Specifically the study aimed towards minimising the likelihood of sludge withdrawal during the decant phase. This required an understanding of the cause of sludge carry-over. Once the mechanisms had been identified, the process and plant design could then be optimised.

An improved understanding of the decant process will ultimately lead to a greater flexibility in the tank design and the selection of an optimum operating sequence.

Following a series of decant tests from 1984 to 1987 the Water Research Laboratory published a Research Report (WRL, 1988) which recommended that further testing should be carried out in deeper aeration tanks. In August–September 1988 this work was carried out at the Port Macquarie T 18 000 aeration tank as part of the author's Master of Engineering Science project. This report examines the properties of sludge flow, the failure conditions of various decant systems and gives recommendations for improved design of these decant systems.

2. SLUDGE PROPERTIES AND THE MECHANISMS OF FAILURE DURING DECANT

2.1 SLUDGE PROPERTIES AFFECTING CARRY-OVER

The properties of sludge affecting the mechanics of carry-over are highly variable and comparable to the variability associated with the transport of sediments in natural channels; an observation which is considered relevant to the conclusions drawn in this study. Previous studies have indicated the irregularity in the biological activity of sludge; it is now apparent, however, that these irregularities also affect the hydraulic properties of sludge. The condition of the floc filaments, the density of the volatile matter, percentage content of non volatile material and the settlement time all affect the stability of the sludge layer A major part of this project was devoted to understanding the flow properties of settled sludge and its relationship to the mechanisms which cause sludge carry-over during the decant phase. To avoid confusion, the following distinction is made between the terms 'mixed liquor' and 'settled sludge'. Mixed liquor refers to the fully mixed state that exists during the aeration cycle, while settled sludge refers to the settled floc blanket which forms once aeration has ceased. The settled sludge blanket is overlain by a relatively clear supernatant liquor with a scum layer often at the very surface.

Settled sludge is composed of two phases, a filamentous floc which is surrounded by a watery medium. It is these filamentous strands that directly influence the settlement and flow characteristics of sludge. The settlement velocity of a floc particle depends on the degree of external disturbance on the fluid, the relative density of the particle, and the degree of intertwining of the filament strands within the floc particle (PWD, 1984). Compaction of the sludge during settlement causes its structure to be non-homogeneous with depth. (Further discussion on these non-homogeneities is given in Section 4.4 of this report.)

The standard test used to identify the settlement characteristics of a sludge is the Water Research Centre (WRC) Stirred Settlement Test. The Stirred Settlement Test (SSV) provides two commonly used sludge parameters, the Stirred Sludge Volume Index (SSVI) and the maximum settlement velocity (w) often referred to as the Initial Settling Rate (ISR). No correlation was found between the maximum settlement velocity and the failure mechanism in the aeration tanks, however, SSVI values proved to be a good indicator of sludge variability. SSVI is the ratio between the relative compaction of stirred sludge and the measured concentration of the sludge.

The flow characteristics of mixed liquor and the settled sludge are very different. While floc particles are still in suspension the mixture exhibits close to Newtonian behaviour in shear with a density and viscosity slightly greater than that of water. However, as settlement continues, forces between floc particles become increasingly important. Settled sludge exhibits Bingham type stress characteristics and will support shear stress without flow occurring.

This difference in behaviour was simply demonstrated by taking a cylinder filled with mixed liquor overlying settled sludge and slowly stirring both layers into solid body rotation as shown in Figure 1. When the stirrer (a thin dowel), was removed, the settled sludge quickly came to rest while the supernatant rotated freely above. The boundary stress was transferred very effectively across the sludge while the much lower viscosity of the mixed liquor enabled it to maintain a high velocity at the fluid boundaries. When shear failure was forced in the sludge layer it occurred along clearly visible planes, see Figure 1. Similar failure planes were observed in experiments performed with settled sludge at North Richmond and Bowral. Because sludge is made up of complex organic compounds and micro-organisms undergoing a cascade of biological reactions, its physical properties and behaviour of the sludge can vary from week to week and, particularly, from one treatment plant to another.

The abovementioned flow characteristics of settled sludge appear to be governed mainly by the presence of the filament strands and the degree of intertwining of these filaments causing interlocking of the individual floc particles. This cohesion between the floc particles may result from either the natural biological growth of the filaments, or the interlocking of the floc particles during settlement.

2.2 DEFINITION OF FAILURE

Treatment plants are generally very successful in the biological conversion of non-settleable and dissolvable pollutants into a more manageable, settleable floc. If the quality of the tank effluent is inferior to that of the tank supernatant due to the effect of sludge carry-over, then the decant mechanism can be considered to have failed to optimise the effluent quality. In the case of NSW treatment plants, the State Pollution Control Commission (SPCC) specifies a required effluent quality based on the Biochemical Oxygen Demand (BOD) and the Suspended Solids (SS). It is this effluent standard that defines the failure point of a wastewater treatment plant. If this condition was used to define the failure point of a decant mechanism then depending on the quality of the supernatant there would be varying degrees of sludge carry-over that could be tolerated. For the purpose of this study, failure was based on the observation of sludge carry-over during the decant cycle and not the standard non-hydraulic parameters of Biochemical Oxygen Demand and Suspended Solids.

Terms such as 'no carry-over', 'minor carry-over', 'critical' and 'failure' have been used in Table 1 in order to provide a qualitative description of the extent of sludge carry-over.

Sludge carry-over via isolated vortices irregularly placed along the weir length was classified as 'minor carry-over'. The 'critical' point appeared to be easily distinguishable with the isolated points of carry-over joining into a steady stream of floc flowing over the decant weir. Beyond the critical point the sludge blanket rose towards the weir crest resulting in a 'failure' condition of severe carry-over and an obvious discolouration of the effluent. During the tests at Port Macquarie it was agreed by all observers that the critical and failure points were clearly distinguishable. The results presented in Table 1 show a consistence in the critical scour velocities during any particular test.

It should be emphasised that the upstream velocities measured during this study apply only to the tank and sludge conditions studied. Design conditions should, wherever possible, be determined from existing plants in which trial and error adjustments have already determined the most appropriate operating conditions given the annual variability in the sludge properties. Design considerations should not only be given to the operation of a treatment plant during periods of normal sludge, but also to the expected periods of adverse sludge condition.

2.3 MODES OF FAILURE DURING DECANT

Failure in this context is viewed to have occurred once the decanting fluid contains a steady fraction of sludge. Sludge carry-over can arise from a number of causes and the various mechanisms are revealed by an examination of the dynamic response of the contents of an aeration tank to the decant process.

When decant first commences the water surface is locally depressed by the local withdrawal of fluid. This then sets up a pressure gradient which drives fluid throughout the tank towards the decant weir. This initial response is very rapid and takes a time of the order of $2L/(gD)^{1/2}$ to become fully established, where L is the length of the tank, D its mean total depth and g gravitational acceleration. For the Macquarie Tank, when $L = 70\,m$ and $D \sim 2.2\,m$ the initial response time is about 30 seconds. The important feature of this initial phase of motion is that velocities are uniform over the full depth of the tank and even though a dense sludge layer is present, the fluid throughout the full depth responds as though it were of uniform density. The reason for this behaviour is that effects caused by the sludge being slightly denser than the supernatant fluid propagate much more slowly and take a time of the order of $2L/(\Delta gd)^{1/2}$ to develop where Δ is the difference in relative density of the sludge and the supernatant, and d is the depth to the sludge blanket. Again for the Macquarie Tank $d \sim 0.5\,m$ and $\Delta \sim 10^{-3}$ so that the time required for establishment of the internal flow throughout the tank is approximately 30 minutes. However selective withdrawal of the supernatant would proceed after times of the order of $30d/(\Delta g d)^{1/2} = 30(\frac{d}{\Delta g})^{1/2}$. For the Macquarie Tank this amounts to about five minutes. Since Δ typically has a value of about 10^{-3}, it takes from 2.5 to 5 minutes before effects due to density differences become established. During the transient phase, viscous effects are relatively unimportant and the flow patterns are close to those of an ideal fluid. Carry-over may occur immediately beneath the weir where vertical velocities may be substantial.

It is worthwhile noting at this stage that at the end of the settlement period the greater proportion of the sludge floc has settled, forming a self-supporting structure on the tank bed. At this point water pressures at the base of the tank would be near hydrostatic. During the start of decant the water particles have no physical knowledge of the presence of the sludge blanket and thus move towards the decant weir as if the tank contained water only. It is only upon moving that the water particles would begin to be restrained by the sludge blanket, however, this initial movement will result in the sludge blanket lifting slightly under the decant weir. This effect can be seen in Figures 33 to 68.

If the sludge were frictionless and the rate of withdrawal was less than some critical value, the pressure gradient set up by the inclination of the free surface would initially cause the sludge to move towards the decant trough. However, this motion would also cause the interface between the sludge and the supernatant to rise beneath the trough and fall at the far end of the tank. This inclination of the interface which occurs during the transient phase is in opposition to that of the free surface and will ultimately set up a pressure gradient in the lower layer which exactly balances that due to the surface inclination. Selective withdrawal of the surface layer can then proceed. Only if the rate of withdrawal exceeds a critical value will the denser layer also commence to be withdrawn. This critical flow rate can be expressed in terms of a densimetric Froude number based on the rate of withdrawal, the length of the decant trough, the depth of the supernatant and the difference in relative densities of the sludge and the supernatant. The value of the critical Froude number will depend on the particular geometry but typically will have a value somewhere between 0.5 and 1.

There is another important property of sludge which is relevant to carry-over and that is its cohesion. As sludge settles, the floc particles bind together enabling the sludge to withstand weak shear forces without separating. Only when the shear stress exceeds some critical value will failure planes develop in the sludge layer causing it to flow. Newtonian fluids such as water are unable to withstand shear stress without flow occurring.

Experiments to be described later suggest that cohesive force between floc particles increases with settlement, but finally asympotes to a limiting value.

The ability of a settled sludge to withstand weak shear forces implies that the interfacial adjustment associated with selective withdrawal may not occur and the pressure gradient set up by the inclination of the free surface is balanced by shear forces within the sludge. Therefore carry-over with a settled sludge will occur when the shear stress caused by flow of the supernatant fluid exceeds some critical value. The selective withdrawal criteria would apply during the early stages of settlement before cohesive forces between floc particles are well established. However with increasing sludge settlement the critical shear criteria would be increasingly important in determining whether carry-over would occur.

2.4 REVIEW OF THE EXPERIMENTAL DATA

Three modes of possible failure have been identified during decant.

Mode 1 Early failure which is due to the initial surge-like response when decant first starts.

Mode 2 A failure to selectively withdraw from the upper layer which may occur during the early stages of settlement when bonding between the floc particles is sufficiently weak.

Mode 3 An erosion failure which occurs when the shear stress at the surface of the sludge blanket is sufficient to break the bonds between floc particles. This mode becomes increasingly important with increasing settlement time.

The transition from Mode 2 to Mode 3 would be continuous. Mode 2 failures are characterised by a critical densimetric Froude number **F** defined by

$$\mathbf{F} = \frac{V}{(\Delta g d)^{1/2}}$$

where V is the mean velocity of the supernatant
Δ is the difference in relative density of the supernatant and the settled sludge (Figure 14)
g is gravitational acceleration, and
d is the depth to the sludge blanket (depth of the supernatant)

The early failure condition can be seen in Figure 2 where the velocity in the supernatant for critical and failure condition is plotted against time from the start of decant. Data values are all from the Port Macquarie tests. It is apparent that some early failures occur at appreciably lower velocities (typically 2 to 3 cm/sec) compared with failures after longer settlement times (3 to 5 cm/sec).

The primary variables governing the control of Mode 3 failure have been established as:

(i) Upstream supernatant velocity (v)
(ii) Settlement time (t_s)
(iii) Stirred sludge volume index (SSVI) as the indicator of sludge variability.

The correlation between these primary variables can be seen in Figure 3. It can be observed that for a given sludge type the critical upstream supernatant velocity increases for increasing settlement time. It should be noted that Figure 3 relates only to the erosion failure mode, and the possibility of early failure or failure to selectively withdraw, should always be considered. Section 3 of this report will describe the criteria for the avoidance of sludge carry-over in more detail. Figure 3 contains all test results in which all three variables were measured. The questionable Pasveer results are not included.

In research studies such as this, often the most difficult and important task is the identification of the primary variables. To date there have been some 140 data points collected from 71 tests, each having around 10 possibly significant variables. In order to reduce this data down to the primary variables, several data plots were produced until a correlation was observed between a set of variables. Figures 69 to 82 show little or no correlation between the chosen variables. These figures have been presented for the reader's own interest.

3. CRITERIA FOR AVOIDANCE OF SLUDGE CARRY-OVER

3.1 EARLY FAILURE

Early carry-over can occur if the weir loading rate is increased too rapidly but can be avoided by gradually increasing the loading rate over a time of approximately $30(d/\Delta g)^{1/2}$, which is the establishment time for selective withdrawal in the vicinity of the outlet weir. This condition is generally satisfied in the Pasveer channels and the Bathurst Box but may not be satisfied in the Port Macquarie Tank if the decant weirs are lowered too rapidly. This type of failure has been avoided in the new Port Macquarie T 18 000 tank via a time-stepping of the weir lowering.

3.2 FAILURE TO SELECTIVELY WITHDRAW

A failure of this type may occur during the adverse conditions of a storm cycle when the tank reaches top water level (TWL) before the sludge has had time to settle. It may be impractical to design for such a condition, however, if design data is required, Figures 69 to 82 contain data relating the densimetric Froude number to other sludge and tank parameters.

If there is a trend towards larger tanks with increased depth, this mode of failure may become important.

3.3 EROSION FAILURE

To avoid sludge carry-over caused by erosion failure, the upstream supernatant velocity should be below the critical velocity determined from Figure 3 for a given settlement time and sludge type.

Observations made during the model tests at North Richmond and Bowral indicated that sludge carry-over was the result of erosion of the supernatant/sludge blanket interface. The most appropriate parameter for such failure is the velocity difference across the interface. It should be noted that both theory and field observations indicated that the velocity is uniform over the full depth of the supernatant, except in the immediate vicinity of the weir.

It is therefore concluded that a maximum upstream velocity is the most appropriate design criterion for a decant mechanism. In that regard, all design formulas and specifications should be based upon a velocity term (v) rather than the often used weir loading rate term (q). In the case of deep tanks in which failure may occur due to a bulking sludge failing to settle to the design level, the selective withdrawal mechanism may apply. Application of this criterion for design requires an accurate determination of Δ and as this is not readily measurable in the field, it is proposed that the use of a reduced critical upstream velocity design criterion would be more practical.

Section 2.1 of this report described how the cohesive strength of the sludge blanket increases with settlement time. Such observations were also made during the lock exchange tests described in Section 5.2. It is not surprising then to find that settlement time, as shown in Figure 3, is considered as one of the primary variables.

Initially it was considered that the maximum settlement velocity (w) of the sludge would be the most appropriate indicator of sludge susceptibility to carry-over, however, as can be seen in Figures 69 to 82, there appeared to be no correlation between settlement velocity and decant failure conditions. Finally a correlation was found between supernatant velocity, settlement time and the stirred sludge volume index (SSVI). Both these latter terms are directly or indirectly related to the compaction and settleability of the sludge and thus the degree of interlocking of sludge particles. It is thus again not surprising that such a correlation should exist between SSVI and the erosion failure of the sludge blanket interface.

4. DESIGN RECOMMENDATIONS

4.1 TYPES OF INTERMITTENT EXTEND AERATION TANKS

The typical layout for a Pasveer Channel is shown in Figure 4 along with the trough type decant weir. Pasveer Channels were operating with a bellmouth weir for several years before the trough system was introduced after the experience gained in the development of the Bathurst Box. The bellmouth system was not investigated during this study because of its inferior performance compared with the trough system which replaced it. The trough mechanism is mechanically driven into the supernatant and its extent of travel is governed by the setting of limit switches. The aeration, settlement and decant phases of the process cycle are set and are independent of the amount of supernatant or the rate of inflow except during storm inflow. The decant mechanism produces a slow increase in the initial rate of decant thereby reducing the likelihood of early failure (see Figures 5 and 6).

If the weir lengths are not proportioned to the decant volumes on either side of the trough then supernatant will flow under and around the trough thereby increasing local velocities. The scum barrier produces a similar increase in velocity that may result in premature failure of the decant system (see Figure 7).

The Bathurst Box decant mechanism is also a mechanically driven trough. This system has the same advantages and disadvantages as previously mentioned for the Pasveer Channel, however because of the greater depth of supernatant under the trough, flow under the trough as a result of non-proportional weir lengths may not be as critical as in the Pasveer. Figures 8 and 9 show a typical layout of the Bathurst Box, decant trough and discharge curve.

Decanting from a Port Macquarie Tank is via floating weirs which are held in a raised position during the aeration and settlement cycles and are lowered to the water surface during decant. The system uses large floating tanks to control the immersion depth of the weir and these also act as scum barriers (see Figures 10 to 13). The duration of decant therefore depends on the water level and the rate of inflow. The weir loading rate is however independent of the inflow rate and is controlled by the float setting and the tank water level. The weir can be adjusted to produce a variety of variable relationships between decant rate and water level.

4.2 DECANT SYSTEM

There are basically two types of decant weirs, floating and mechanically driven. Floating weirs such as those used on the Port Macquarie T 15 000 are lowered quickly to the water surface and thereafter the submersion depth of the weirs is controlled by floats which give a discharge rate that is dependent only on the float settings and the water level in the tank. In the new T 18 000 tank the weirs were lowered slowly to the water surface to avoid problems of early failure. The mechanically driven weirs are lowered into the supernatant at a constant speed, thus producing a decant rate which is dependent upon the tank inflow rate, decant time, total weir length and the surface area of the tank. Mechanically driven weirs have the advantage of a relatively slow increase in discharge rate thus avoiding the early failure mode. During periods of low inflow when the surface level is low the weir troughs may spend only a small fraction of the cycle actually immersed. This of course may be considered as an advantage in times of poor sludge settlement.

The decant rate (q) of floating weirs is independent of the total weir length whereas the upstream velocity (v) is directly proportional to the total weir length provided the velocity distribution of the approach flow is reasonably uniform. The weir loading rate of mechanically driven weirs is dependent on the total weir length, however, the maximum velocity in the flow upstream from the weir is independent of the total weir length provided again the approach flow is reasonably uniform.

There are numerous weir designs that would yield the preferred 'rate of decant' profile shown in Figure 14 where there is a gradual increase in upstream velocity to the design maximum over a period of approximately five minutes. It is emphasised that the accurate setting of the weir crest levels is essential, however, there is no advantage in using sharp crested weir plates such as are currently employed on the floating decant weirs.

4.3 SCUM BARRIER

The blockage caused by a scum barrier to the flow approaching the decant weir produces an increase in local velocities which may destabilise floc at the surface of the sludge blanket and cause sludge carry-over. The blockage effect is most pronounced when the depth of supernatant liquor reaches a minimum. This phenomenon is easily observed on Pasveer trough decant systems in which the scum barrier can be manually immersed or raised, thus bringing the decant system in and out of the failure mode. For this reason it is considered that scum growth on the underside of the Port Macquarie floating scum barriers could adversely affect the operation of the weir.

The problem is more critical when the depth of supernatant liquor is small and the scum barrier is wide in the direction of supernatant flow (see Figures 7 and 10). The optimum design of scum barriers and the determination of their influence on the flow velocities can only be assessed by means of physical or numerical models.

4.4 TANK GEOMETRY

Weirs have either been located at the end of a tank as in the Port Macquarie units, or within the tank as in the case of the Pasveer and Bathurst Box. Weir troughs located within the tank should be designed such that flow does not occur under or around the trough. Proportioning the weir lengths in relation to the relative surface areas and the expected rate of raw sewage inflow is an obvious solution to this problem.

Depending on the efficiency of the inlet diffuser, the degree of short circuiting of raw inflow can be affected by the location of the weirs. The study of short circuiting is outside the scope of this study, however it is noted that the answer to this problem is not a simple case of placing the weirs as far from the inlet as possible. The basic principle to be followed in the design of the decant system and tank geometry in its vicinity, should be to minimise velocities in the supernatant liquor.

The total tank depth, concentration of mixed liquor and the shape of the floc particles all affect the final settled depth of the sludge. The maximum settlement velocity of the sludge is independent of the depth of the tank, however the settlement of the sludge blanket is indirectly related to the tank depth. Consider a horizontal $x-y$ plane through the tank, the volume above and below that plane must remain constant assuming there is no inflow to the tank. Thus the volumetric upflow of water past this plane must be equal to the volume of sludge settling past this plane over a given time period. A wide range of floc particles with a range of maximum settling velocities occur throughout the sludge. At the start of settlement, sludge particles with high settling velocities, will settle first causing an upflow of water that may be greater than the settlement velocity of some other floc particles thus keeping them in suspension. Ideally once a particle has passed this $x-y$ plane it will no longer cause any upflow past that plane and thus the settlement of the sludge blanket would be independent of tank depth. The tank, however, does not behave ideally and is not fully mixed in a totally homogeneous state. This results in the upwell being concentrated at certain points in the tank. Localised turbulence at the surface of the sludge blanket caused by the upwell was found to be randomly distributed over the tank demonstrating the lateral inhomogeneities that exist within the sludge blanket. As the tank depth is increased, the period in which these turbulent currents continue to keep the lighter floc particles in suspension also increases. Figure 15 shows that for the deeper T 18 000 tank, the sludge blanket interface took longer to settle than was the case in the T 15 000 tank. It should be noted, however, that the higher SSVI value of the sludge in the T 18 000 tank would also delay the settlement of the sludge blanket. Generally it may be found that deeper tanks require longer effective settlement times.

4.5 TANK INFLOW

Intermittent extended aeration plants operate with a continuous inflow even during decant. As previously mentioned this inflow does affect the upstream velocities in tanks with mechanically driven troughs, however in the floating trough system the inflow only increases the total decant time. In times of poor sludge settlement it may be beneficial to divert inflow during the decant of tanks with mechanically driven weirs. It is considered unlikely that the disturbance to the sludge blanket caused by a submerged inflow diffuser would have any measurable influence on the critical scour velocity.

4.6 BAFFLE BOARDS

The Port Macquarie tanks have been designed with baffle boards contained throughout the tank. These baffle boards do not appear to aid in preventing the effects of wind disturbance during settlement and it was observed that these baffles actually increased the effects of wind disturbance. With the introduction of an inlet box to the Port Macquarie tank it is unlikely that the baffle boards are still required to reduce short-circuiting of raw inflow.

5. TEST PROCEDURES AND RESULTS

5.1 NORTH RICHMOND AND BOWRAL MODEL TESTS

After the publication of the 1984 results it was considered that the first step in any further research would be an investigation into the failure mode. In order to do this a test tank was built with a clear acrylic side wall. The test tank was used to model the decant process and to allow observation of movement within the settled sludge blanket during failure. A layout of the test tank is shown in Figure 16.

Mixed liquor was pumped out of the North Richmond Pasveer into the test tank and allowed to settle. The surface of the sludge blanket during these tests was found to be rough and irregular so that when the weir plate was lowered causing the decant rate to slowly increase, there was an initial failure which removed the surface irregularities from the sludge blanket leaving a smooth stable surface. Further failure did not occur until the rate of decant was substantially increased. At the start of sludge carry-over in the second phase the movement in the sludge blanket was restricted to the region immediately below the interface and the eroded floc particles were advected up to the supernatant flow. All tests were recorded on video tape and it was from these tests that the notion of a scour failure originated. Had the failure been due to exceedance of the critical rate for selective withdrawal, flow would have been initiated over the full depth of the sludge blanket. Such behaviour was not observed.

After the critical point, failure continued with increasing decant rate. The shear stresses caused failure planes to appear in sludge blanket and large clumps of floc broke away from the blanket and passed into the flow above. The rate of decant was monitored during these tests by volumetric weighing. The test results are included in Table 1 and Figures 73 to 75 and show appreciable variation in the critical velocity of scour. This scatter is believed to be the result of varying degrees of settlement in the different experiments.

Similar decant tests were carried out at Bowral within a small rectangular container. Mixed liquor was collected from the Pasveer tank and allowed to settle in the container. Using a simple siphon and control valve the supernatant could be withdrawn from the container. Upon commencement of the decant, the sludge layer experienced a linear shear throughout its full depth. After this initial shear the settled sludge held its position until the critical surface velocity was exceeded and scour commenced on the interface (see Figure 17).

5.2 LOCK EXCHANGE EXPERIMENTS

One of the greatest difficulties experienced during the 1984 decant tests was the determination of the relative density difference between the settled sludge and supernatant. This density factor is required in the calculation of the densimetric Froude number which is the basic parameter of selective withdrawal. The 1984 tests relied on the weighing of one litre samples, however this method was subject to excessive error and an alternative method of determining the fluid density was required.

An alternative means of indirectly determining the density of the sludge was by means of a lock exchange experiment. The lock exchange experiment was originally developed to study the intrusion of salt water into a river channel following the opening of a shipping lock which separated the fresh river water from ocean waters. The same experiment can be used to indirectly determine the relative density difference between two fluids by measuring the velocity of the intruding fronts. The lock facility was calibrated using fresh and saline water. The experiment does however gauge the effective roles of gravity and inertia and is therefore relevant to the behaviour of the sludge during the process of selective withdrawal when a similar force balance is operative. Figure 18 shows the testing equipment used and the results of the calibration with fresh and saline water. The actual unit used was a rectangular box with clear acrylic sides, $1500 \times 105 \times 150$ mm deep with a water level depth of approximately 138 mm. The velocity of the density front is given by:

$$u = c\ (g.\Delta.h)^{0.5}$$

where u = velocity of density front ($m.s^{-1}$)

c = coefficient whose value depends on the relative depth of the dense layer h/H. Experiments have shown that C = 0.574 – 0.129 h/H.

Note: for mixed liquor (no settlement) h = H and C = 0.445

Δ = difference in relative densities of the sludge and the supernatant fluid

$$= \left[\frac{\rho_s - \rho_w}{\rho_w} \right]$$

ρ_s = density of mixed liquor or sludge

ρ_w = density of supernatant which is assumed to be equal to the density of water at the given temperature

g = gravitational acceleration ($m.s^{-2}$)

h = depth of sludge layer (m)

H = total liquid depth (m)

Due to the unknown effects of settlement on the flow characteristics of sludge, only those tests performed on the fully mixed liquor collected at bottom water level (BWL) were used to calculate the average relative density difference.

The results of the lock exchange tests have been presented in Table 2. A number of test results were treated with caution or totally discarded for the following reasons:

1. Bowral 17/2/87 tests LE5 and LE6 were discarded due to the suspected problems of having the temperature of the mixed liquor greater than that of the effluent. The density anomaly due to temperature was estimated as being comparable to that due to the sludge.

2. Tests LE22, 31A, 34, 37 to 40, 42 to 45, 51, 52 and 62 were discarded because of the variable velocity of the density front. It was apparent that cohesive forces in the floc structure were significant in comparison with the gravitational forces.

3. Tests X18–X22, X25–X28 were discarded due to the variable velocity of the density front. It is interesting to note that the initial velocity of these tests produced a relative density difference which was equivalent to that determined from tests X23 and X24. This indicates that initially the velocity of the density front was controlled by gravitational forces only, with the cohesive forces progressively becoming more apparent. The results of the 1988 lock exchange tests at Port Macquarie can be seen in Figures 19 and 20.

Ideally if the concentration and specific gravity of the sludge floc is known, then the relative density difference can be calculated directly:

$$\Delta = \text{MLSS} \times 10^{-6} \left[\frac{1}{b} - \frac{1}{S_{FLOC}} \right]$$

where S_{FLOC} = relative density of dried mixed liquor at BWL
b = relative density of water at the temperature of the supernatant
MLSS = mixed liquor suspended solids concentration ($mg.l^{-1}$) at BWL

Similarly if the sludge concentration is known and the difference in relative density is measured, then the relative density of the dried sludge particles can be determined using:

$$S_{FLOC} = \left[\frac{1}{a} - \frac{(\Delta' + 1)\, b/a - 1}{\text{MLSS} \times 10^{-6}} \right]^{-1}$$

where a = relative density of water at the temperature of the mixed liquor
Δ = difference in relative density at BWL
Δ' = difference in relative density uncorrected for any temperature difference between the two fluids. This is the relative density as initially calculated from the lock exchange test.

Figure 21 shows relative density of dry sludge plotted against the percentage of volatile matter. The results show that the relative density of dried sludge is not constant and its variation was assumed to be dependent on the percentage of volatile matter and the relative density of the volatile material. Non volatile matter was assumed to have a relative density of 2.5 (Fair and Geyer, 1954). Given the relative density of the mixed liquor floc and non volatile proportion, the relative density of the volatile matter can be calculated knowing the percentage volatility:

$$\frac{1}{S_{FLOC}} = \frac{\text{MLVSS}}{\text{MLSS}} \frac{1}{S_{VOLATILE}} + \frac{(\text{MLSS} - \text{MLVSS})}{\text{MLSS}} \frac{1}{S_{NONVOLATILE}}$$

where MLVSS = mixed liquor volatile suspended solids concentration ($mg.l^{-1}$).

Figures 21 and 22 show the relationship between the relative density of mixed liquor, the SSV sludge settlement rate and the volatile fraction for different sludges. The collection of more data may provide a clearer indication of the influence of the sludge volatile fraction on settlement.

A number of unforeseen complications developed in the lock exchange experiment due to the temperature difference between the two fluids and the filamentous properties of the mixed liquor. It is considered that if the temperature difference was adjusted to within $\pm 0.5°C$ then the movement of the mixed liquor in the lock exchange test as well as the final resting angle of repose, may, with further experience, provide an indicator for the filamentous properties of the mixed liquor. It is however noted that the present WRC stirred settlement test already provides a satisfactory indicator for the various sludge properties.

A number of lock exchange tests were performed on sludges which had been allowed to settle for up to 60 minutes in the lock exchange box. The results are shown in Figure 23 together with some typical results of the standard lock exchange experiment. It can be seen that the initial velocity of the density front was generally consistent with that of the fully mixed liquor, however, as the sludge moved the induced cohesive strength of the settled sludge would eventually halt the movement of the density front.

5.3 WRC STIRRED SETTLEMENT TESTS

The WRC stirred settlement test is a standard test developed by the Water Research Centre and has proven to be a reliable indicator of the in-tank settlement properties of sludge (Figure 1.a). There has been research carried out on the relationship between the intank settlement rate and that observed in the WRC cylinder, however, for this study, settlement rate is based on values obtained from the WRC stirred cylinder test. The results of these settlement tests are shown in Figures 24 to 32, with a summary given in Table 1.

5.4 DECANT TESTS

5.4.1 Port Macquarie 1984

The results of the 1984 decant tests and the test procedures used have been reported in the NSW Public Works Department Wastewater Engineering Research Bulletin Number 7 (PWD, 1986). A summary of these results is also presented in Table 1 and Figures 33 to 42. All the decant tests performed at Port Macquarie during 1984–86–88 were based on a similar procedure with water and sludge level measurements being made next to the baffle boards about 6 m out from the decant weirs (see Figures 10 and 12).

The decant rate for a relatively small portion of the flow passing over the centre floating weir was diverted through a triangular-notch, thin plate weir. Because of the variability of the weir settings along the total weir length of the tank, it is likely that the decant rate was higher and lower at various other locations as compared with the flow rate measured. It was also observed that varying degrees of sludge carry-over occurred across the total width of the decant weirs. For the purpose of this study the flow rate was measured at one location and the sludge carry-over condition was only recorded as that observed at the location of flow measurement.

The 1984 tests were carried out in the T 15 000 Aeration Tank No. 1 with a sludge of typical quality, however, prior to the commencement of these tests an excess amount of sludge had built up in the tank due to maintenance being carried out on one of the aerators. During the testing period some cases of excessive sludge carry-over did occur when heavy rain caused the tank to enter into the Storm Cycle resulting in only a short settlement period prior to decanting.

5.4.2 Sawtell B4000 1984

Preliminary investigation into the failure mechanism of a Bathurst Box B4000 was described in the above report although in the light of recent experimentation further discussion is warranted.

In December 1984 a decant failure condition was observed in the Sawtell Wastewater Treatment plant B4000. The depth to the sludge blanket at the start of decant was 0.58 m. During decant failure was observed when the depth to the sludge blanket as measured from the decant trough walkway was 0.4 m. The trough lowering rate was measured at 19.8 $mm.min^{-1}$ and the inflow was estimated at 880 $l.min^{-1}$. These figures give the upstream velocity as:

$$d = 0.58\,m \qquad v = 2.02\,cm.s^{-1}$$
$$d = 0.4\,m \qquad v = 2.93\,cm.s^{-1}$$
$$d = 1.0\,m \qquad v = 1.17\,cm.s^{-1}$$

It is apparent that when the supernatant depth is at the design value of 1.0 m the upstream velocity is well below the value which produces failure. However with a poor settling sludge it was still in the settling phase at the start of decant and the shallow depth of supernatant may have made selective withdrawal of the upper layer impossible. As a result the sludge was also caused to flow when the velocity in the supernatant upstream of the trough reached a velocity of about 2 $cm.s^{-1}$. This failure would have lifted the sludge blanket under the weir thus resulting in the 0.4 m depth to the sludge blanket measured during failure.

Note: Upstream velocity (v) for a Bathurst Box Tank:

$$v = \frac{\text{Trough Lowering Rate} \times \text{Tank Upstream Surface Area} + \text{Inflow Rate}}{\text{Width of Weir} \times \text{Depth Sludge Blanket}}$$

5.4.3 Port Macquarie 1986

In September 1986 a second series of decant tests was carried out at Port Macquarie on the T 15 000 Aeration Tank. A summary of the results of these tests is given in Table 1 and a record of the water surface and sludge levels during settlement and decant is given in Figures 43 to 50. The lifting of the sludge blanket at the start of decant can clearly be seen in these figures.

TEST PROCEDURE

1. Near the end of the aeration cycle an observer was positioned about 6 m out from the centre floating weir, next to the baffle boards. Measurements of water level and depth to the sludge blanket were made during the settlement and decant cycles.

2. After 60 minutes settlement, or when the sludge blanket had reached the required test level, the decant was commenced manually.

3. The flow depth through the triangular-notch, thin plate weir was measured using a WRL 'wave probe' and recorded on a chart recorder.
4. A second observer adjusted the water ballast to control the discharge rate and watched the flow over the weirs for signs of sludge carry-over.
5. After the completion of the decant, mixed liquor samples were collected for the lock exchange test and the WRC settlement tests upon the commencement of aeration while the water level was at BWL.

5.4.4 Pasveer Decant Tests

The Pasveer decant tests were performed by the Public Works Department and the results were analysed by the Water Research Laboratory. Tests were performed on three plants — Bowral, Bundanoon and Huskisson. All three contained P2000 Pasveer units. Lock exchange and WRC settlement tests were performed concurrently and the results are presented in Figures 27 to 31 and Tables 1 and 2.

The test procedure consisted of manually over-riding the weir lowering mechanism at the start of the decant cycle thereby allowing settlement to proceed to the required depth. The decant was then permitted to proceed. The rate of decant was calculated as shown in Figures 5 and 6. During the initial tests it was observed that scour failure was occurring beneath the trough and that the disturbed sludge was carried over the weir plate which faced the shorter end of the Pasveer. This failure condition was the result of mismatching of the weir geometry to the surface area of the Pasveer on either side of the trough causing flow to pass under and around the decant mechanism. As a result of this condition failure was initiated by the high velocities induced by the non-uniform flow distribution. Subsequently a proportionate section of the weir facing the shorter length of the Pasveer was blanked off producing near equal velocities on either side of the trough. This resulted in much more consistent values of the critical velocity. Only those tests performed with proportional weir length setting were plotted in Figure 3. All results shown in Table 1 for the Pasveer decant tests with a 12 m weir length (L) should be treated with caution.

At this stage there is no explanation for the poor fit of test P13 from Bowral on 31 March 1987. Figure 3 shows that either a higher critical velocity or a higher SSVI value would have been expected. Generally all the results from Bowral during that test period appeared to be out of the ordinary with the SSV maximum settlement velocity (w) being unusually high.

5.4.5 Port Macquarie 1988

The Water Research Laboratory's Research Report No. 172 recommended that further testing be carried out on deep tanks following the results of the 1986–87 decant tests. It was also discussed that work should be done on poor settling sludges to observe the variation in the critical scour velocity. In August–September 1988 a testing program was carried out in the new T 18 000 Aeration Tank No. 2 at Port Macquarie. This tank, as shown in Figure 12, was designed to have a depth to the sludge blanket of one metre at the start of decant. Prior to the commencement of these tests the aeration tank had been heavily overloaded causing the production of a poor settling sludge. The decant weirs were programmed to lower in steps so as to avoid the early failure of the sludge blanket, and the settlement time had been increased to 90 minutes.

A summary of the results from these tests is given in Tables 1 and 2 and a record of the in-tank sludge settlement is shown in Figures 51 to 68. Once again the disturbance to the sludge blanket at the start of decant can be seen in these figures.

6. CONCLUSIONS

(i) Three possible modes of failure may occur:

Mode 1 Early failure which is due to the initial surge-like response when decant first starts.

Mode 2 A failure to selectively withdraw from the upper layer which may occur during the early stages of settlement when bonding between the floc particles is weak. This failure mode was, however, not observed to occur independently of a Mode 3 failure condition.

Mode 3 An erosion failure which occurs when the shear stress at the surface of the sludge blanket is sufficient to break the bonds between floc particles. This mode becomes increasingly dominant with increasing settlement time.

The experimental program indicates that Mode 3 failure is the prime cause of sludge carry-over in existing extended aeration tanks.

(ii) The primary variables governing the control of Mode 3 sludge carry-over have been established as:

(a) Upstream supernatant velocity (v)
(b) Settlement time (t_s)
(c) Stirred sludge volume index (SSVI) as the indicator of sludge variability.

The correlation between these primary variables can be seen in Figure 3.

(iii) Design of the decant system should be based on a maximum velocity in the supernatant which is less than that which would cause erosion of the sludge blanket. In that regard, all design formulas and specifications should be based upon velocity rather than a weir loading rate as currently employed.

7. DEFINITION OF TERMS

1. a = correction term for the relative density difference of settled sludge

$$a = \frac{\text{depth of sludge below interface}}{\text{depth of liquor at BWL}}$$

2. a = relative density of water at the temperature of the mixed liquor

3. b = relative density of water at the temperature of the supernatant

4. c = lock exchange coefficient

5. d = depth to sludge blanket from water surface (m). (Depth of the supernatant.)

6. Final Slope = maximum final angle of repose of the resting sludge at the completion of the lock exchange test.

7. g = gravitational acceleration ($m.s^{-1}$)

8. H = lock exchange; total liquid depth (m)

9. h = lock exchange: depth of sludge layer (m)

10. L = total weir length (m)

11. Mixed Liquor Suspended Solids (MLSS)
This is the concentration of suspended solids in the mixed liquor calculated from a portion of a one litre sample taken at bottom water level (BWL) and recorded in units of $mg.l^{-1}$. The sample is dried at 103°C. The MLSS is representative of the workforce which carries out the treatment.

12. Mixed Liquor Volatile Suspended Solids (MLVSS)
The dried and weighed MLSS sample is heated to 600°. This burns off all 'volatiles' to leave an ash. The weight of MLSS in the sample dried at 103°C minus the weight of ash gives the weight of MLVSS.

13. q = weir discharge rate per unit length ($m^3.s^{-1}.m^{-1}$)

14. S_{FLOC} = relative density of dried sludge floc

15. $S_{VOLATILE}$ = relative density of volatile sludge matter

16. S_{NON} VOLATILE = relative density of non volatile sludge matter

17. WRC Stirred Settlement Test (SSV)
This is a standard test for sludge settleability. The test was developed by the Water Research Centre and consists of a large Perspex cylinder graduated to a height of 50 cm. A stirrer unit is placed in the cylinder which is filled with mixed liquor collected at BWL from the aeration tank. The test cylinder is shown in Figure 1.a. Settlement readings are taken at intervals of five minutes up to 30 minutes, then at 45 and 60 minutes.

18. Stirred Sludge Volume Index (SSVI)
This is is a measure of sludge settleability and is calculated on the percentage settlement after 30 minutes.

$$\mathrm{SVI} = \frac{\text{settled volume} \times 1000,\ (\mathrm{mg}.l^{-1})}{\mathrm{MLSS}\ (\mathrm{mg}.l^{-1})}$$

The constant ‘2 000’ is a unit conversion to relate the settlement level in a 50 cm cylinder to percentage settlement.

19. t_s = Initial sludge settlement time (min).

20. u = Velocity of density front in lock exchange test ($\mathrm{m.s^{-1}}$).

21. Upstream Supernatant Velocity (v)
Calculated average velocity upstream of the decanting mechanism using effective discharge per unit width divided by the depth to the sludge blanket given in this report as units ($\mathrm{cm.s^{-1}}$).

22. v_1 = Pasveer supernatant velocity assuming uniform velocity across full Pasveer width ($\mathrm{cm.s^{-1}}$).

23. v_2 = Adopted upstream supernatant velocity in Pasveer assuming an effective flow area 1 × d (m) away from the weir crest ($\mathrm{cm.s^{-1}}$).

24. Maximum Settlement Velocity (w_{max})
Settlement readings from the stirred settlement test are plotted against time to determine the maximum settlement velocity in units of ($\mathrm{mm.min^{-1}}$).

25. Froude Number ($\mathbf{F}$)
Dimensionless number expressing the ratio of inertial forces to gravitational forces.

$$\mathbf{F} = \frac{v}{(g.d)^{0.5}}$$

26. Densimetric Froude Number ($\mathbf{F}_\Delta$)
Similar to the Froude number except that inertial forces are compared with internal buoyancy forces.

$$\mathbf{F} = \frac{v}{(g.\Delta.d)^{0.5}}$$

27. Relative Density Difference Δ

$$\Delta = \frac{\text{density of settled sludge} - \text{density of supernatant}}{\text{density of supernatant}}$$

Δ' = uncorrected term calculated lock exchange without temperature correction

Δ_{TEMP} = temperature difference correction term

$$= \frac{\text{density of water at supernatant temperature} - \text{density of water at MLSS temperature}}{\text{density of water at supernatant temperature}}$$

Δ_{BWL} = relative density difference at the mixed liquor concentration at bottom water level (BWL)

NOTE: $\Delta = \Delta_{BWL}/a$

28. s = specific gravity of sludge

$$= \frac{\text{density of dry sludge (kg/m}^3)}{1000}$$

29. ρ_1 = density of supernatant ($kg.m^{-3}$)

30. ρ_2 = density of settled sludge ($kg.m^{-3}$)

31. ρ_w = density of effluent in lock exchange test ($kg.m^{-3}$)

32. ρ_s = density of mixed liquor or settled sludge in lock exchange test ($kg.m^{-3}$)

8. REFERENCES

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[2] PWD (1984) Augmentation of an intermittent extended aeration box using CIG Enviroshield Vitox III oxygen system. Public Works Department Sewerage Branch Technical Bulletin No. 3, September 1984.

[3] PWD (1986) Selective withdrawal from a stratified medium. Public Works Department, Wastewater engineering Research Bulletin No. 7, February 1986.

[4] Fair, G.M. and Geyer, J.C. (1954) Water supply and waste-water disposal. Wiley, Toppan.

9. ADDITIONAL DATA PLOTS

Listed below are a number of figures which have been used in the development of this study, however, little or no correlation was found between the chosen variables.

Figure 69	Supernatant velocity vs settlement time.
Figure 70	Supernatant velocity vs settlement time with maximum. settlement velocity
Figure 71	Supernatant velocity vs settlement time with SSVI (30 min). as for Figure 3
Figure 72	Supernatant velocity vs depth to sludge blanket reliable results only.
Figure 73	Supernatant velocity vs depth to sludge blanket including all results except Pasveer tests with non proportional weir lengths.
Figure 74	Supernatant velocity vs depth to sludge blanket including non carry-over and minor carry-over test results.
Figure 75	Supernatant velocity vs depth to sludge blanket with maximum settlement velocity.
Figure 76	Supernatant velocity vs depth to sludge blanket with SSVI (30 min) values.
Figure 77	Densimetric Froude number vs settlement time.
Figure 78	Densimetric Froude number vs settlement time with maximum settlement velocity.
Figure 79	Densimetric Froude number vs settlement time with SSVI (30 min) values.
Figure 80	Densimetric Froude number vs depth to sludge blanket, reliable results only.
Figure 81	Densimetric Froude number vs depth to sludge blanket, all test results excluding Pasveer tests with non proportional weir lengths.
Figure 82	Densimetric Froude number vs depth to sludge blanket including non carry-over and minor carry-over test results.

TABLE 1

DECANT TEST RESULTS

LEGEND

Test	Test number
t_s	Initial sludge settlement time (min)
d	Depth to sludge blanket (m)
q	Discharge per unit width ($l.s^{-1}.m^{-1}$)
v	Upstream supernatant velocity ($m.s^{-1}$)
w_{MAX}	Maximum sludge settlement velocity WRC Cylinder ($mm.min^{-1}$)
a	Sludge compaction ratio relative to concentration at Bottom Water Level (BWL)
$\mathbf{F}_{\Delta}$	Densimetric Froude number
$\mathbf{F}$	Froude number
L	Total weir length (m)
Δ_{BWL}	Difference in relative density at BWL
v_1	Pasveer supernatant velocity assuming uniform velocity across full Pasveer width ($cm.s^{-1}$)
v_2	Adopted upstream supernatant velocity in Pasveer assuming an effective flow area $1 \times d$(m) away from the weir crest ($cm.s^{-1}$).
SSVI	Stirred sludge volume index ($ml.g^{-1}$)

PORT MACQUARIE 11 – 16/10/84 $\Delta = \Delta_{BWL}/a = 0.0011$ $w_{MAX}(av) = 17.8\ mm.min^{-1}$ SSVI (30 min) = 135 $ml.g^{-1}$

Test	t_s (min)	d (m)	q $l.s^{-1}m^{-1}$	v $cm.s^{-1}$	-	a	F_Δ	F	Comment
3	45	0.46	14.3	2.8			0.40	0.0132	Early failure
7	37	0.47	12.9	2.5			0.35	0.0115	Early failure
8	60	0.51	15.6	2.7			0.37	0.0123	Early failure
11	≈60	0.62	26.3	3.82			0.47	0.0155	Failure
		0.62	23.4	3.40			0.42	0.0138	No carry-over
		0.62	24.7	3.59			0.44	0.0145	Minor failure
		0.62	26.5	3.85			0.47	0.0156	Failure
		0.62	25.8	3.75			0.46	0.0152	Failure

16/10/84 MLSS = 2960, MLVSS = 2560 $mg.l^{-1}$
17/10/84 MLSS = 2530, MLVSS = 2130 $mg.l^{-1}$ NOTE: $v = \frac{0.9 \times q}{d}$

NORTH RICHMOND AUGUST 1986 $w_{MAX}(av) = 13.0mm/min^{-1}$

Test	L (m)	d (m)	q $l.s^{-1}m^{-1}$	v $cm.s^{-1}$	-	a	F_Δ	F	Comment
2	-	0.174	6.56	3.77		0.42		0.0289	Failure
3	-	0.122	4.98	4.08		0.58		0.0373	Failure
4	-	0.165	4.22	2.56		0.44		0.0201	Minor carry-over
	-	0.195	6.32	3.24		0.34		0.0234	Failure
5	-	0.105	2.37	2.26		0.64		0.0223	Critical
	-	0.135	3.28	2.43		0.54		0.0211	Failure
	-	0.170	4.75	2.79		0.42		0.0216	No carry-over

PORT MACQUARIE 9 – 12/9/86 $\Delta_{BWL} = 0.00061$ $w_{MAX}(av) = 18.4\ mm.min^{-1}$ SSVI (30 min) = 103 $ml.g^{-1}$

Test	t_s (min)	d (m)	q $l.s^{-1}\ m^{-1}$	v $cm.s^{-1}$	w ($mm.min^{-1}$)	a	F_Δ	F	Comment
1	50	0.77	32.4	3.79	17.5	0.68	0.460	0.0138	No carry-over
2	115	0.9	36?	3.60	16.5	0.62	0.385	0.0121	No carry-over
3	39	0.56	15.4	2.48	19.0	0.82	0.386	0.0106	Early failure
		0.48	23.2	4.35		0.84	0.744	0.0201	Failure
		0.51	22.9	4.04		0.80	0.655	0.0181	Failure
		0.53	19.3	3.28		0.77	0.511	0.0144	Minor carry-over
		0.53	22.9	3.89		0.77	0.606	0.0171	Critical
		0.54	18.4	3.07		0.76	0.471	0.0133	Stopped
		0.54	21.0	3.50		0.75	0.534	0.0152	Critical
		0.57	25.5	4.03		0.71	0.581	0.0170	Critical
4	53	0.59	22.0	3.36	-	0.77	0.496	0.0140	Early failure
		0.59	31.2	4.76		0.76	0.699	0.0198	Failure
		0.59	24.0	3.66		0.76	0.537	0.0152	Stopped
		0.59	29.2	4.45		0.75	0.650	0.0185	Critical
		0.56	24.8	3.99		0.75	0.597	0.0170	Stopped
		0.56	29.2	4.69		0.75	0.702	0.0200	Failure
		0.56	21.5	3.46		0.74	0.514	0.0147	Stopped
		0.57	25.6	4.04		0.73	0.592	0.0171	No carry-over
5	65	0.75	28.2	3.38	18.8	0.70	0.423	0.0125	No carry-over
		0.72	37.8	4.73		0.71	0.607	0.0178	Failure
		0.69	29.2	3.81		0.72	0.503	0.0146	Stopped
		0.70	36.5	4.69		0.70	0.607	0.0179	Critical
		0.71	29.2	3.70		0.70	0.475	0.0140	Stopped
		0.72	35.1	4.39		0.68	0.552	0.0165	No carry-over

PORT MACQUARIE 9 – 12/9/86 $\Delta_{BWL} = 0.00061$ $w_{MAX}(av) = 18.4\ mm.min^{-1}$ SSVI (30 min) = 103 $ml.g^{-1}$

Test	t_s (min)	d (m)	q $l.s^{-1}\ m^{-1}$	v $cm.s^{-1}$	w $(mm.min^{-1})$	a	$\mathbb{F}_\Delta$	$\mathbb{F}$	Comment
6	49	0.65	28.2	3.90	21.4	0.78	0.553	0.0155	Failure
		0.60	25.6	3.84		0.79	0.570	0.0158	Critical
		0.60	24.9	3.74		0.79	0.554	0.0154	Stopped
		0.59	29.1	4.44		0.78	0.660	0.0185	Critical
		0.60	17.6	2.64		0.76	0.384	0.0109	Minor carry-over
		0.60	29.0	4.35		0.75	0.629	0.0179	Failure
		0.60	19.3	2.90		0.74	0.416	0.0119	Stopped
		0.60	29.0	4.35		0.73	0.621	0.0179	Critical
		0.60	16.8	2.52		0.73	0.360	0.0104	Stopped
		0.60	26.5	3.98		0.71	0.559	0.0164	Critical
7	50	0.47	10.4	1.99	16.9	0.84	0.344	0.0093	No carry-over
		0.47	18.5	3.54		0.84	0.613	0.0165	Minor carry-over
		0.47	20.5	3.93		0.83	0.675	0.0183	Failure
		0.48	10.7	2.01		0.83	0.341	0.0093	Stopped
		0.49	17.4	3.20		0.82	0.535	0.0146	No carry-over
		0.49	20.5	3.77		0.82	0.630	0.0172	Critical
		0.51	17.6	3.11		0.78	0.497	0.0139	No carry-over
		0.52	20.1	3.48		0.78	0.551	0.0154	Failure
		0.52	18.8	3.25		0.76	0.509	0.0144	Minor carry-over
		0.52	20.0	3.46		0.75	0.538	0.0153	Critical
		0.50	17.2	3.10		0.74	0.487	0.0140	Minor carry-over

PORT MACQUARIE 9 – 12/9/86 $\Delta_{BWL} = 0.00061$ $w_{MAX}(av) = 18.4\ mm.min^{-1}$ SSVI (30 min) = $103\ ml.g^{-1}$

Test	t_s (min)	d (m)	q $l.s^{-1}\ m^{-1}$	v $cm.s^{-1}$	w ($mm.min^{-1}$)	a	F_Δ	F	Comment
8	42	0.43	10.3	2.16	-	0.85	0.392	0.0105	Early failure
		0.44	9.7	1.98		0.84	0.355	0.0096	Minor carry-over
		0.45	14.8	2.96		0.82	0.517	0.0141	Failure
		0.47	15.0	2.87		0.80	0.485	0.0134	Critical
		0.49	11.0	2.02		0.78	0.330	0.0092	No carry-over
		0.52	16.7	2.89		0.75	0.449	0.0128	Minor carry-over
		0.53	17.7	3.01		0.74	0.459	0.0132	Failure
		0.53	12.4	2.11		0.74	0.322	0.0092	Stopped
		0.53	17.6	2.99		0.74	0.457	0.0131	Critical
9	?	0.50	20.5	3.69	18.3	0.84	0.619	0.0167	Failure
		0.50	19.1	3.44		0.83	0.573	0.0155	Stopped
		0.50	22.9	4.12		0.83	0.687	0.0186	Critical
		0.50	22.1	3.98		0.81	0.655	0.0180	Critical
		0.50	23.8	4.28		0.78	0.692	0.0194	Minor carry-over
		0.50	25.9	4.66		0.77	0.748	0.0211	Failure
		0.50	14.1	2.54		0.77	0.407	0.0115	No carry-over
		0.50	22.1	3.98		0.75	0.630	0.0180	Just prior to critical
10	89	0.77	8.2	0.96		0.68	0.117	0.0035	No carry-over

Note: $v = \frac{0.9q}{d}$ $F_\Delta = \frac{v}{(g.\Delta.d)^{0.5}}$ $F = \frac{v}{(g.d)^{0.5}}$

BOWRAL 17–18/2/87 $\Delta_{BWL} = 1.17 \times 10^{-3}$ $w_{MAX}(av) = 12.6$ mm.min^{-1} SSVI (30 min) = 90 ml.g^{-1}

Test	t_s (min)	d (m)	q $l.s^{-1}$ m^{-1}	v_1 cm.s^{-1}	v_2 cm.s^{-1}	a	$\mathbb{F}_\Delta$	$\mathbb{F}$	Comment	L (m)
P1	45	0.34	8.0	2.3	2.4	0.726	0.33	0.0129	No failure	12
P2	31	0.33	8.3	2.4	2.5	0.70	0.342	0.0140	No failure	12
P3	24	0.20	4.2	2.0	2.1	0.85	0.404	0.0150	Failure	12

BOWRAL 24–25/2/87 $\Delta_{BWL} = 1.08 \times 10^{-3}$ $w_{MAX}(av) = 15.3$ mm.min^{-1} SSVI (30 min) = 90 ml.g^{-1}

Test	t_s (min)	d (m)	q $l.s^{-1}$ m^{-1}	v_1 cm.s^{-1}	v_2 cm.s^{-1}	a	$\mathbb{F}_\Delta$	$\mathbb{F}$	Comment	L (m)
P4	21	0.22	5.4	2.27	2.45	0.83	0.464	0.0167	Failure	12
		0.30	7.0	2.21	2.33	0.74	0.357	0.0136	No carry-over	12
P5	19	0.23	4.2	1.68	1.83	0.85	0.341	0.0122	Non failure	12
									Failure under trough	
		0.28	~7.0	2.35	2.50	0.77	0.403	0.0151	Failure	12
		0.45	5.4	1.18	1.20	0.59	0.134	0.0057	No carry-over	12
P6	29	0.36	7.0	1.88	1.94	0.67	0.258	0.0104	Non failure	12
P7	26	0.27	8.0	2.81	2.96	0.75	0.481	0.0182	Pre-critical	12
P8	27	0.30	8.1		2.70	0.77	0.42	0.0157	Non failure	12

HUSKISSON 24–25/3/87 $\Delta_{BWL} = 0.95\times10^{-3}$ $w_{MAX}(av) = 16.3\,mm.min^{-1}$ SSVI (30 min) - 129 $ml.g^{-1}$

Test	t_s (min)	d (m)	q $l.s^{-1}\,m^{-1}$	v_1 $cm.s^{-1}$	v_2 $cm.s^{-1}$	a	$\mathbb{F}_\Delta$	$\mathbb{F}$	Comment	L (m)
P9	31	0.28	4.0	1.27	1.43	0.75	0.243	0.0086	Critical?	12
		0.32	7.7	2.17	2.41	0.71	0.371	0.0136	Failure	12
P10	43	0.36	10.9		3.03	0.73	0.447	0.0161	Failure on far side of trough	12
P11	40	0.33	10.2	2.75	3.09	0.73	0.477	0.0172	Failure	12

BOWRAL 31/3–1/4/87 $\Delta_{BWL} = 1.67\times10^{-3}$ $w_{MAX}(av) = 18.0\,mm.min^{-1}$ SSVI (30 min) = 99 $ml.g^{-1}$

Test	t_s (min)	d (m)	q $l.s^{-1}\,m^{-1}$	v_1 $cm.s^{-1}$	v_2 $cm.s^{-1}$	a	$\mathbb{F}_\Delta$	$\mathbb{F}$	Comment	L (m)
P12	58	0.36	8.3	2.20	2.31	0.70	0.252	0.0123	Slight carry-over	12
		0.33	8.3	2.39	2.50	0.71	0.289	0.0140	Failure	12
P13	65	0.34	11.2	2.28	3.29	0.70	0.369	0.0180	~ Critical	8.67
P14	55	0.36	12.2	2.01	3.39	0.68	0.365	0.0180	Non Failure	7.43
P15	62	0.38	13.0	2.03	3.42	0.67	0.354	0.0177	Minor carry-over	7.4
P16	37	0.34	13.0	2.25	3.82	0.70	0.429	0.209	Failure on back face	7.4
P17	32	0.28	8.3	2.81	2.96	0.74	0.378	0.0179	Failure on back face	12

HUSKISSON 6–7/4/87 $\Delta_{BWL} = 1.07\times10^{-3}$ $w_{MAX}(av) = 12.6\,mm.min^{-1}$ SSVI (30 min) = 141 $ml.g^{-1}$

Test	t_s (min)	d (m)	q $l.s^{-1}\,m^{-1}$	v_1 $cm.s^{-1}$	v_2 $cm.s^{-1}$	a	$\mathbf{F}_\Delta$	$\mathbf{F}$	Comment	L (m)
P18	48	0.33	10.2	3.04	3.09	0.73	0.449	0.0172	Failure	12
		0.36	8.8		2.44		0.341	0.0130	Non failure	12
P19	58	0.38	11.5	1.72	3.03	0.66	0.390	0.0157	No failure	7.5
P20	45	0.50	15.3	1.77	3.06	0.57	0.319	0.0138	No failure	7.5
P21	42	0.35	11.5	1.83	3.29	0.72	0.461	0.0177	Failure Good data point	7.5
P22	60	0.38	9.7	2.32	2.55	0.66	0.328	0.0132	Pre-critical	12

BOWRAL 12 – 13/5/87 $\Delta_{BWL} = 0.30 \times 10^{-3}$ LOW! $w_{MAX}(av) = 10.3\ mm.min^{-1}$ SSVI (30 min) = 139 $ml.g^{-1}$

Test	t_s (min)	d (m)	q $l.s^{-1}\ m^{-1}$	v_1 $cm.s^{-1}$	v_2 $cm.s^{-1}$	a	$\mathbf{F}_\Delta$	$\mathbf{F}$	Comment	L (m)
P23	56	0.27	10.8	2.44	4.0	0.75	1.23	0.0246	Failure	8.7
		0.30	7.5		2.5	0.78	0.744	0.0146	No carry-over	8.7
P24	90	0.41	10.0	1.67	2.44	0.67	0.576	0.0122	No failure	8.6
		0.37	11.2		3.03	0.67	0.752	0.0159	(Drowned weir) No carry-over	8.6
P25	66	0.39	10.4	1.76	2.67	0.77	0.689	0.0136	No failure (Drowned weir)	8.6
		0.35	8.6	1.62	2.46	0.79	0.679	0.0133	No failure	8.6
		0.28	11.2	2.7	4.0	0.77	1.22	0.0241	Failure	8.6

BOWRAL 12/6/87 $\Delta_{BWL} = 0.46 \times 10^{-3}$ $w_{MAX}(av) = 8.3\ mm.min^{-1}$ SSVI = 232 $ml.g^{-1}$

Test	t_s (min)	d (m)	q $l.s^{-1}\ m^{-1}$	v_1 $cm.s^{-1}$	v_2 $cm.s^{-1}$	a	$\mathbf{F}_\Delta$	$\mathbf{F}$	Comment	L (m)
P27	79	0.30	9.9	2.57	3.3	0.76	0.780	0.0192	Critical-failure	9.95
P28	62	0.29	8.0	2.4	2.76	0.95	0.744	0.0164	Failure	12
		0.27	6.3		2.33	1.0	0.669	0.0143	No failure	12
		0.34	8.1		2.38	0.81	0.548	0.0131	No failure	12

PORT MACQUARIE T18000 31/8/88 – 6/9/88 $\Delta_{BWL} = 0.00024$ $w_{MAX}(av) = 11.5\ mm.min^{-1}$ SSVI (30 min) av = 280 $ml.g^{-1}$

Test	t_s (min)	d (m)	q ($l.s^{-1}.m^{-1}$)	v ($cm.s^{-1}$)	w_{MAX} ($mm.min^{-1}$)	a	F_Δ	SSVI (ml/g^{-1})	Comment
2	60	0.69	18.4	2.45	14.0	0.792	0.541	260	Failure
3	60	0.69	18.48	2.48	14.0	0.763	0.540	260	Approx. critical
		0.67	19.25	2.64		0.765	0.582		Failure
		0.64	15.95	2.29		0.759	0.514		No carry-over
4	60	0.58 *	18.11	2.90 *	11.5	0.875	0.738 *	300	Failure
5	60	0.63	17.01	2.50	11.5	0.820	0.591	300	Approx. critical
		0.65	19.7	2.79		0.808	0.642		Failure
6	90	0.89 *	25.6	2.65 *	11.5	0.739	0.498 *	250	No carry-over
		0.86 *	30.5	3.26 *		0.735	0.622 *		Minor carry-over
		0.83 *	23.8	2.64 *		0.711	0.504 *		Minor carry-over
7		0.87	21.2	2.24	11.5	0.719	0.420	250	No carry-over
		0.85	30.4 *	3.29 *		0.706	0.618 *		Minor carry-over

* Less Reliable Results

Note: $v = \frac{0.92q}{d}$ $\Delta_{BWL} = \Delta.a$ $F_\Delta = \frac{v}{(g.\Delta.d)^{0.5}}$

PORT MACQUARIE T18000 31/8/88–6/9/88 Δ_{BWL}=0.00024 w_{MAX}(av) = 11.5 mm.min^{-1} SSVI (30 min) av = 280 ml.g^{-1}

Test	t_s (min)	d (m)	q (l.s^{-1}.m^{-1})	v (cm.s^{-1})	w_{MAX} (mm.min^{-1})	a	$\mathbb{F}_\Delta$	SSVI (ml/g^{-1})	Comment
8	90	0.80 *	24.7	2.84 *		0.723	0.557 *		No carry-over
9	90	0.97	32.6	3.09		0.735	0.555		Minor carry-over
		0.97	35.4	3.36		0.729	0.601		Critical
		0.97	27.5	2.62		0.715	0.465		Reduced to minor
		0.95	32.6	3.16 *		0.692	0.556 *		Critical
		0.93 *	22.5	2.23 *		0.686	0.395		Reduced to minor
		0.93 *	27.8	2.75 *					Minor carry-over
10	90	0.88 *	27.0	2.82 *		0.719	0.526 *		No carry-over
		0.88 *	31.5 *	3.29 *		0.711	0.610 *		Critical
		0.87 *	22.5	2.38 *		0.709	0.443 *		Stopped
		0.86 *	27.0	2.89 *		0.688	0.533 *		No carry-over

* Less Reliable Results

Note: $v = \frac{0.92\,q}{d}$ $\quad \Delta_{BWL} = \Delta.a$ $\quad \mathbb{F}_\Delta = \frac{v}{(g.\Delta.d)^{0.5}}$

PORT MACQUARIE T18000 31/8/88–6/9/88 Δ_{BWL}=0.00024 w_{MAX}(av) = 11.5 mm.min^{-1} SSVI (30 min) av = 280 ml.g^{-1}

Test	t_s (min)	d (m)	q (l.s^{-1}.m^{-1})	v (cm.s^{-1})	w_{MAX} (mm.min^{-1})	a	F_Δ	SSVI (ml/g^{-1})	Comment
11	90	0.73	21.2	2.67		0.755	0.560		No carry-over
		0.73	22.1	2.80		0.753	0.588		Failure
		0.71	18.5	2.40		0.739	0.505		Reduced to minor
12									Flow rate at failure point too difficult to identify
13									Heavy carry-over occurred during decant due to poor settlement
14	90	0.80 *	25.1	2.89 *	8.5	0.781	0.589 *	320	Minor carry-over
		0.79 *	26.1	3.04 *		0.777	0.622 *		Critical
		0.79 *	27.0	3.14 *		0.775	0.641 *		Failure
		0.75 *	24.9	3.05 *		0.759	0.633 *		Very minor
		0.70 *	24.0 *	3.15 *		0.743	0.669 *		Failure
15									Flow rate at failure point too difficult to identify

* Less Reliable Results

Note: $v = \frac{0.92\,q}{d}$ $\quad \Delta_{BWL} = \Delta.a$ $\quad F_\Delta = \frac{v}{(g.\Delta.d)^{0.5}}$

PORT MACQUARIE T18000 31/8/88–6/9/88 Δ_{BWL}=0.00024 w_{MAX}(av) = 11.5 $mm.min^{-1}$ SSVI (30 min) av = 280 $ml.g^{-1}$

Test	t_s (min)	d (m)	q ($l.s^{-1}.m^{-1}$)	v ($cm.s^{-1}$)	w_{MAX} ($mm.min^{-1}$)	a	F_Δ	SSVI (ml/g^{-1})	Comment
16	90	0.79	22.9	2.67		0.775	0.545		Very minor
		0.77	25.1	3.00		0.747	0.609		Critical
		0.66	21.0	2.93		0.783	0.657		Stopped
17	135	0.90	42.6	4.35		0.763	0.826		No carry-over
		0.89	50.6	5.23		0.757	0.995		Failure
		0.88	32.6	3.41		0.755	0.651		Stopped
		0.87	46.5	4.92		0.753	0.944		Failure
		0.86	30.0	3.21		0.739	0.614		Very minor
		0.83	35.1	3.89		0.739	0.757		Minor carry-over
		0.82	37.7	4.23		0.739	0.828		Critical

* Less Reliable Results

Note: $v = \frac{0.92\,q}{d}$ $\Delta_{BWL} = \Delta.a$ $F_\Delta = \frac{v}{(g.\Delta.d)^{0.5}}$

TABLE 2

LOCK EXCHANGE RESULTS

LEGEND

Test	Test number
TEMP DIFF	Temperature of MLSS – Temperature of supernatant (°C)
u	Velocity of density front ($cm.s^{-1}$)
Settlement	Settlement time allowed before start of test (min)
Δ'	Difference in relative density uncorrected for temperature difference
Δ_{TEMP}	Difference in relative density temperature correction factor
Δ_{BWL}	Difference in relative density at Bottom Water Level
S_{FLOC}	Relative density of dried sludge floc
Final Slope	Final resting angle of repose of the sludge in the lock exchange box.
*	Results used to calculate average Δ_{BWL}
SSVI	Stirred Sludge Volume Index ($ml.g^{-1}$)
$S_{VOLATILE}$	Relative density of volatile sludge matter
$S_{NON\ VOLATILE}$	Relative density of non volatile sludge matter
MLSS	Mixed liquor suspended solids ($mg.l^{-1}$)
MLVSS	Mixed liquor volatile suspended solids ($mg.l^{-1}$)

PORT MACQUARIE SEPTEMBER 1986 $MLSS_{av}$ = 3308 at 87% VOLATILITY

Test	TEMP DIFF °C	u $\times 10^{-2}(m.s^{-1})$	Settlement min.	Δ' $\times 10^{-3}$	Δ_{TEMP} $\times 10^{-3}$	Δ_{BWL} $\times 10^{-3}$	S_{FLOC}	Final Slope	Comment
X1	Unknown	1.25	-	0.58					
X2	–1.6°	1.47	-	0.81	–0.30	0.51	1.18		*
X3	–1.6	1.60	-	0.96	–0.30	0.66	1.25		*
X4	–1.6?	1.47	-	0.81	–0.30?	0.51?	1.18?		*
X5	–2.6	1.82	-	1.24	–0.51	0.73	1.28		*
X7	–0.8	1.48	-	0.82	–0.15	0.67	1.25		*
X8	–2.0	1.52	10		–0.38	0.47	1.16	0.084	
X9	–1.0	1.60	20		–0.20	0.70	1.26	0.100	
X10	–1.2	1.58	-	0.93	–0.22	0.71	1.27	0.053	*
X11	–1.4	1.41	-	0.74	–0.26	0.48	1.17	0.068	*
X12	–0.8	Curved	30					0.076	
X13	–1.7	1.66	-	1.03	–0.33	0.70	1.27	0.011	* Slight wind effects
X14	–0.6	Curved	60					0.220	
X15	–2.1	1.44	-	0.77	–0.42	0.35	1.11	0.038	*
X16	+0.2	1.54	20		+0.04	0.82	1.33	0.083	
X17	–2.0	1.75	-	1.14	–0.40	0.74	1.29	0.024	*

Average of 10 tests (marked *) $\Delta_{BWL} = 0.61 \times 10^{-3}$, $S_{FLOC} = 1.23$, Excluding settled sludge.

Av. Max. Settled Velocity = 18.4 $mm.min^{-1}$ SSVI (30 min) = 103 $ml.g^{-1}$

$$\text{Av. } S_{FLOC} = 1.23 = \left[\frac{0.87}{S_{VOLATILE}} + \frac{0.13}{2.5}\right]^{-1}$$

$S_{VOLATILE} = 1.14$ assuming, $S_{NON\ VOLATILE} = 2.5$

BOWRAL 28/1/87 $MLSS_{av}$ = 3180 at 75% VOLATILITY

Test	TEMP DIFF °C	u $\times10^{-2}$(m.s^{-1})	Settlement min.	Δ' $\times10^{-3}$	Δ_{TEMP} $\times10^{-3}$	Δ_{BWL} $\times10^{-3}$	S_{FLOC}	Final Slope	Comment
LE1	+0.5	?	-					0.020	Wind effects
LE2	Not given	1.56	-	0.91					
LE3	–0.6	1.59	10		–0.14	0.81	1.34		

BOWRAL 17 – 18/2/87 $MLSS_{av}$ = 5320 at 80% VOLATILITY

Test	TEMP DIFF °C	u $\times10^{-2}$(m.s^{-1})	Settlement min.	Δ' $\times10^{-3}$	Δ_{TEMP} $\times10^{-3}$	Δ_{BWL} $\times10^{-3}$	S_{FLOC}	Final Slope	Comment
LE5	+0.3	1.92	-	1.38	+0.06	1.44	1.37	0.024	* Problems may result in Lock when $T°_{MLSS} > T°_{EFF}$
LE6	+1.0	1.81	-	1.23	+0.22	1.45	1.37	0.024	*
LE7	–3.0	2.08	-	1.63	–0.71	0.91	1.20	0.005	* Not level ground
LE8	–3.9	2.19	-	1.82	–0.94	0.88	1.19	Level	*
LE9	–3.1	2.25	10		–0.75	1.16	1.27	0.011	
LE10	–3.5	2.20	20		–0.87	0.96	1.22	0.015	
LE11	–4.2	Curved	30		–1.05	1.37	1.34	0.029	

Average of 4 tests (marked *) $\Delta_{BWL} = 1.17\times10^{-3}$, $S_{FLOC} = 1.28$

Av. Max. Settled Velocity = 12.6 mm.min^{-1} SSVI (30 min) = 90 ml.g^{-1}

$$\text{Av. } S_{FLOC} = 1.28 = \left[\frac{0.80}{S_{VOLATILE}} + \frac{0.20}{2.5}\right]^{-1}$$

$S_{VOLATILE}$ = 1.14

HUSKISSON 24–25/3/87 $MLSS_{av}$ = 3090 at 81% VOLATILITY

Test	TEMP DIFF °C	u $\times10^{-2}(m.s^{-1})$	Settlement min.	Δ' $\times10^{-3}$	Δ_{TEMP} $\times10^{-3}$	Δ_{BWL} $\times10^{-3}$	S_{FLOC}	Final Slope	Comment
LE29	–0.6	1.82	-	1.26	–0.13	1.13	1.57	–0.130	*
LE30	–0.5	1.61	-	0.99	–0.11	0.88	1.39	0.156	*
LE31	Ø		20					0.163	Lack of data points
LE31A	–0.3	Curved	-					0.100	
LE32	–1.7	1.69	-	1.07	–0.37	0.70	1.29	0.099	*
LE33	+0.3	1.63	-	1.01	+0.07	1.08	1.53	0.142	*
LE34	+0.3	Curved 1.36?	-	(0.70)	+0.07	(0.77)	(1.33)	0.152	Problem with plot
LE35	Ø	Curved	20					0.180	

Average of 4 tests (marked *) $\Delta_{BWL} = 0.95\times10^{-3}$, $S_{FLOC} = 1.45$

Av. Max. Settled Velocity = 16.3 $mm.min^{-1}$ SSVI (30 min) = 129 $ml.g^{-1}$

$$\text{Av. } S_{FLOC} = 1.45 = \left[\frac{0.81}{S_{VOLATILE}} + \frac{0.19}{2.5}\right]^{-1}$$

$$S_{VOLATILE} = 1.32$$

BOWRAL 31/3 – 1/4/87 $MLSS_{av}$ = 4335 † at 72% ‡ VOLATILITY

† average of 4640, 4030
‡ same for both samples

Test	TEMP DIFF °C	u $\times 10^{-2}$(m.s^{-1})	Settlement min.	Δ' $\times 10^{-3}$	Δ_{TEMP} $\times 10^{-3}$	Δ_{BWL} $\times 10^{-3}$	S_{FLOC}	Final Slope	Comment
LE36	–1.3	2.26	-	1.92	–0.23	1.69	1.63	0.117	* Breezy
LE37	–0.9	Curved 2.22	-	(1.88)	–0.15	(1.73)	(1.66)	0.142	
LE38	–2.7	Curved 3.57	-	(4.83)	–0.54	(4.29)	(84!)	0.119	
LE39	–4.0	Curved 4.90	-	(9.10)	–0.81	(8.29)	(–1.10)	0.111	
LE40	–3.3	Curved 3.41	20		–0.68	(3.70)	(6.68)	0.130	
LE41A	–1.6	Curved 2.27	-	1.96	–0.31	1.65	1.61	0.118	*
LE42	–1.6	Curved	-					0.110	
LE43	–1.9	Curved	10					0.109	
LE44	–3.2	Curved	20					0.128	
LE45	–6.3	Curved	30					0.124	

Average of 2 tests (marked *) $\Delta_{BWL} = 1.67 \times 10^{-3}$, $S_{FLOC} = 1.62$

Av. Max. Settled Velocity = 18.0 mm.min^{-1} SSVI = 99 ml.g^{-1}

$S_{VOLATILE}$ = 1.42 ?

BOWRAL 24–25/2/87 $MLSS_{av}$ = 4480 at 82% VOLATILITY

Test	TEMP DIFF °C	u $\times10^{-2}(m.s^{-1})$	Settlement min.	Δ' $\times10^{-3}$	Δ_{TEMP} $\times10^{-3}$	Δ_{BWL} $\times10^{-3}$	S_{FLOC}	Final Slope	Comment
LE12	–0.4	1.75	-	1.16	–0.08	1.08	1.31	0.019	*
LE13	–1.7	1.76	-	1.17	0.37	0.80	1.21	Level	*
LE14	–3.4	1.88	10		–0.79	0.54	1.13	0.013	
LE15	–1.1	1.78	30		–0.28	0.87	1.24	0.088	
LE16	–4.5		60					0.133	Lack of data
LE17	–1.4	2.12	-	1.70	–0.34	1.36	1.43	Level	*
LE18	–1.4	2.08	10		–0.35	1.25	1.38	0.016	
LE19	–2.8	1.98	20		–0.71	0.76	1.20	0.067	
LE20	–2.6	1.74	30		–0.67	0.50	1.12		
LE21	–1.1	1.86	-	1.32	–0.24	1.08	1.31	0.016	*
LE22	–1.4	Curved	-						
LE24	–3.1	1.87	20		–0.73	0.60	1.15	0.078	
LE25	–4.2	1.72?	30		–1.05	0.23	1.05	0.125	

Average of 4 tests (marked *) $\Delta_{BWL} = 1.08\times10^{-3}$, $S_{FLOC} = 1.32$

Av. Max. Settled Velocity = 15.3 $mm.min^{-1}$ SSVI (30 min) = 90 $ml.g^{-1}$

$S_{VOLATILE}$ = 1.20

BUNDANOON 10/3/87 $MLSS_{av}$ = 3590 at 52% VOLATILITY

Test	TEMP DIFF °C	u $\times 10^{-2}(m.s^{-1})$	Settlement min.	Δ' $\times 10^{-3}$	Δ_{TEMP} $\times 10^{-3}$	Δ_{BWL} $\times 10^{-3}$	S_{FLOC}	Final Slope	Comment
LE26	−0.8	2.01	-	1.53	−0.17	1.36	1.61	Level	*
LE27	−0.8	1.89	-	1.35	−0.17	1.18	1.48	Level	*
LE28	−0.8		10					−0.097	Not enough points

Average of 2 tests (marked *) $\Delta_{BWL} = 1.27 \times 10^{-3}$, $S_{FLOC} = 1.55$

Av. Max. Settled Velocity = 27.7 mm.min^{-1} SSVI (30 min) = 69 ml.g^{-1}

$$\text{Av. } S_{FLOC} = 1.55 = \left[\frac{0.52}{S_{VOLATILE}} + \frac{0.48}{2.5} \right]^{-1}$$

$$S_{VOLATILE} = 1.15$$

HUSKISSON 6-7/4/87 MLSS$_{av}$ = 3435† at 79% VOLATILITY

† good average of two tests

Test	TEMP DIFF °C	u $\times 10^{-2}$(m.s^{-1})	Settlement min.	Δ' $\times 10^{-3}$	Δ_{TEMP} $\times 10^{-3}$	Δ_{BWL} $\times 10^{-3}$	S_{FLOC}	Final Slope	Comment
LE46	Unknown		-					0.145	
LE47	Unknown		-					0.125	
LE48	Unknown		60					~0.525	
LE49	-0.4	1.74	-	1.12	-0.09	1.03	1.43	0.132	*
LE50	-0.1		-					0.123	Problem with data
LE51	-0.1	Curved 1.74	10		-0.02	1.11	1.47	0.180	
LE52	+0.7	Slight curve 1.71	20		+0.18	1.18	1.52	0.156	
LE53	-0.2	1.74	-	1.15	-0.05	1.10	1.47	0.141	*
LE54	-0.4	(2.01)	-	(1.51)	-0.08	(1.43)	(1.71)	0.113	Problem with data
LE55	-1.3	1.87	10		-0.29	1.05	1.40	0.133	
LE56	-2.1	2.03	30		-0.49	0.99	1.40	0.153	

Average of 2 tests (marked *) $\Delta_{BWL} = 1.07\times10^{-3}$, $S_{FLOC} = 1.45$

Av. Max. Settled Velocity = 12.6 mm.min^{-1} SSVI (30 min) = 141 ml.g^{-1}

$$\text{Av. } S_{FLOC} = 1.45 = \left[\frac{0.79}{S_{VOLATILE}} + \frac{0.21}{2.5}\right]^{-1}$$

$$S_{VOLATILE} = 1.30$$

BOWRAL 12 – 13/5/87 $MLSS_{av}$ = 3970† at 81% VOLATILITY‡

† average of 4060 & 3880

‡ good average

Test	TEMP DIFF °C	u $\times 10^{-2} (m.s^{-1})$	Settlement min.	Δ' $\times 10^{-3}$	Δ_{TEMP} $\times 10^{-3}$	Δ_{BWL} $\times 10^{-3}$	S_{FLOC}	Final Slope	Comment
LE57	–2.7	1.64	-	1.00	–0.53	0.47	1.13	>0.05	*
LE58	–2.7	1.60	-	0.96	–0.53	0.43	1.12		*
LE59	–1.6	1.18	-	0.53	–0.31	0.22	1.06		*
LE60	–0.8	1.16	-	0.51	–0.22	0.29	1.08		*
LE61	–1.6	1.16	-	0.51	–0.31	0.20	1.05		*
LE62	–1.9	Curved 1.35	-	0.70	–0.38	0.31	1.08		
LE63	–1.9	1.19	-	0.54	–0.37	0.17	1.04		*
LE64	–1.8								Just slumped!
LE65	–1.9	Curved							
LE66	–5.0 High ?	1.60	-	0.96	–1.04	–ve			Sludge slows; Temp effects!

Average of 6 tests (marked *) $\Delta_{BWL} = 0.30\times10^{-3}$, $S_{FLOC} = 1.08$

Av. Max. Settled Velocity = $10.3\,mm.min^{-1}$ SSVI (30 min) = $139\,ml.g^{-1}$

$$\text{Av. } S_{FLOC} = 1.08 = \left[\frac{0.81}{S_{VOLATILE}} + \frac{0.19}{2.5}\right]^{-1}$$

$S_{VOLATILE} = 0.95$?

BOWRAL 12/6/87 $MLSS_{av}$ = 2900 at 80% VOLATILITY

Test	TEMP DIFF °C	u $\times 10^{-2}(m.s^{-1})$	Settlement min.	Δ' $\times 10^{-3}$	Δ_{TEMP} $\times 10^{-3}$	Δ_{BWL} $\times 10^{-3}$	S_{FLOC}	Final Slope	Comment
LE69	−0.1	1.12	-	0.47	−0.02	0.45	1.18		*
LE70	−0.1	1.09	-	0.45	−0.02	0.43	1.17		*
LE71	Ø	1.14	-	0.49	Ø	0.49	1.20		*
LE72	Ø	1.13	-	0.48	Ø	0.48	1.20		*

Average of 4 tests (marked *) $\Delta_{BWL} = 0.46\times 10^{-3}$, $S_{FLOC} = 1.19$

Av. Max. Settled Velocity = 8.3 mm.min^{-1} SSVI (30 min) = 232 ml.g^{-1}

$$\text{Av. } S_{FLOC} = 1.19 = \left[\frac{0.80}{S_{VOLATILE}} + \frac{0.20}{2.5}\right]^{-1}$$

$$S_{VOLATILE} = 1.05$$

PORT MACQUARIE T18000 31/8/88 – 6/9/88 MLSS = 1900‡ AT 81% VOLATILITY

Test	TEMP DIFF °C	u $\times 10^{-2}$(m.s^{-1})	Settlement min.	Δ' $\times 10^{-3}$	Δ_{TEMP} $\times 10^{-3}$	Δ_{BWL} $\times 10^{-3}$	S_{FLOC}	Final Slope	Comment
X18									Questionable results
X19	0.0	0.943		0.33	0.0	0.33	1.21		Variable velocity
X20	+0.1	0.988		0.36	0.02	0.38	1.25		Variable velocity
X21	−0.1	0.870		0.28	−0.02	0.26	1.16		Variable velocity
X22	−0.1	0.885		0.29	−0.02	0.27	1.16		Variable velocity
X23	−0.5	0.957		0.34	−0.10	0.24	1.14		Good result *
X24	−0.5	0.953		0.34	−0.10	0.24	1.14		Good result *
X25	−0.3	0.629		0.15	−0.06	0.09	1.05		Variable velocity
X26	−0.5	0.855		0.27	−0.09	0.18	1.10		Variable velocity
X27	−0.2	0.897		0.30	−0.04	0.26	1.16		Variable velocity
X28	−0.5	0.997		0.37	−0.11	0.26	1.16		Variable velocity
							av = 1.15		

31/8/88	MLSS = 1600	MLVSS = 1310	w_{MAX} = 14.0 mm.min^{-1}	SSVI = 263 ml.g^{-1}	TESTS –
1/9/88	= 1600	= 1470	= 11.5	= 300	× 18
2/9/88	= 1900	= 1540	= 11.5	= 252	× 19 – × 24
5/9/88	= 1900	= 1600	= 8.5	= 321	× 25 – × 26

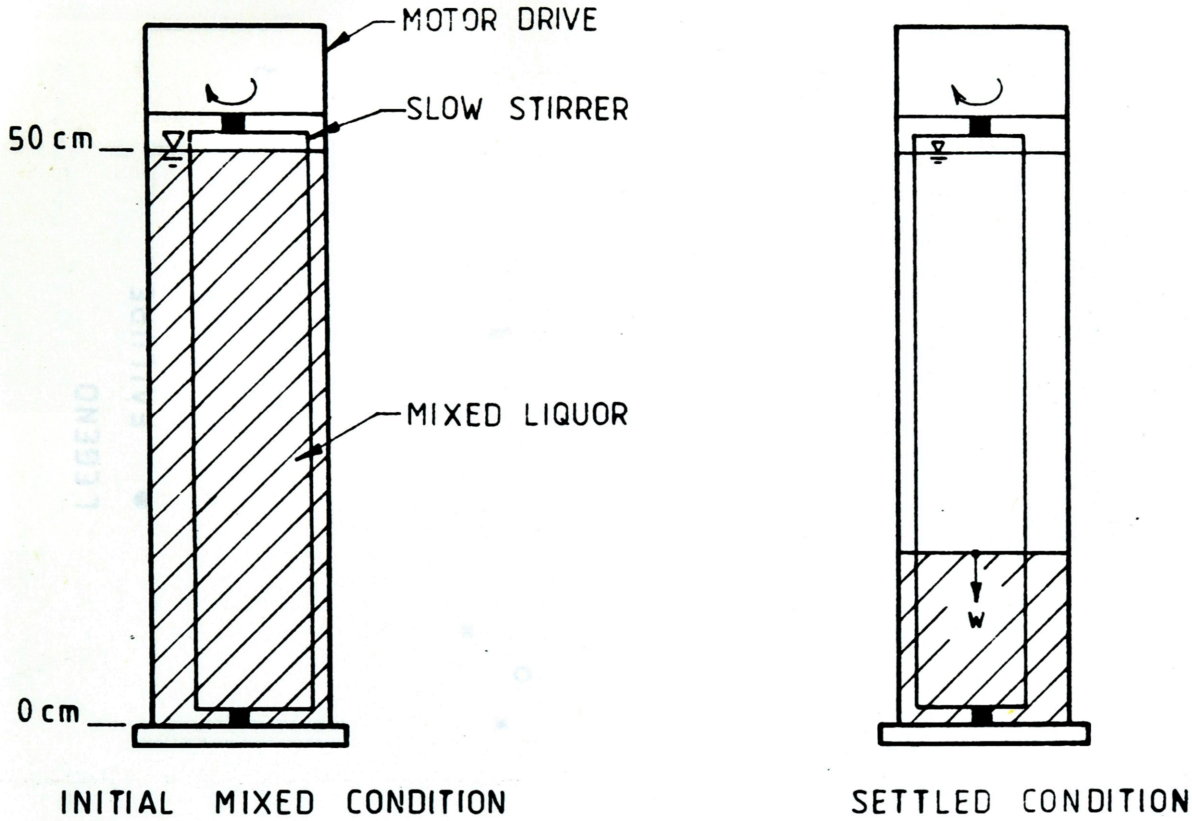
‡ MLSS determined on same day as tests X23, X24

Average of 2 tests (marked *) $\Delta_{BWL} = 0.24 \times 10^{-3}$

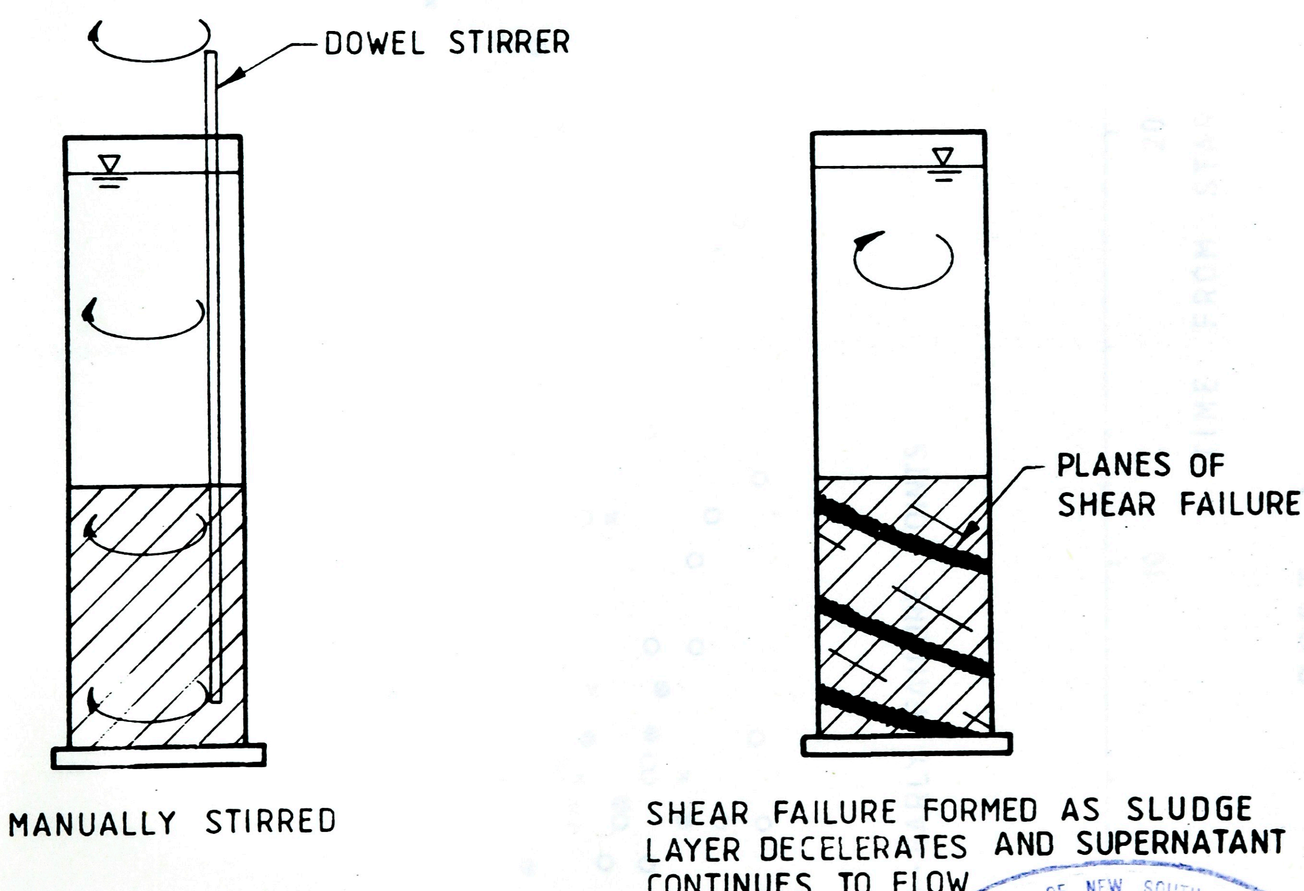
Av. Max. Settled Velocity ≈ 11.5 mm.min^{-1}

$S_{FLOC} = 1.14$ SSVI (30 min) av ≈ 280 ml.g^{-1}

$S_{VOLATILE} = 1.01$ assuming $S_{NON\ VOLATILE} = 2.5$



W.R.C. STIRRED SETTLEMENT TEST
FIGURE 1a



SLUDGE FLOW CHARACTERISTICS
FIGURE 1b

FIGURE 1

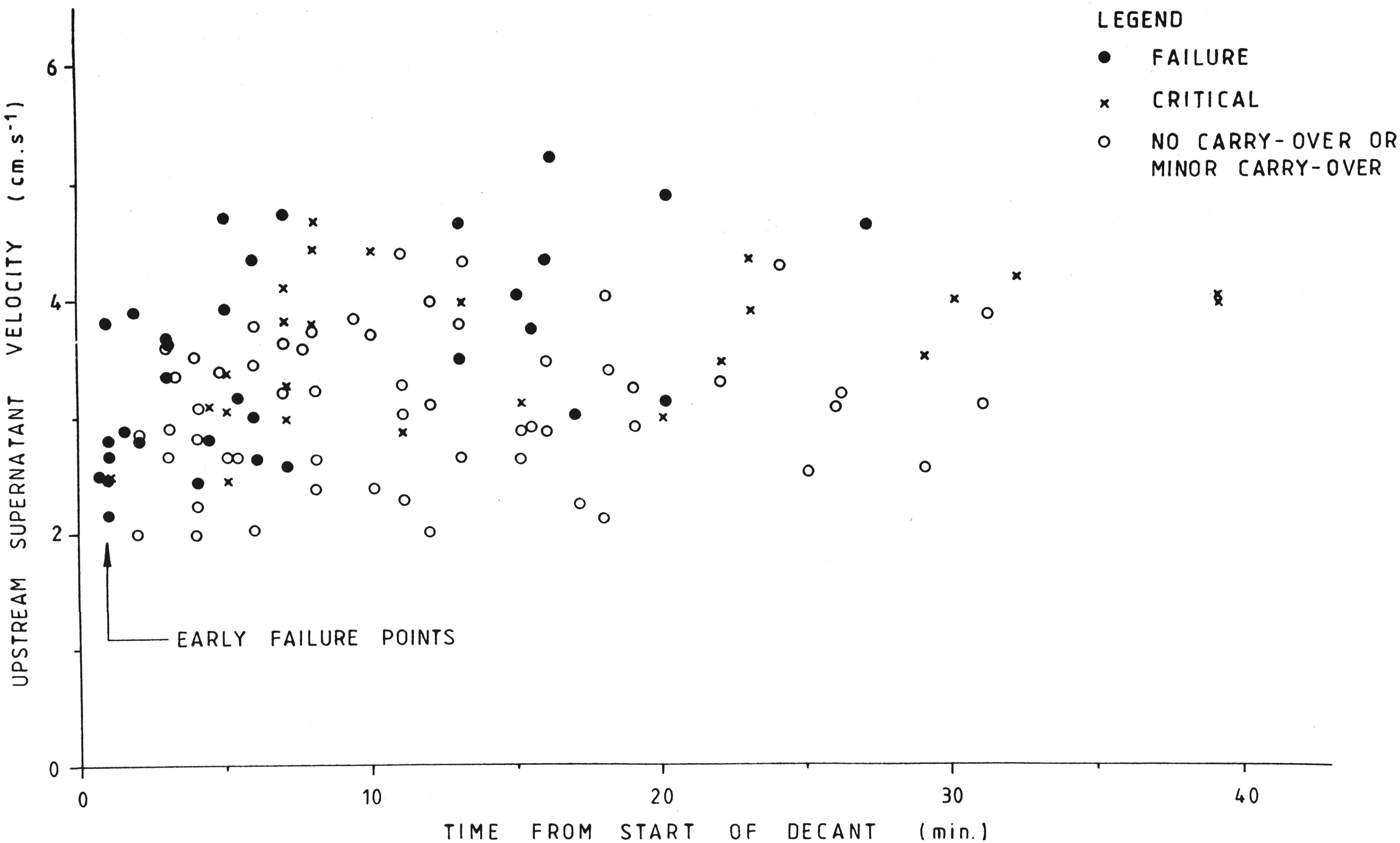


FIGURE 2

PORT MACQUARIE DECANT TESTS 1984-86-88

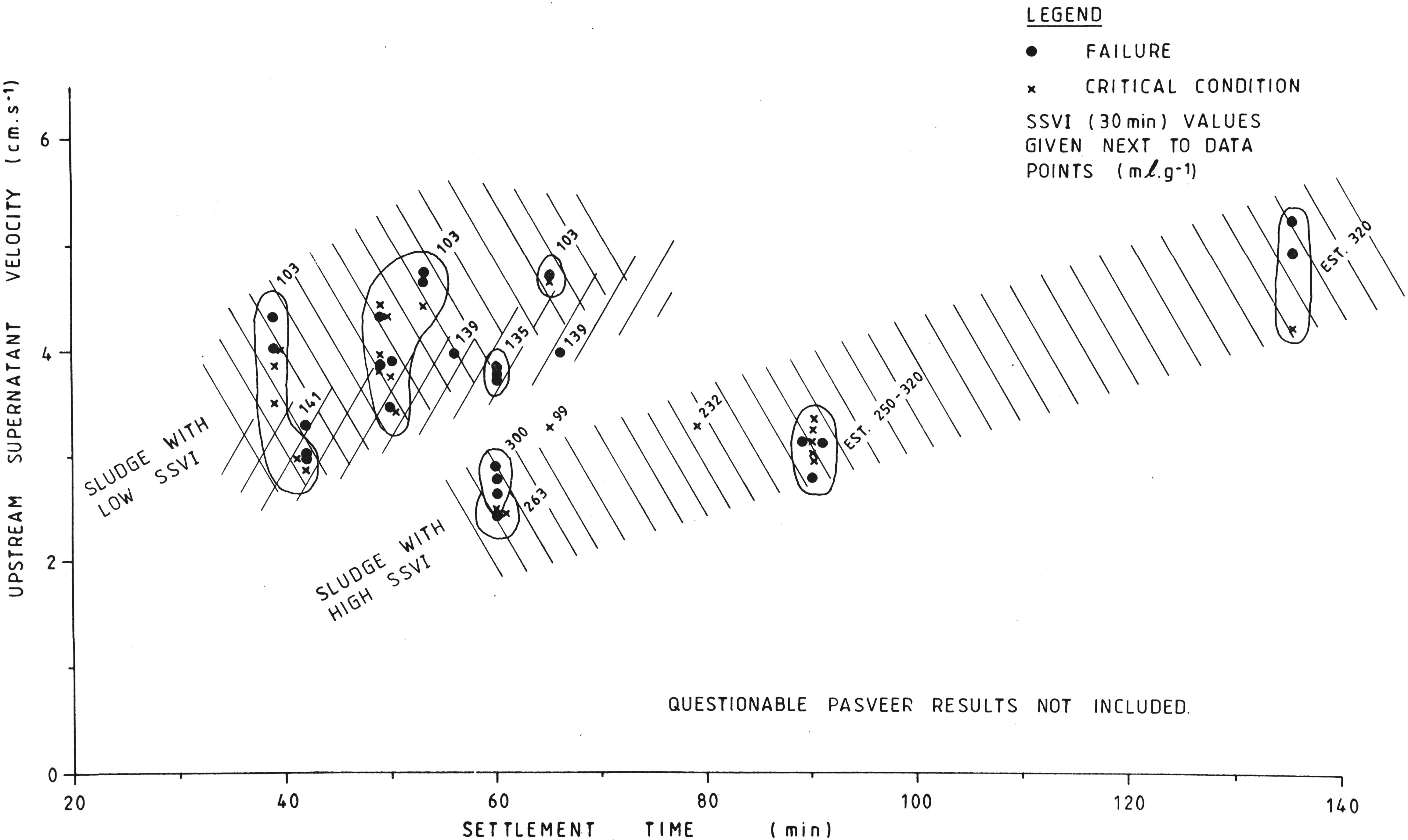
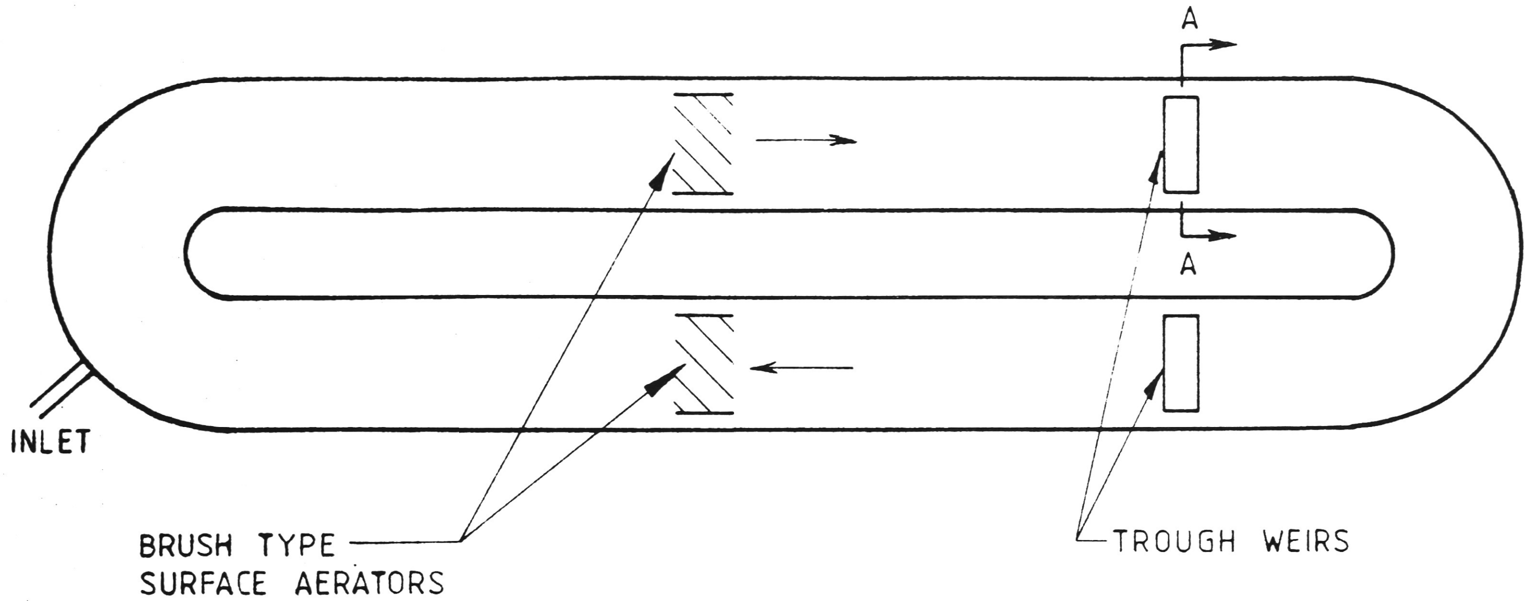
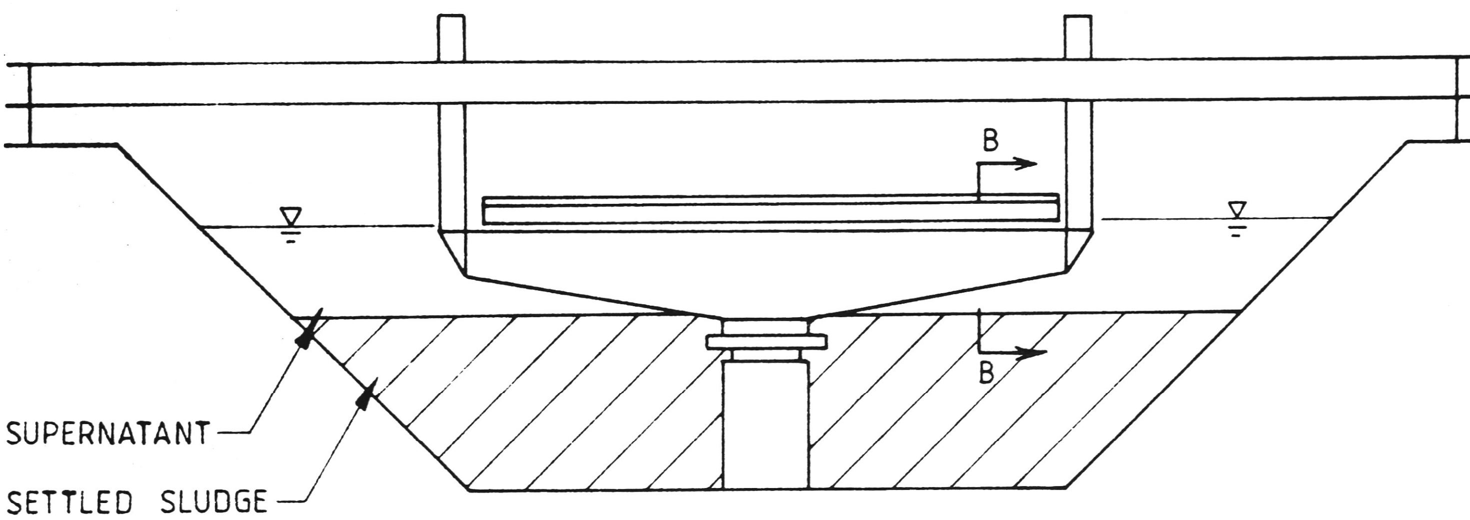


FIGURE 3

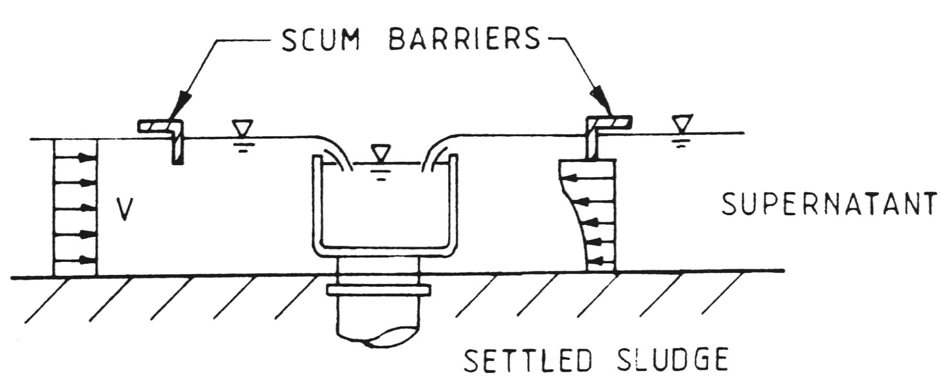
DECANT TEST RESULTS



PLAN



DECANT TROUGH SECTION A-A

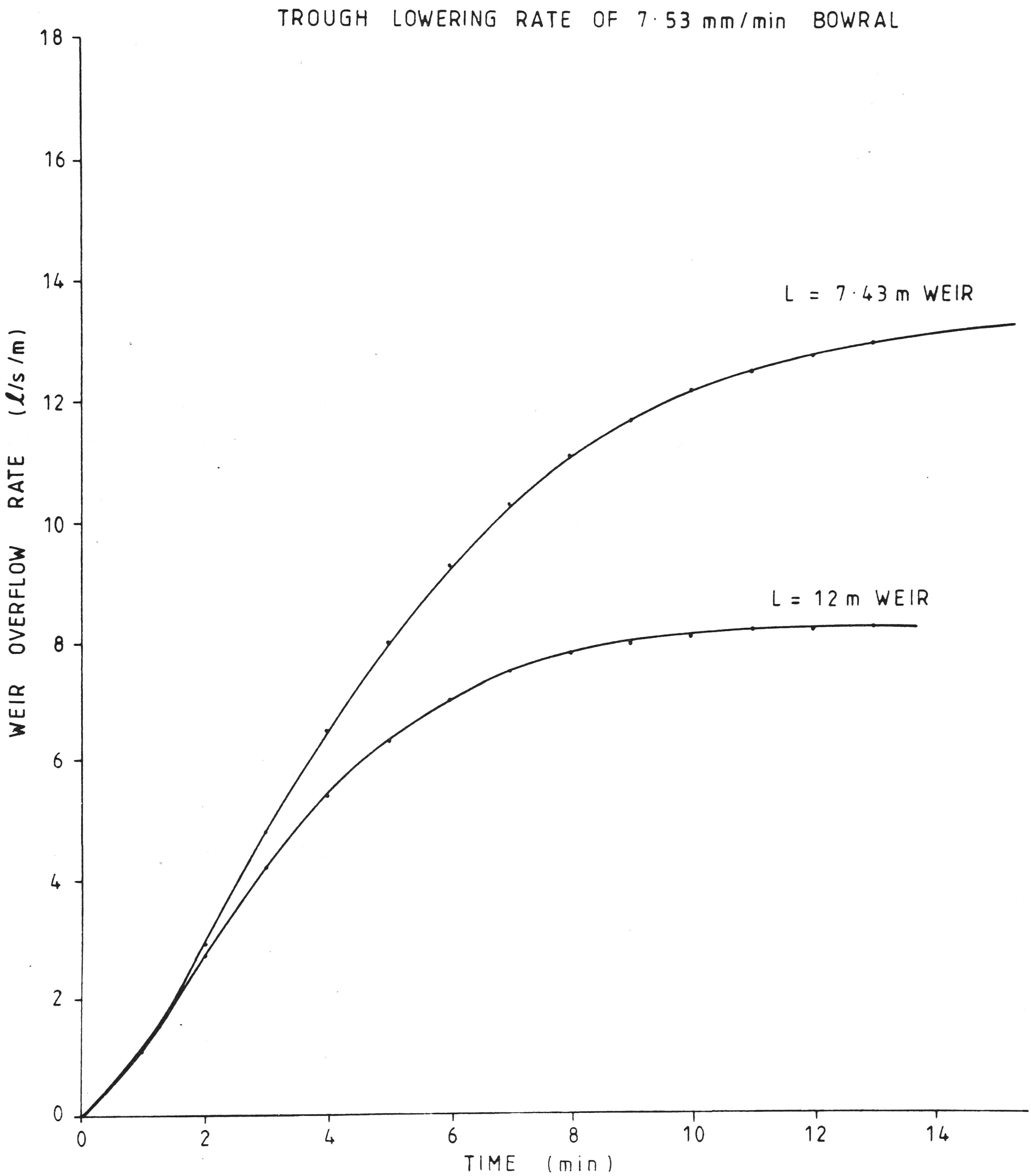


WEIR TROUGH SECTION B-B

NOT TO SCALE

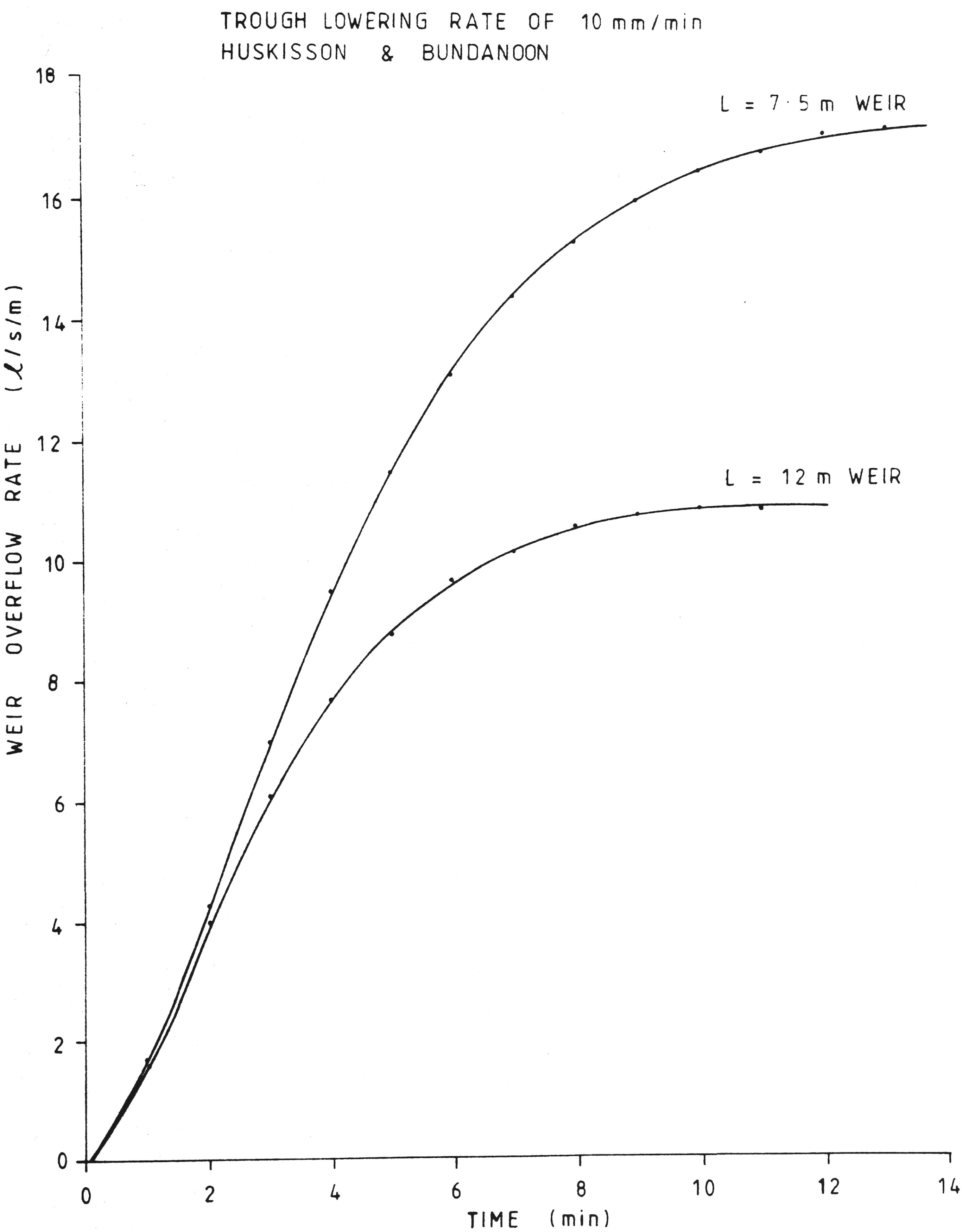
PASVEER CHANNEL

FIGURE 4



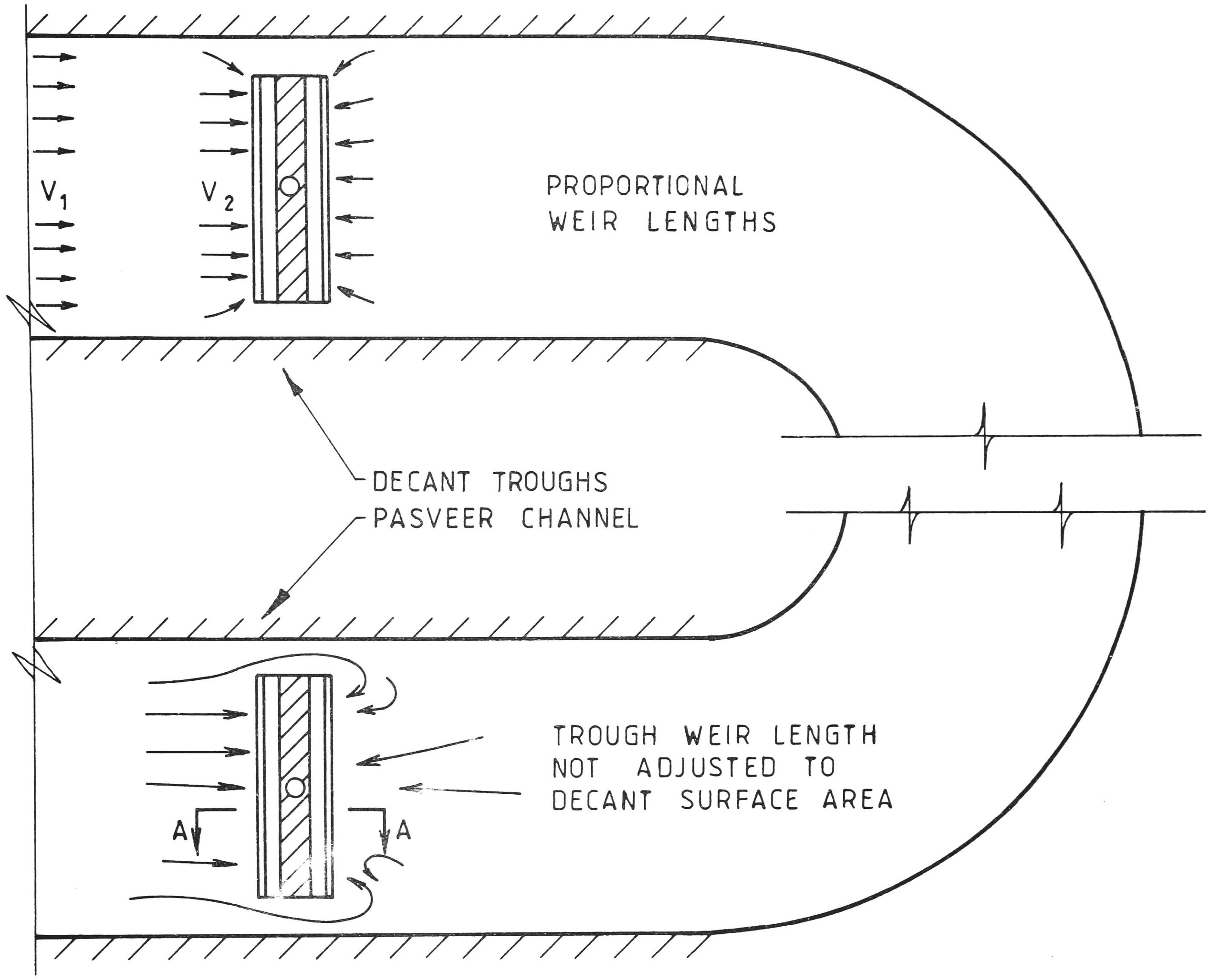
PASVEER TROUGH DECANTING RATE

FIGURE 5



PASVEER TROUGH DECANTING RATE

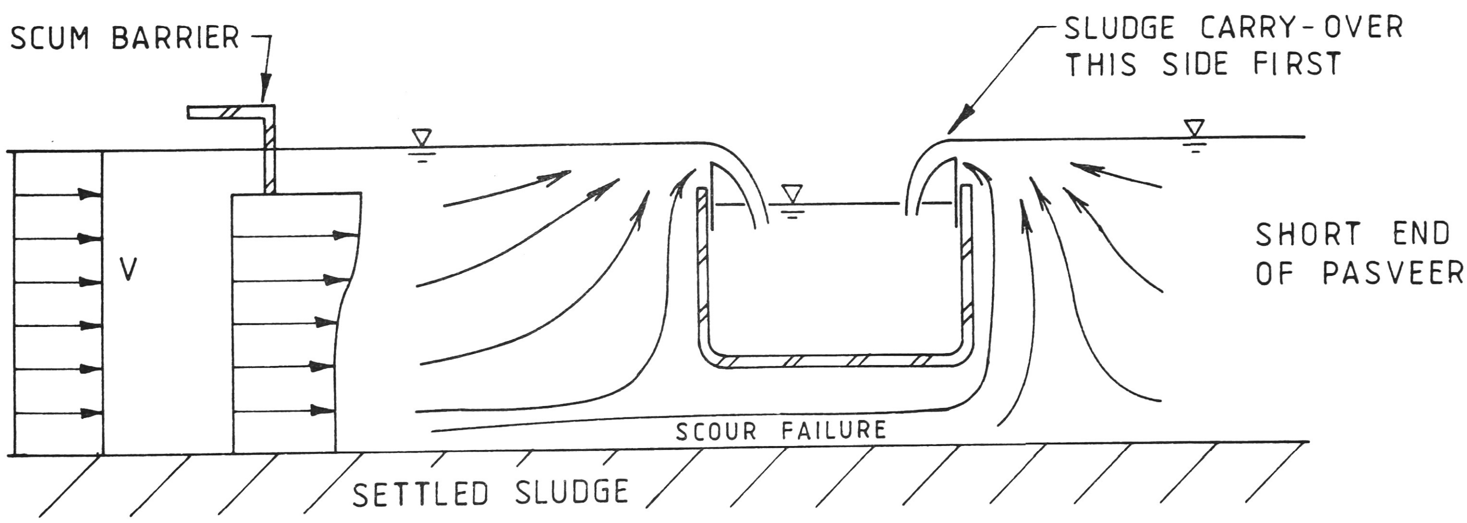
FIGURE 6



PLAN

FLOW AROUND TROUGH

NOT TO SCALE

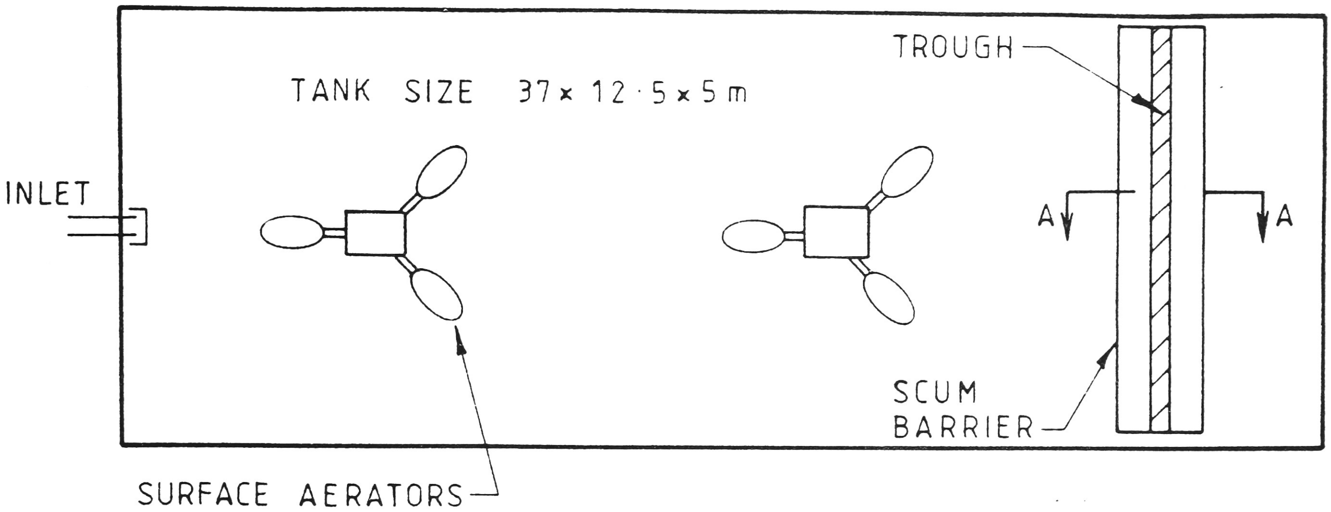


SECTION A-A

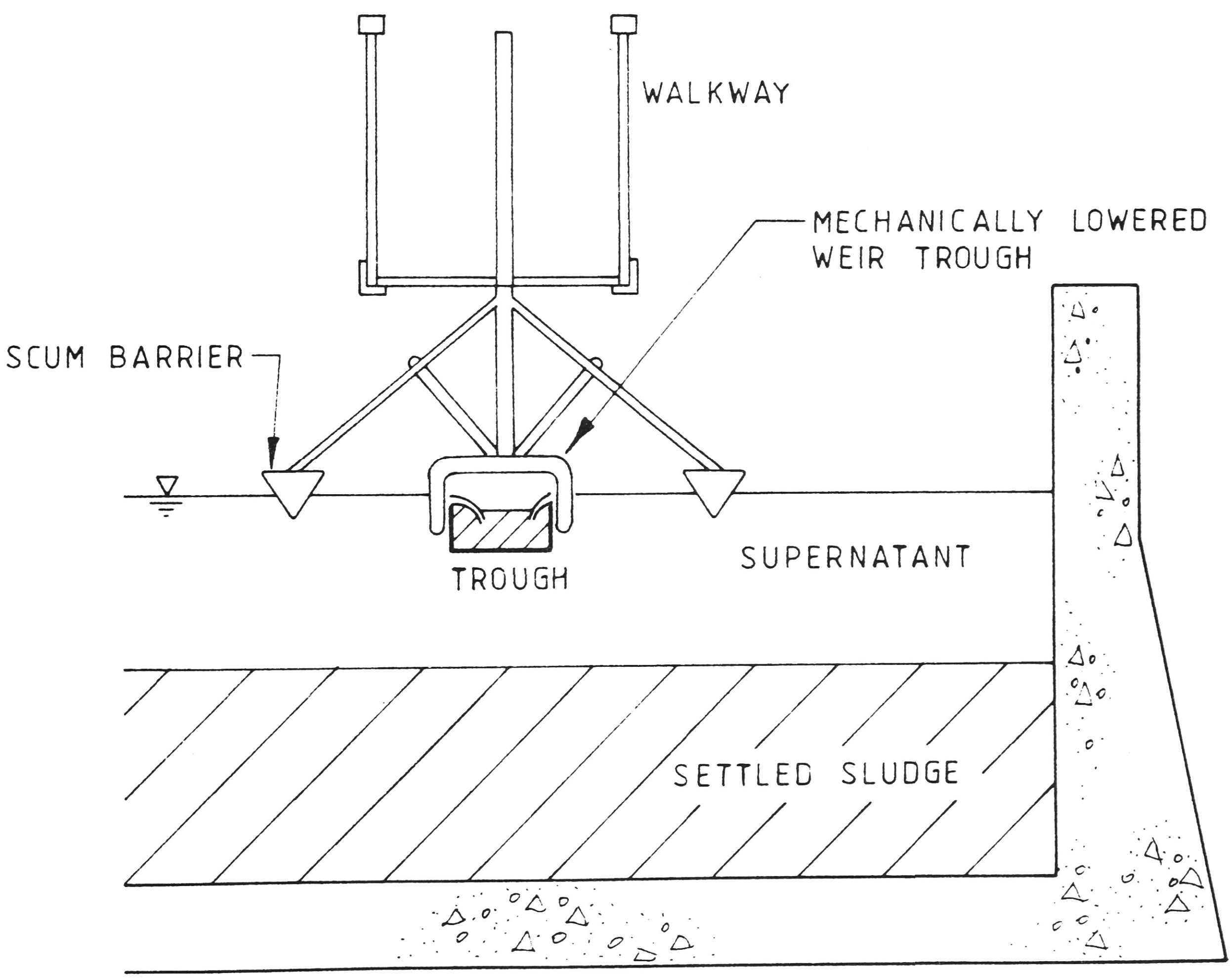
FLOW UNDER TROUGH

SCOUR FAILURE UNDER PASVEER TROUGH

FIGURE 7



PLAN



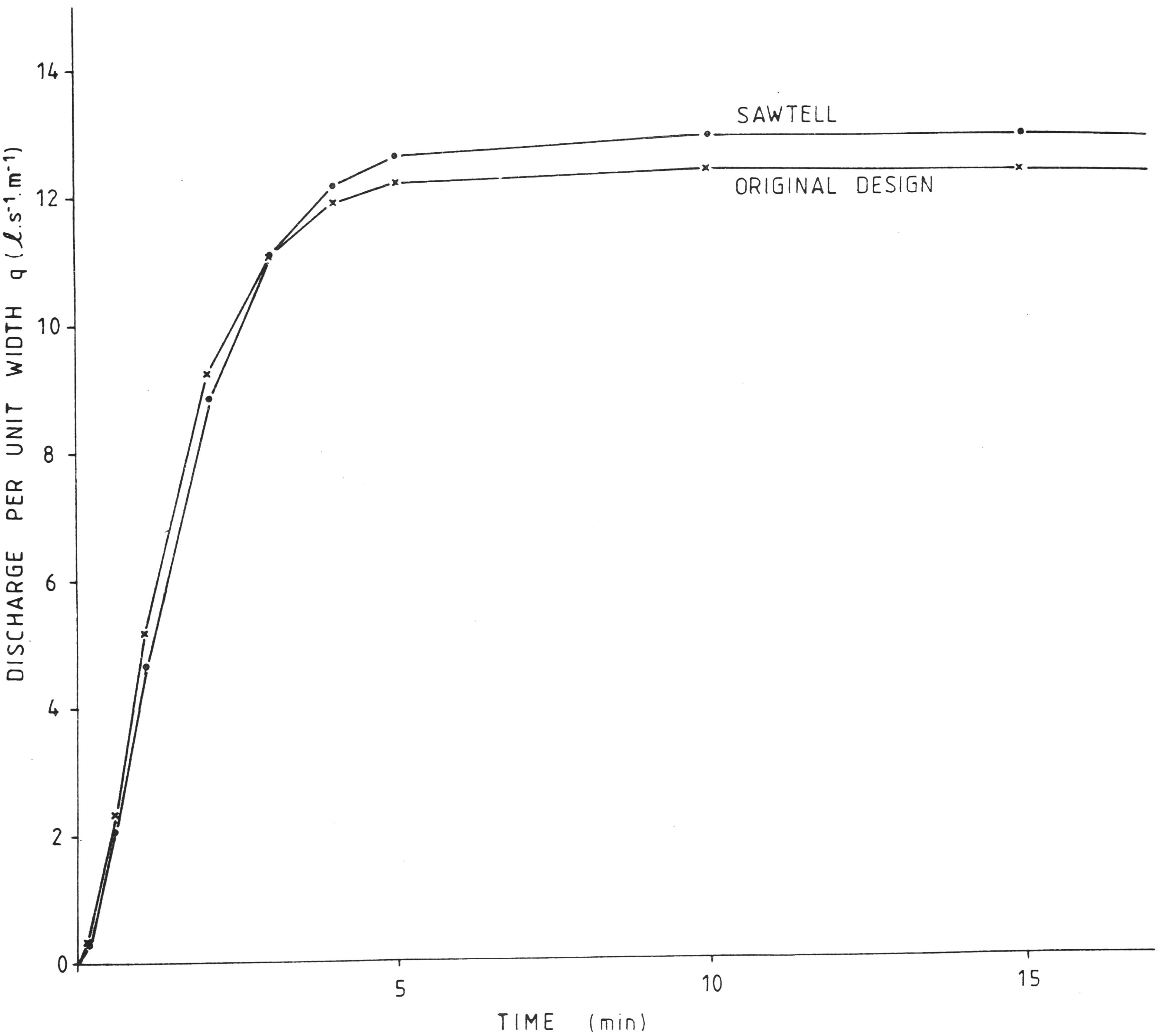
WEIR SECTION A-A

BATHURST BOX LAYOUT

FIGURE 8

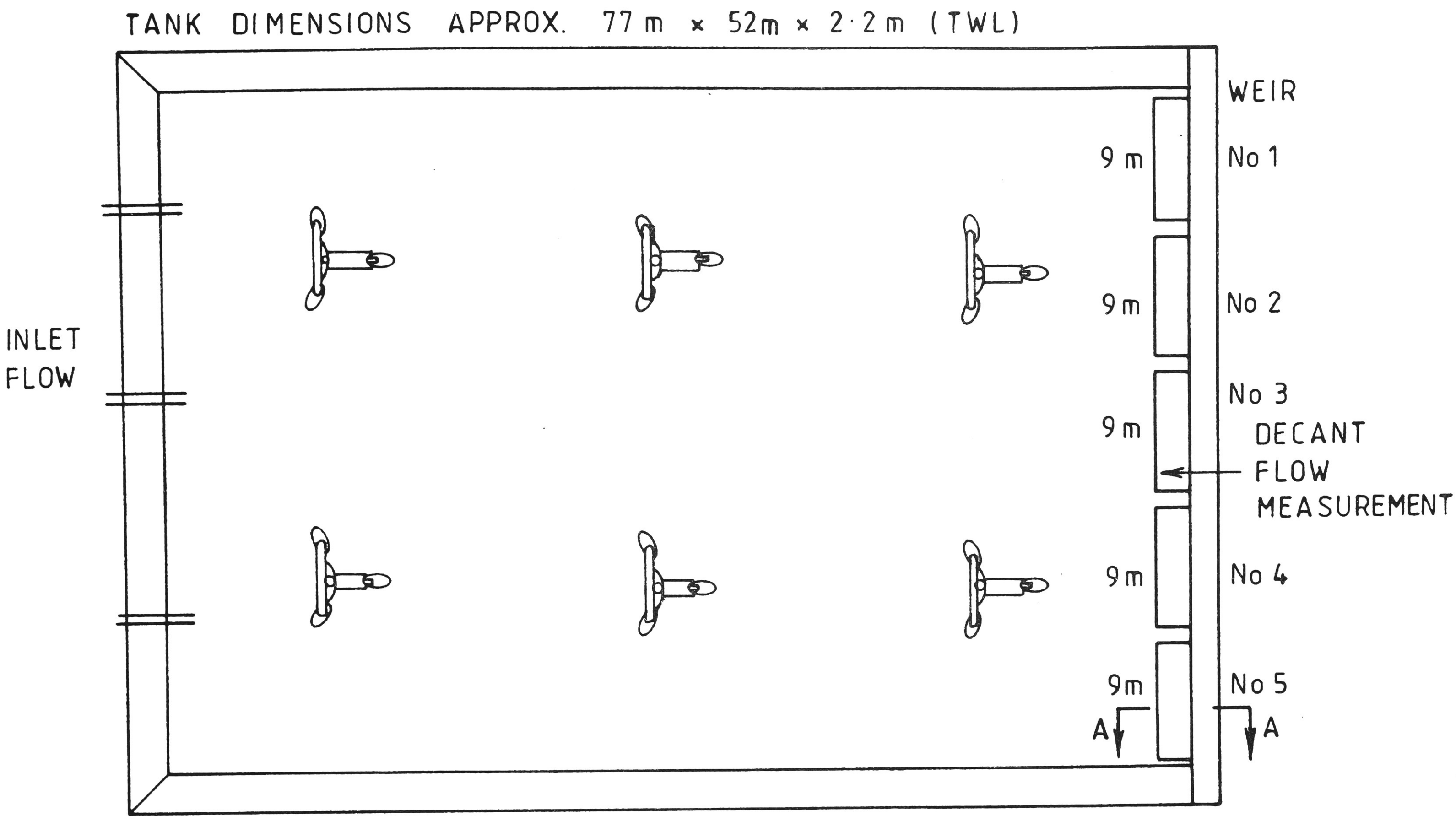
TYPICAL B4000 : WEIR LOWERING RATE 17·7 mm. min^{-1}
P.D.W.F. 1333 ℓ .min^{-1}

SAWTELL B4000 : WEIR LOWERING RATE 19·8 mm. min^{-1}
INFLOW EST. 880 ℓ .min^{-1}



BATHURST BOX DISCHARGE CURVE

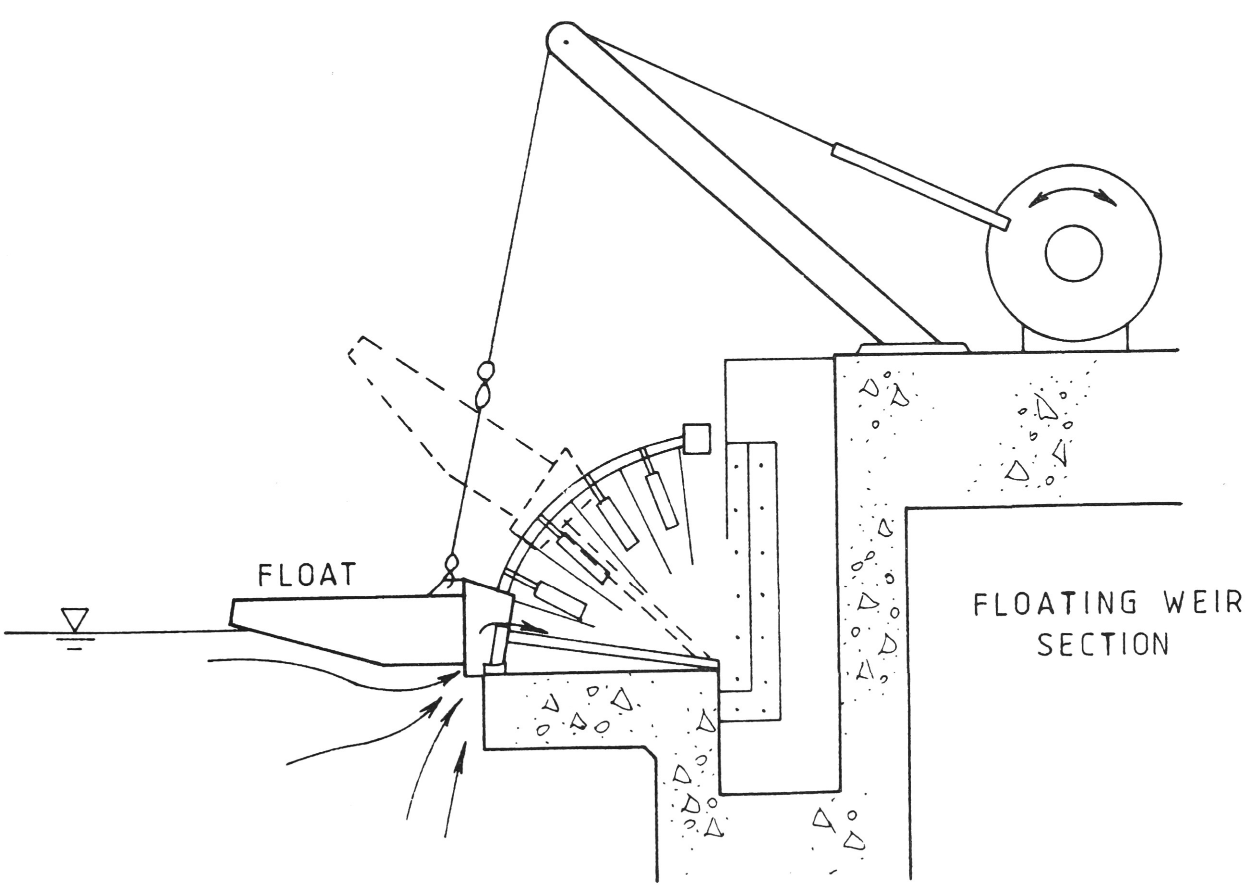
FIGURE 9



PLAN

PORT MACQUARIE T 15,000
AERATION TANK No 1

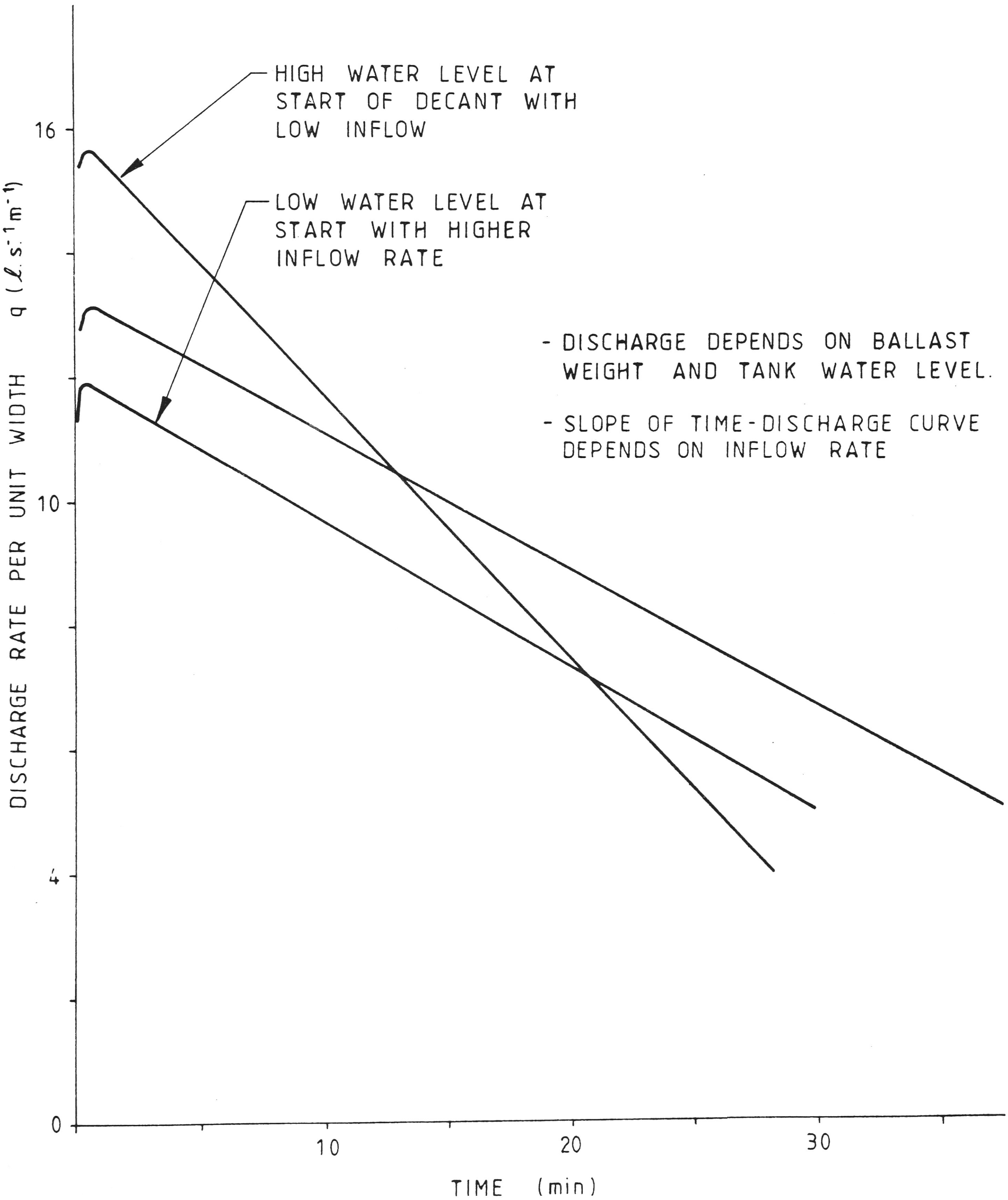
NOT TO SCALE



SECTION A - A

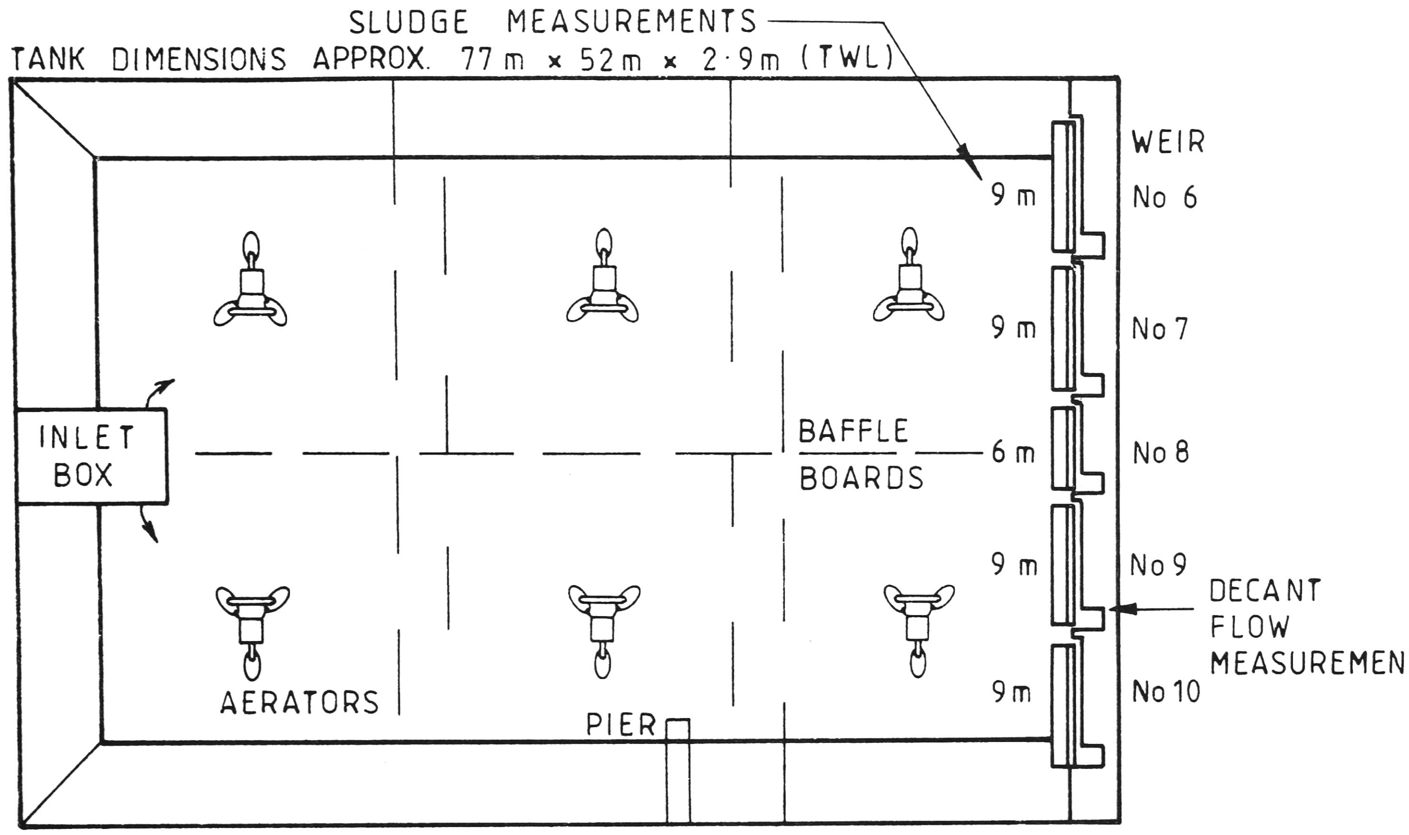
PORT MACQUARIE TANK LAYOUT

FIGURE 10

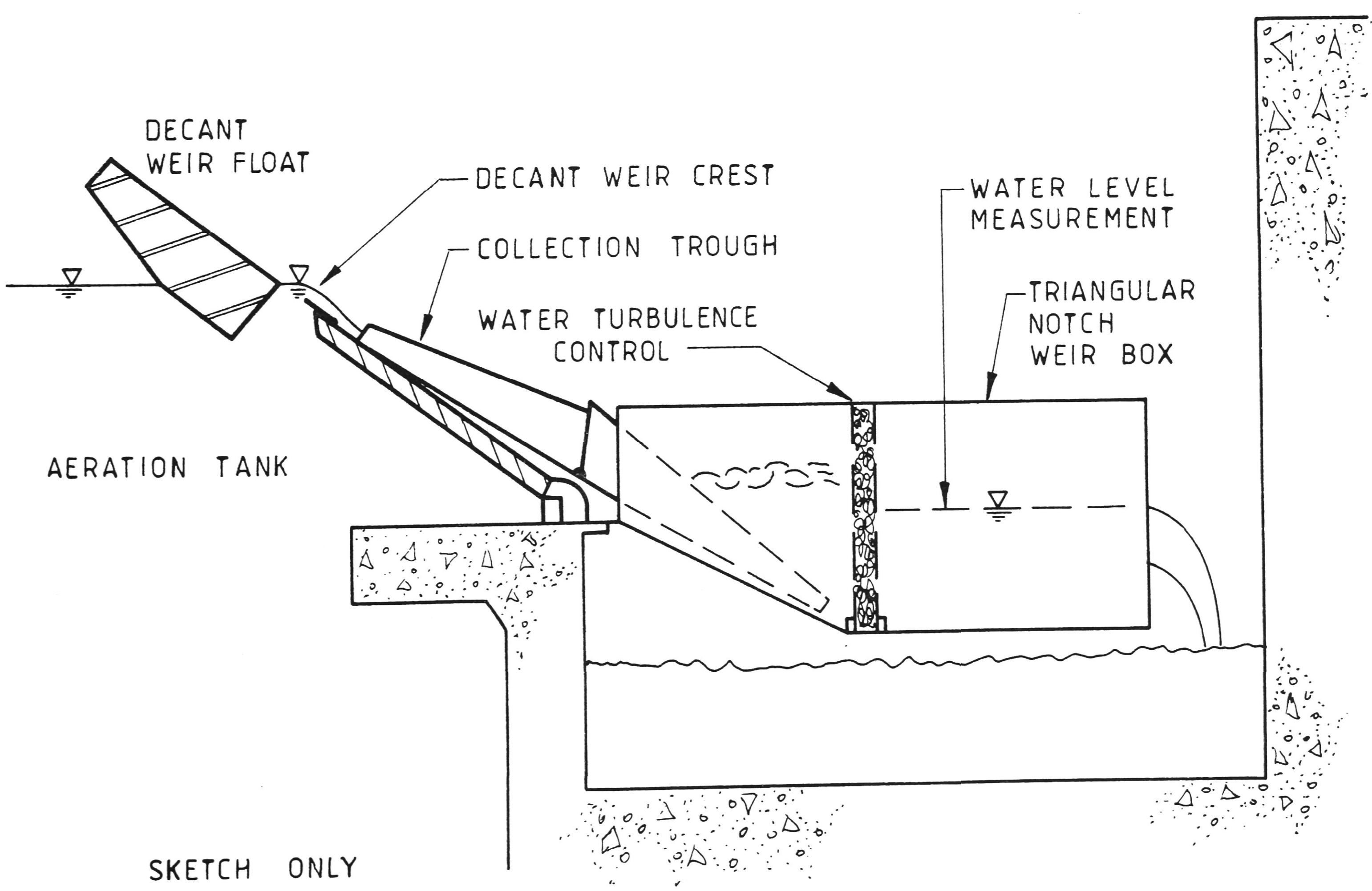


TYPICAL TIME - DISCHARGE CURVES
PORT MACQUARIE FLOATING WEIRS
T 15,000

FIGURE 11

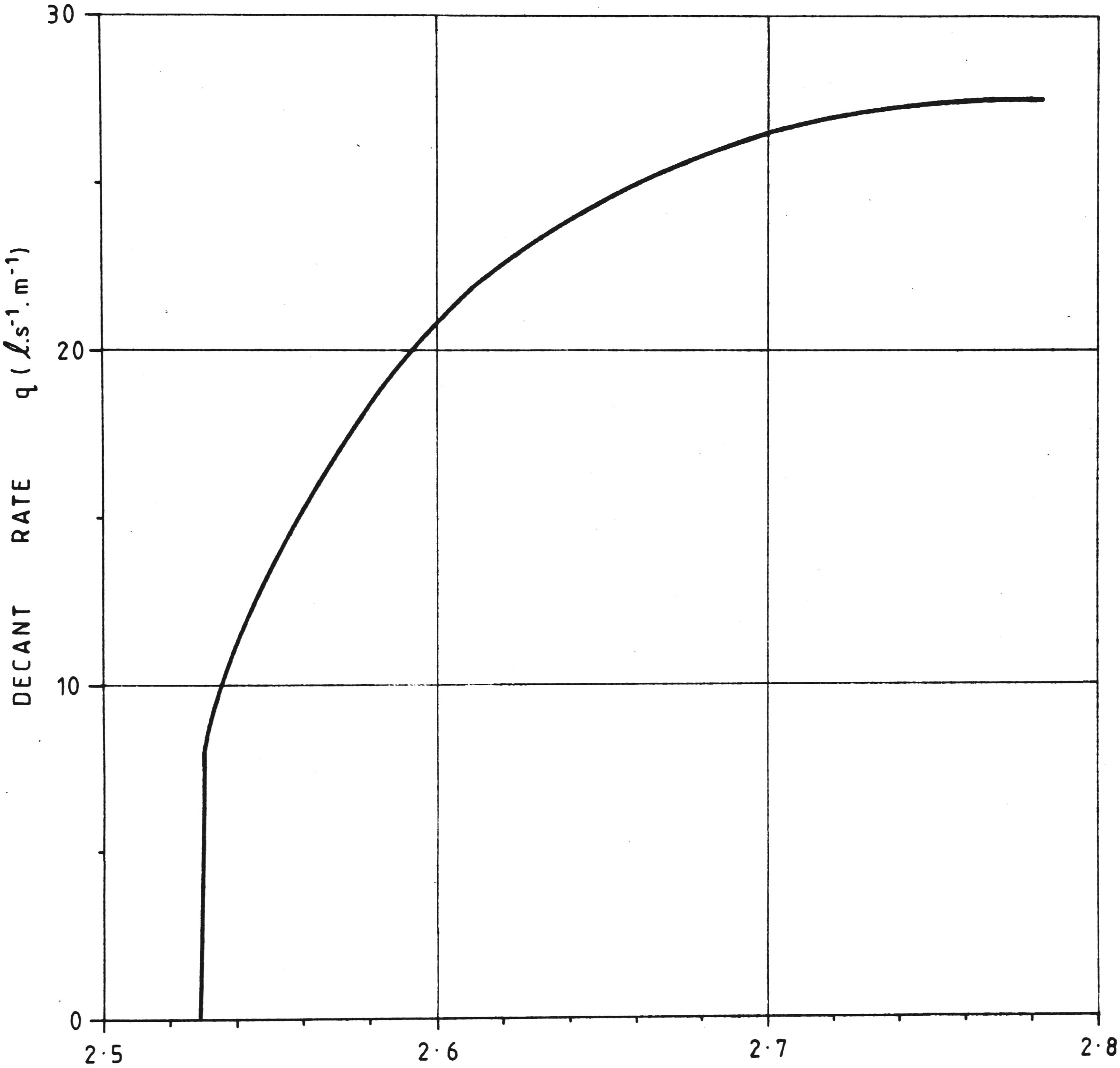


PORT MACQUARIE T 18,000
AERATION TANK No. 2



FLOW MEASUREMENT ON PORT MACQUARIE TANK

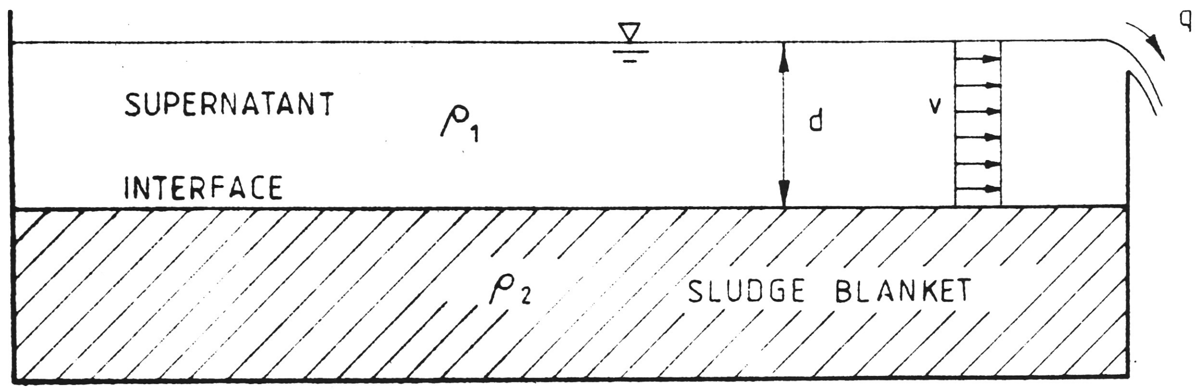
FIGURE 12



PORT MACQUARIE T 18,000

WEIR No. 9 DISCHARGE CURVE 1988

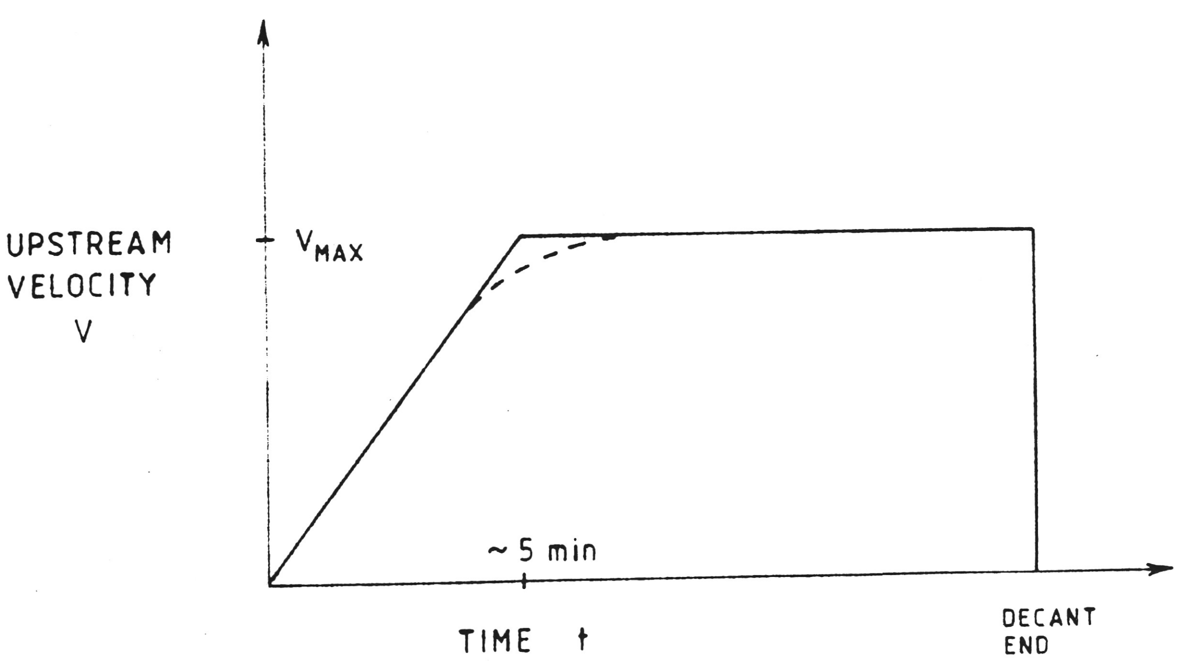
FIGURE 13



DENSIMETRIC FROUDE NUMBER $\mathbb{F}_\Delta = \frac{v}{\sqrt{g \cdot \Delta \cdot d}}$

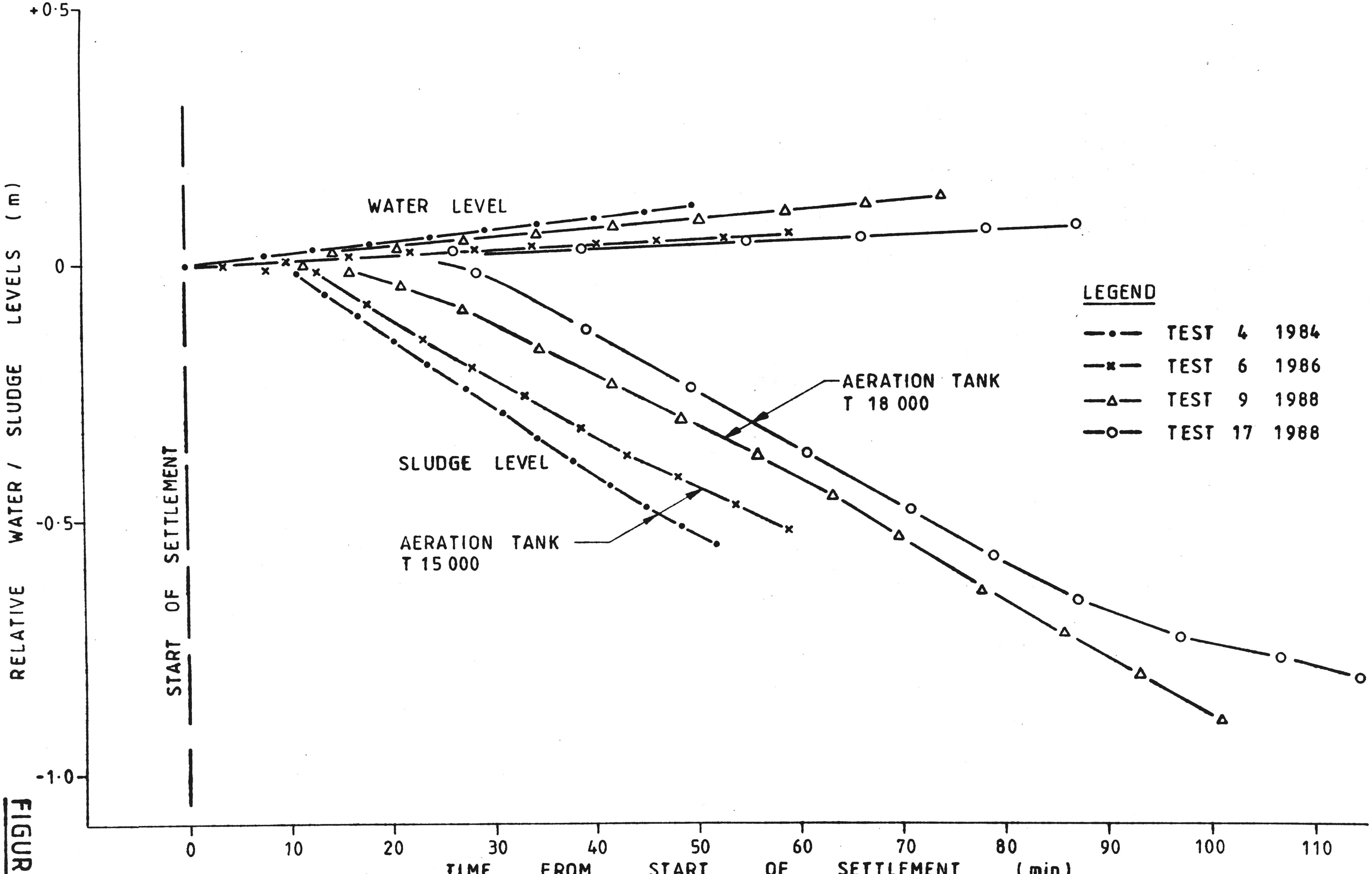
$$\Delta = \frac{\rho_2 - \rho_1}{\rho_1}$$

SELECTIVE WITHDRAWAL THEORY



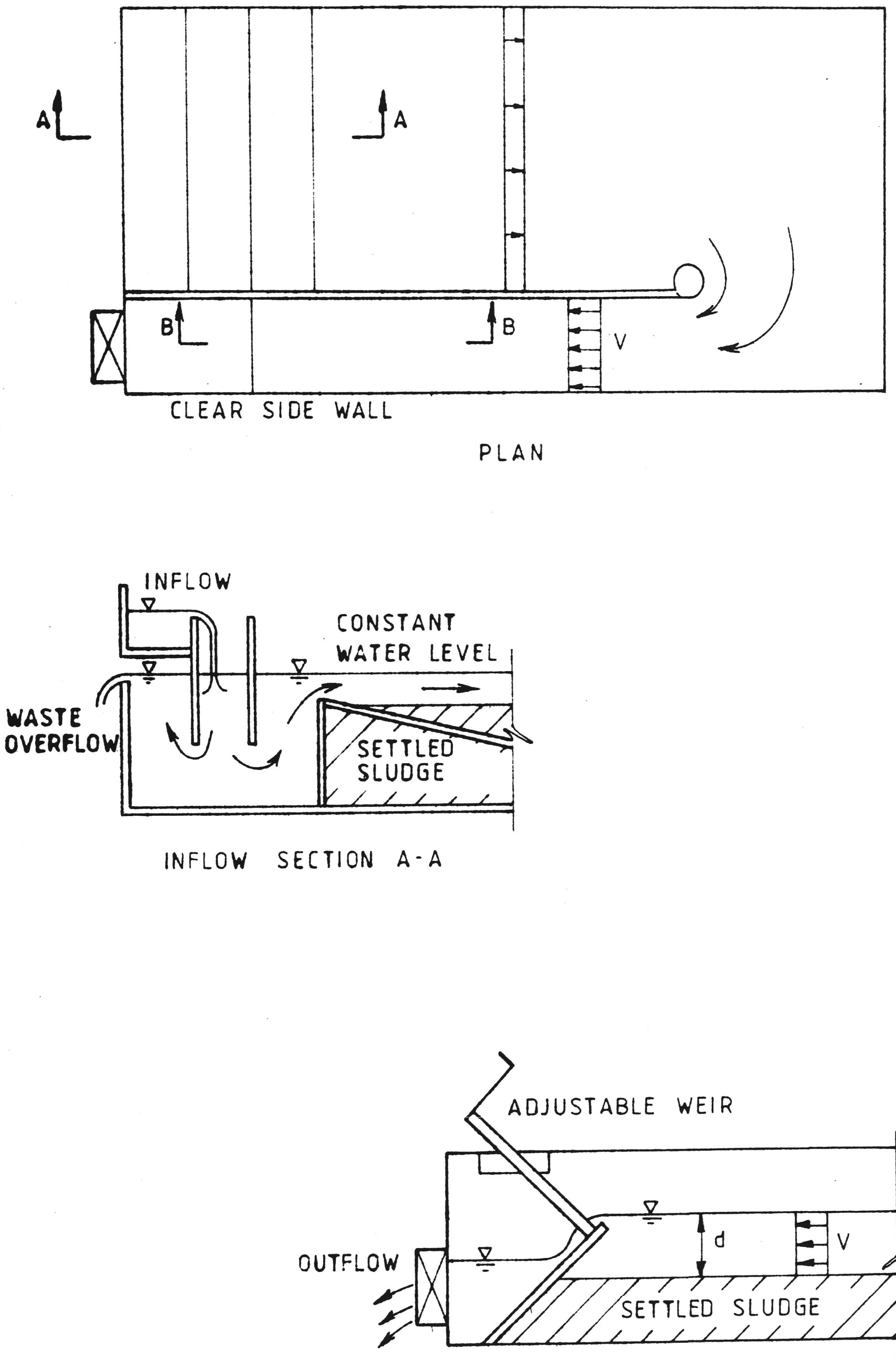
PROPOSED DESIGN DECANT CURVE

FIGURE 14



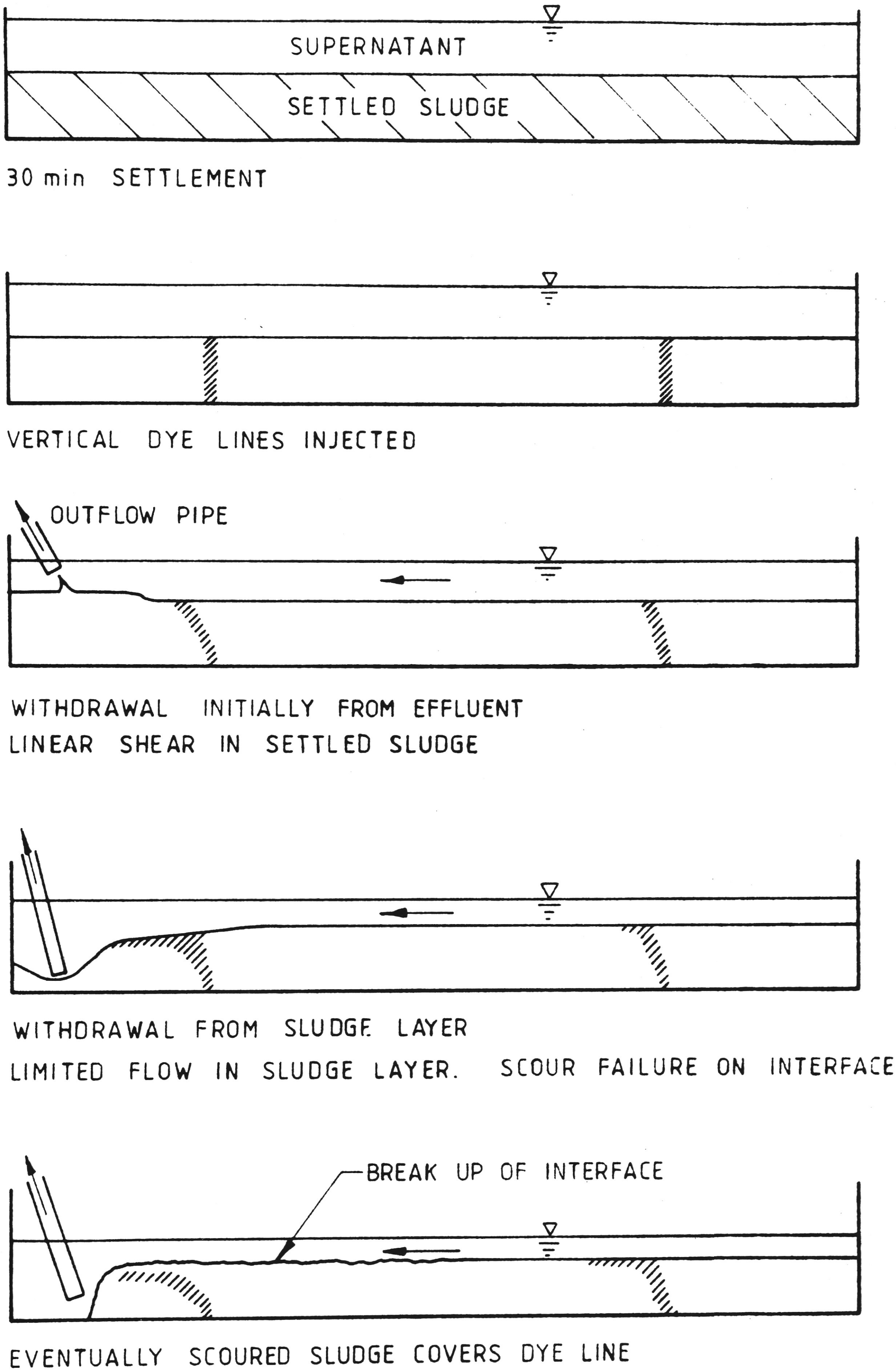
PORT MACQUARIE IN-TANK SETTLEMENT

FIGURE 15



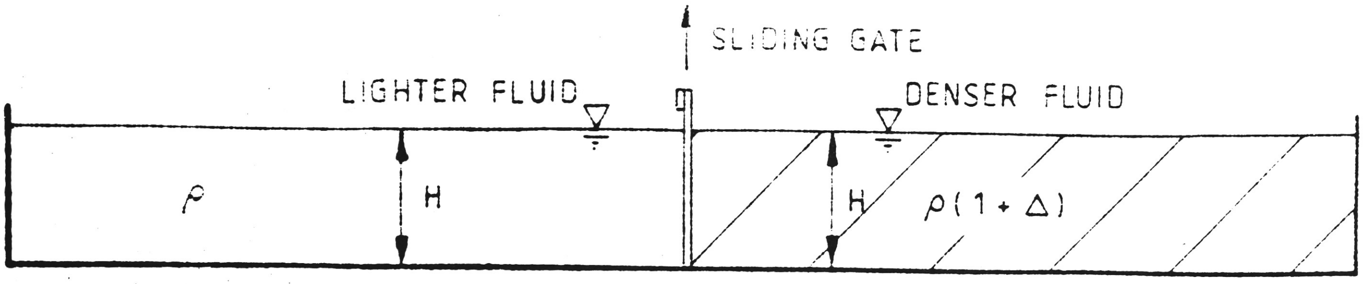
NORTH RICHMOND DECANT MODEL

FIGURE 16

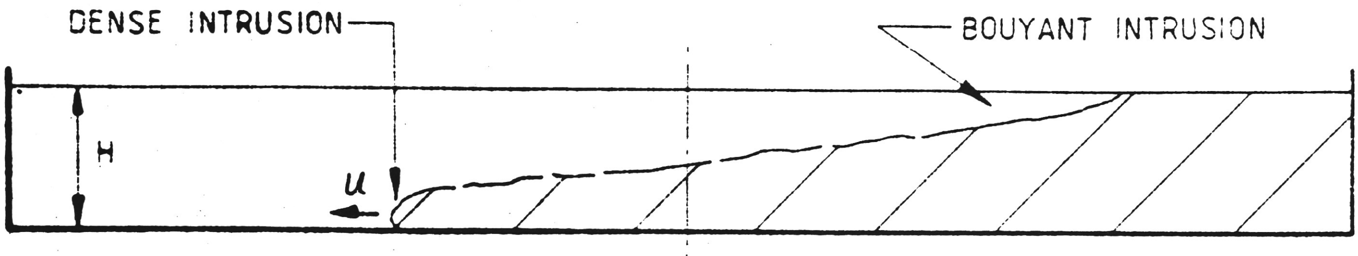


BOWRAL MODEL TESTS

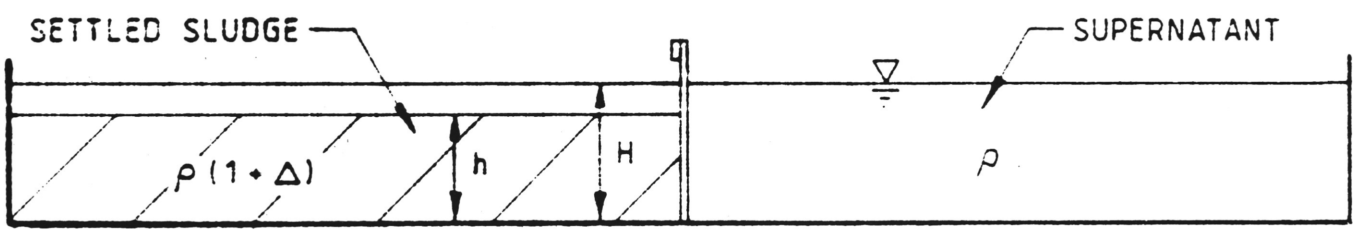
FIGURE 17



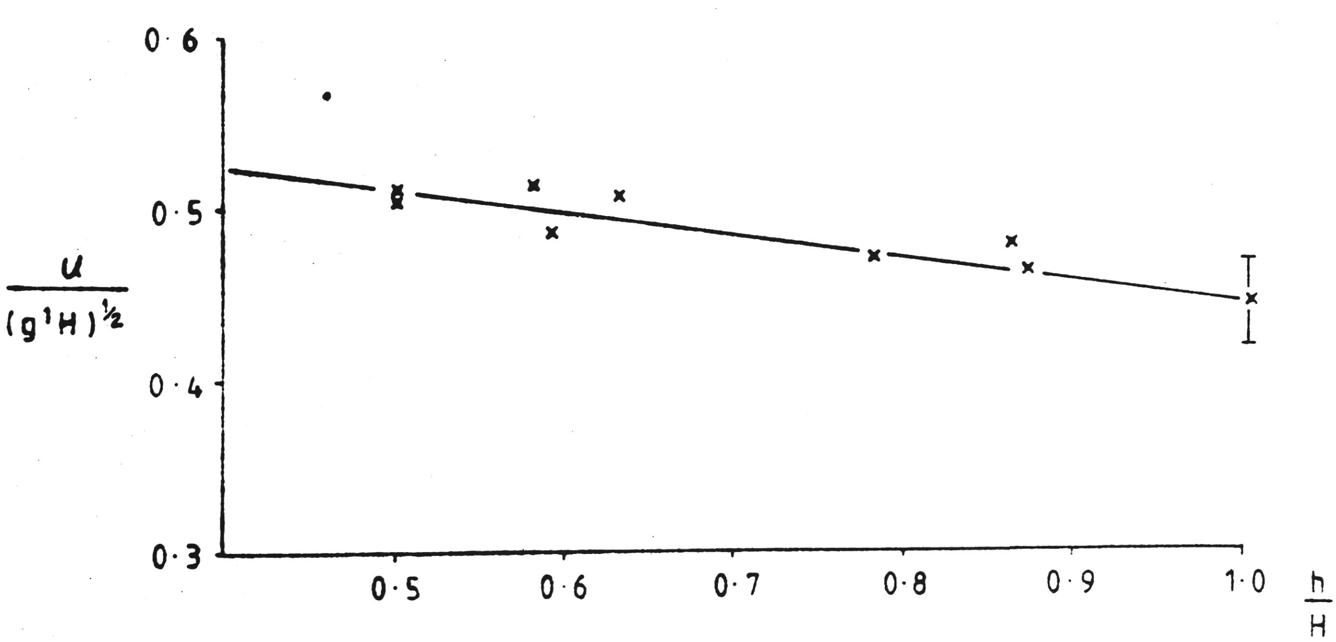
LOCK EXCHANGE TANK PRIOR TO REMOVAL OF GATE



EXCHANGE FLOW ESTABLISHED AFTER REMOVAL OF GATE



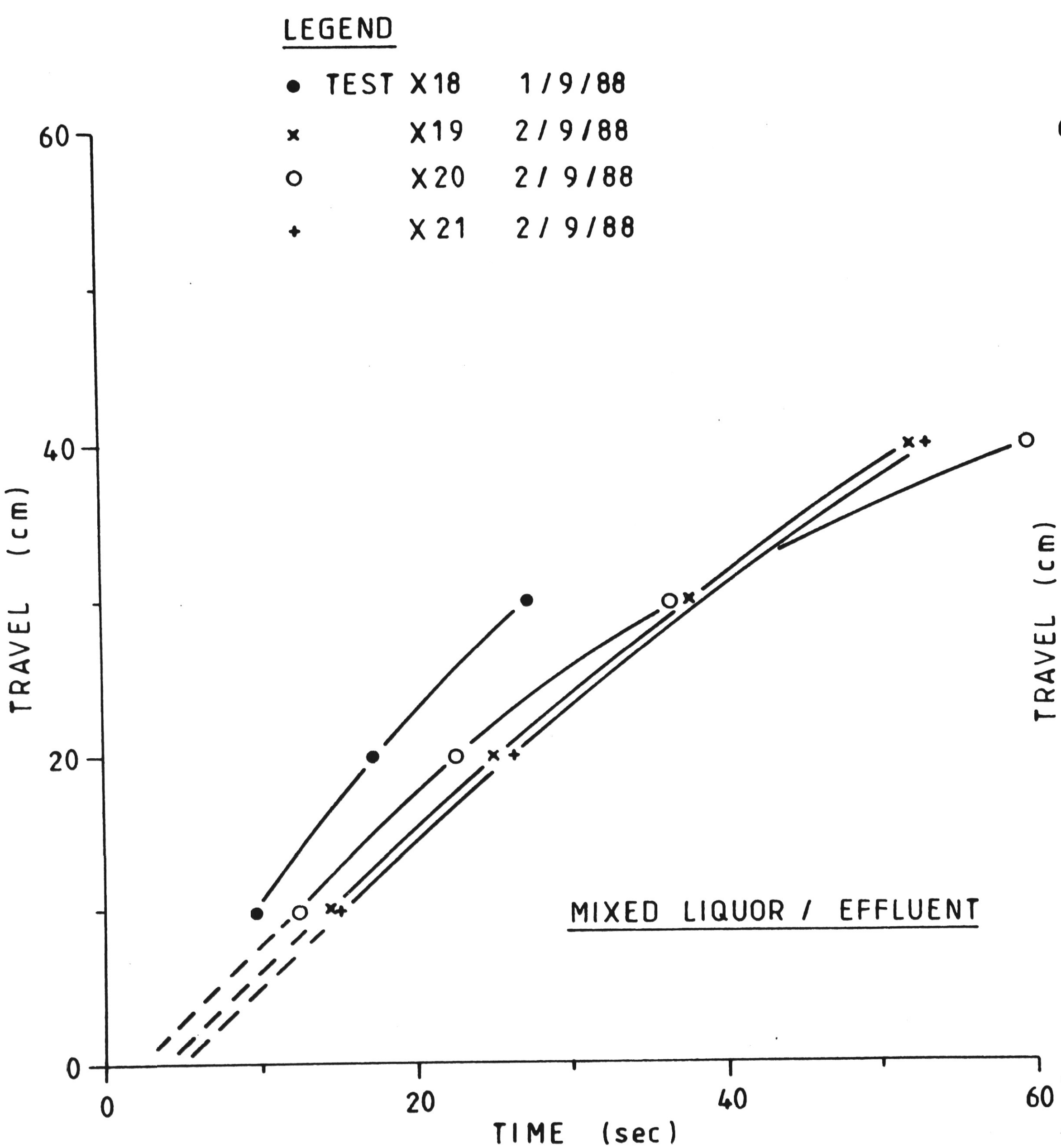
CONSOLIDATED SLUDGE PRIOR TO REMOVAL OF GATE

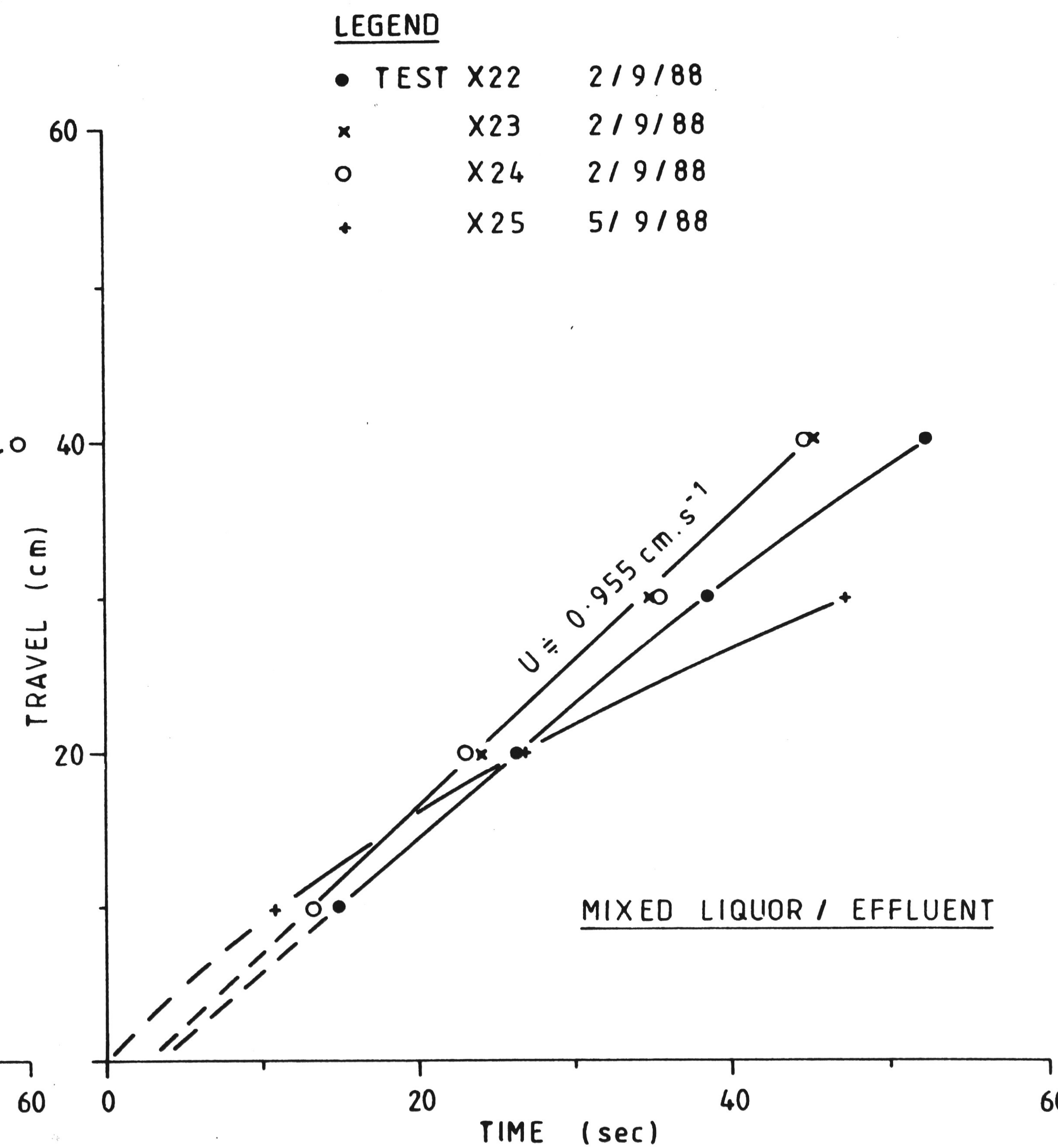


LOCK EXCHANGE TEST

FIGURE 18

FIGURE 19





LOCK EXCHANGE RESULTS PORT MACQUARIE 1988

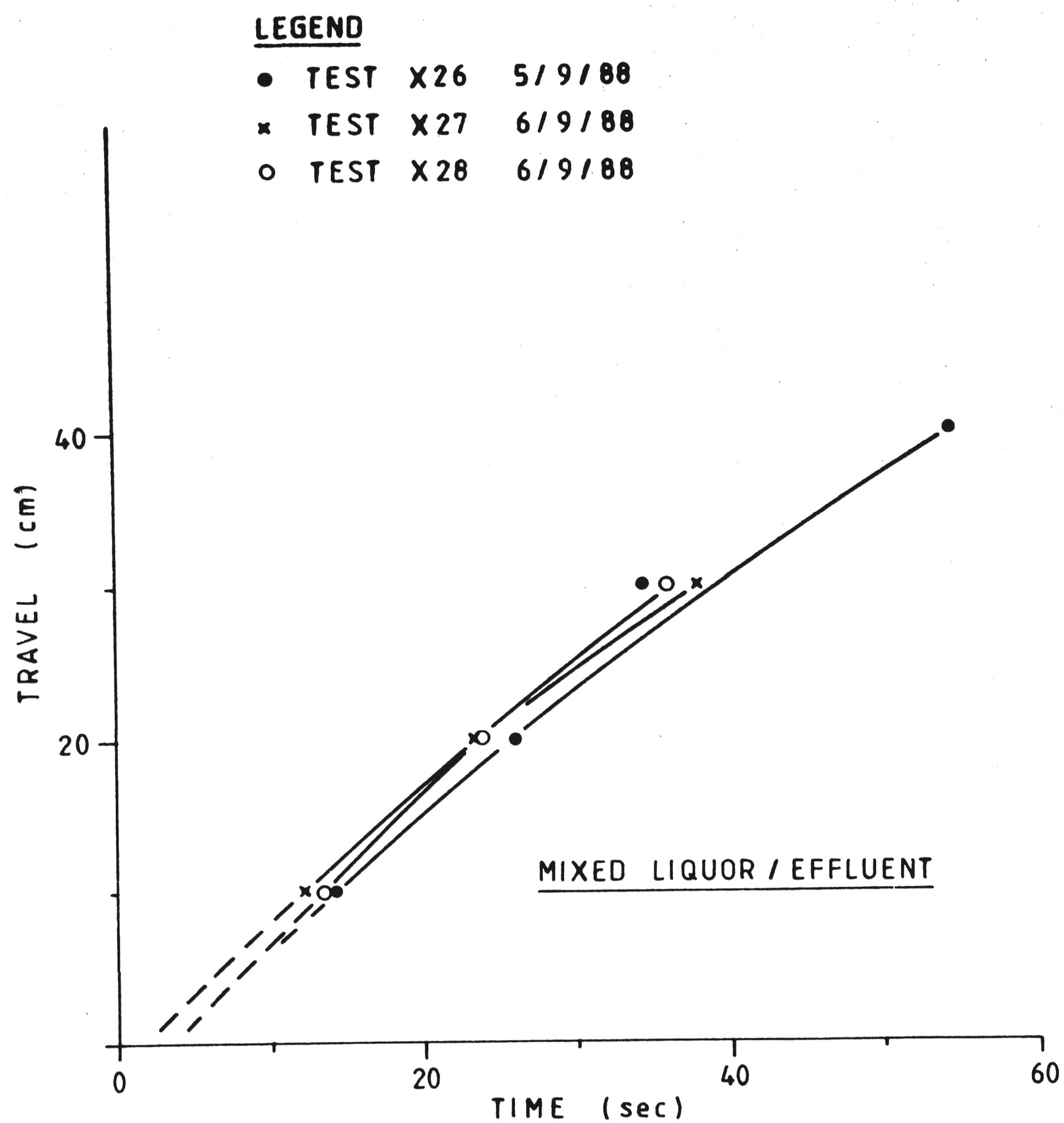
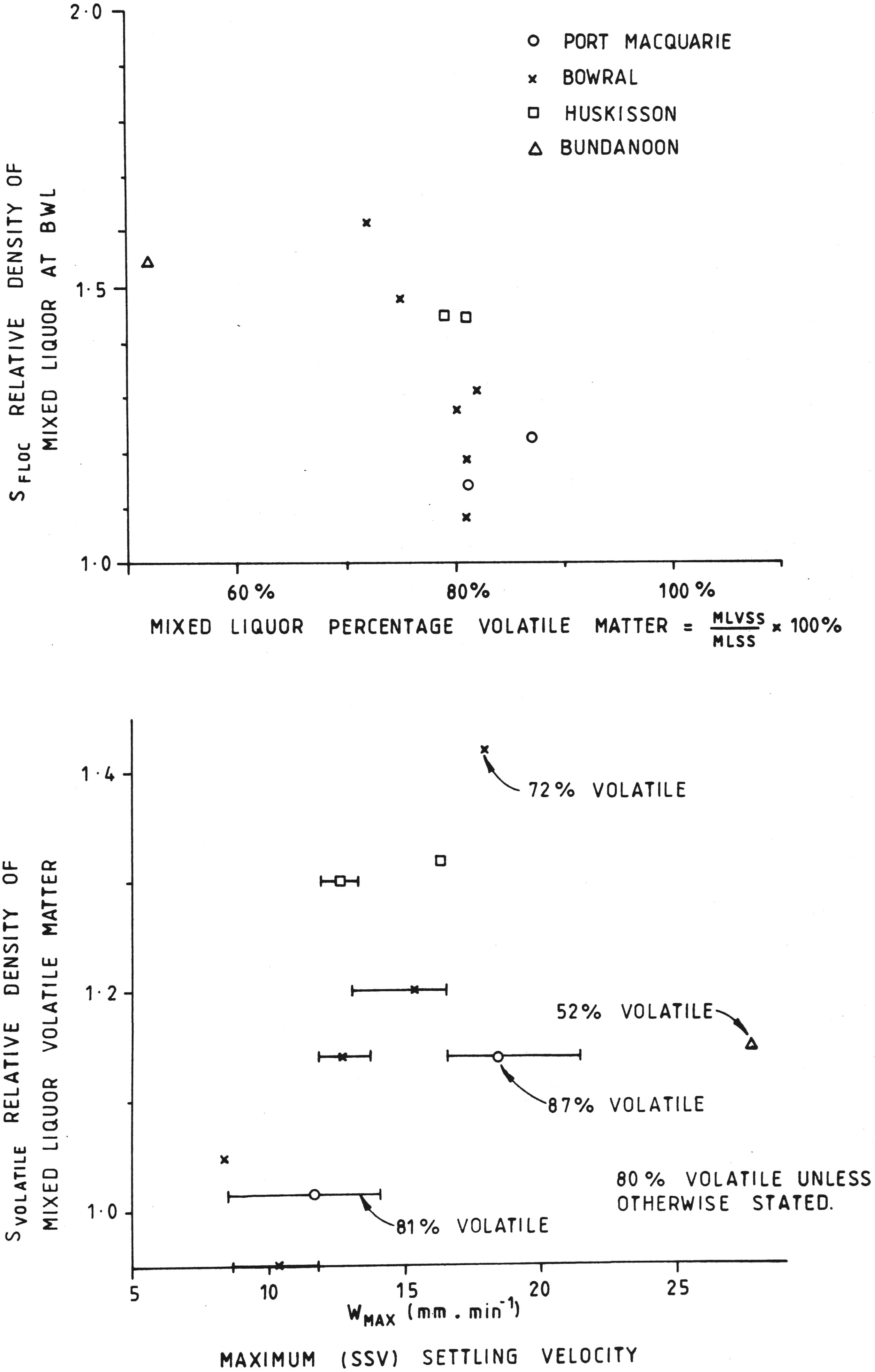


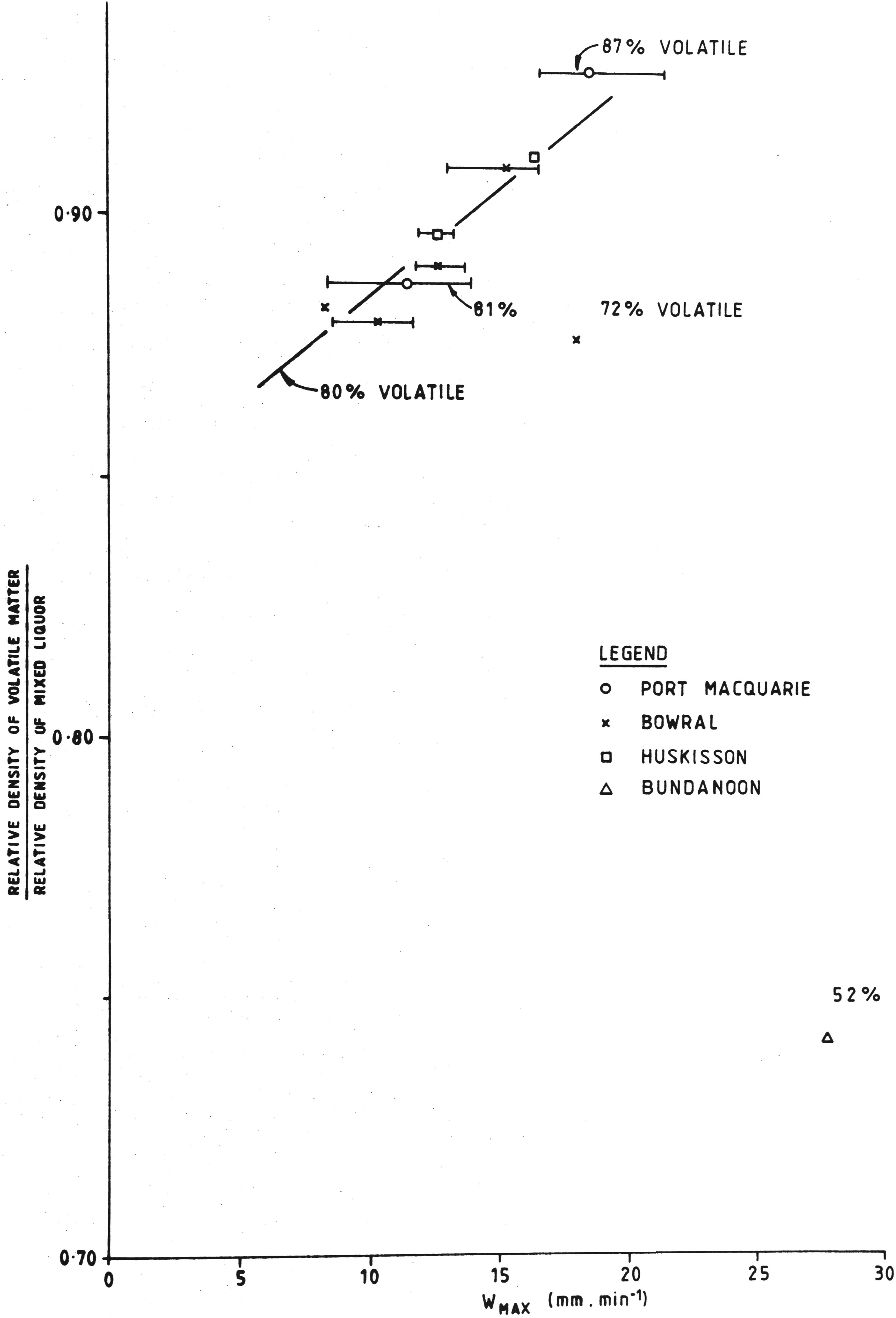
FIGURE 20

LOCK EXCHANGE RESULTS PORT MACQUARIE 1988



AVERAGED RESULTS OF LOCKED EXCHANGE TESTS

FIGURE 21



SLUDGE SPECIFIC GRAVITY RATIO

FIGURE 22

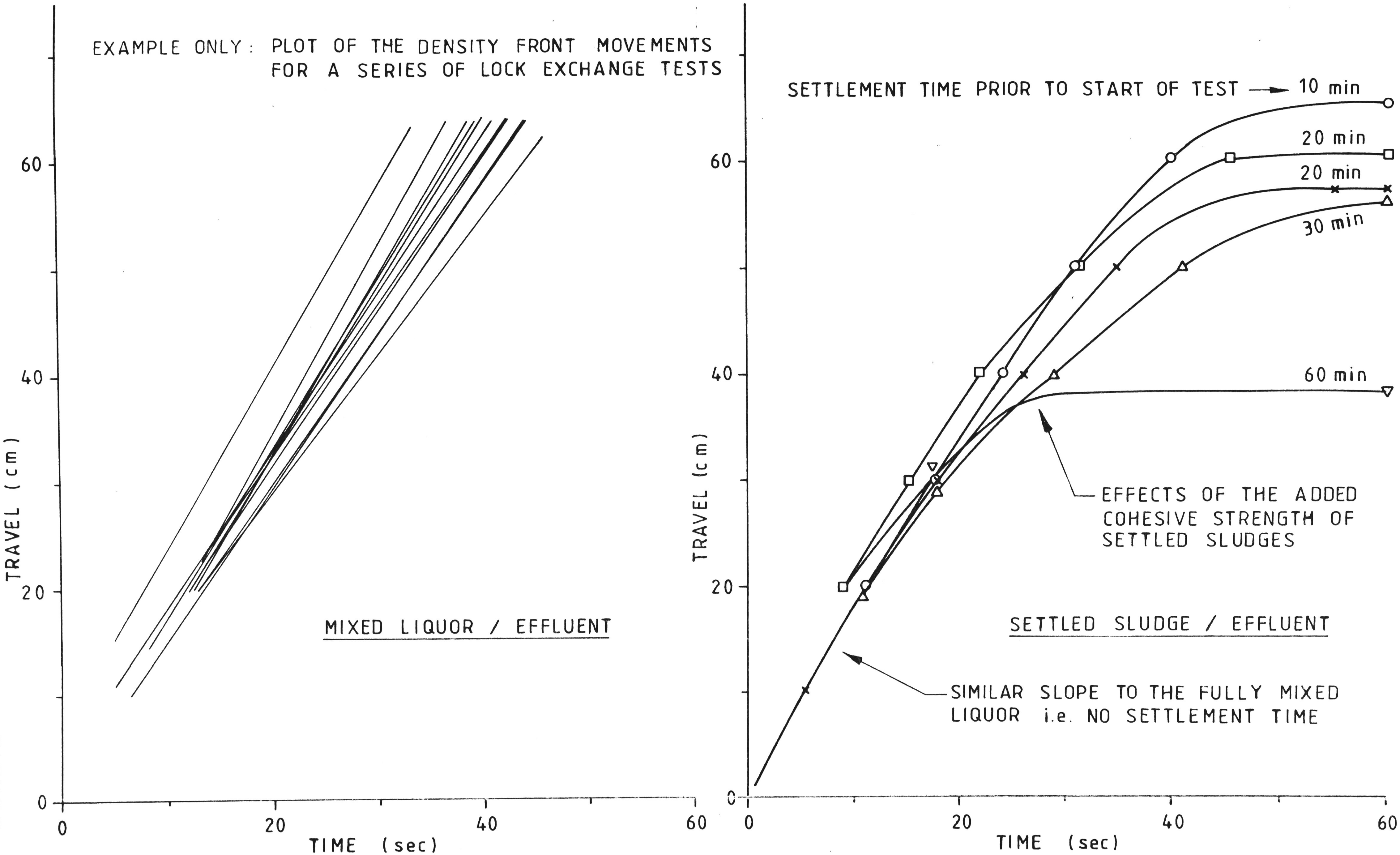
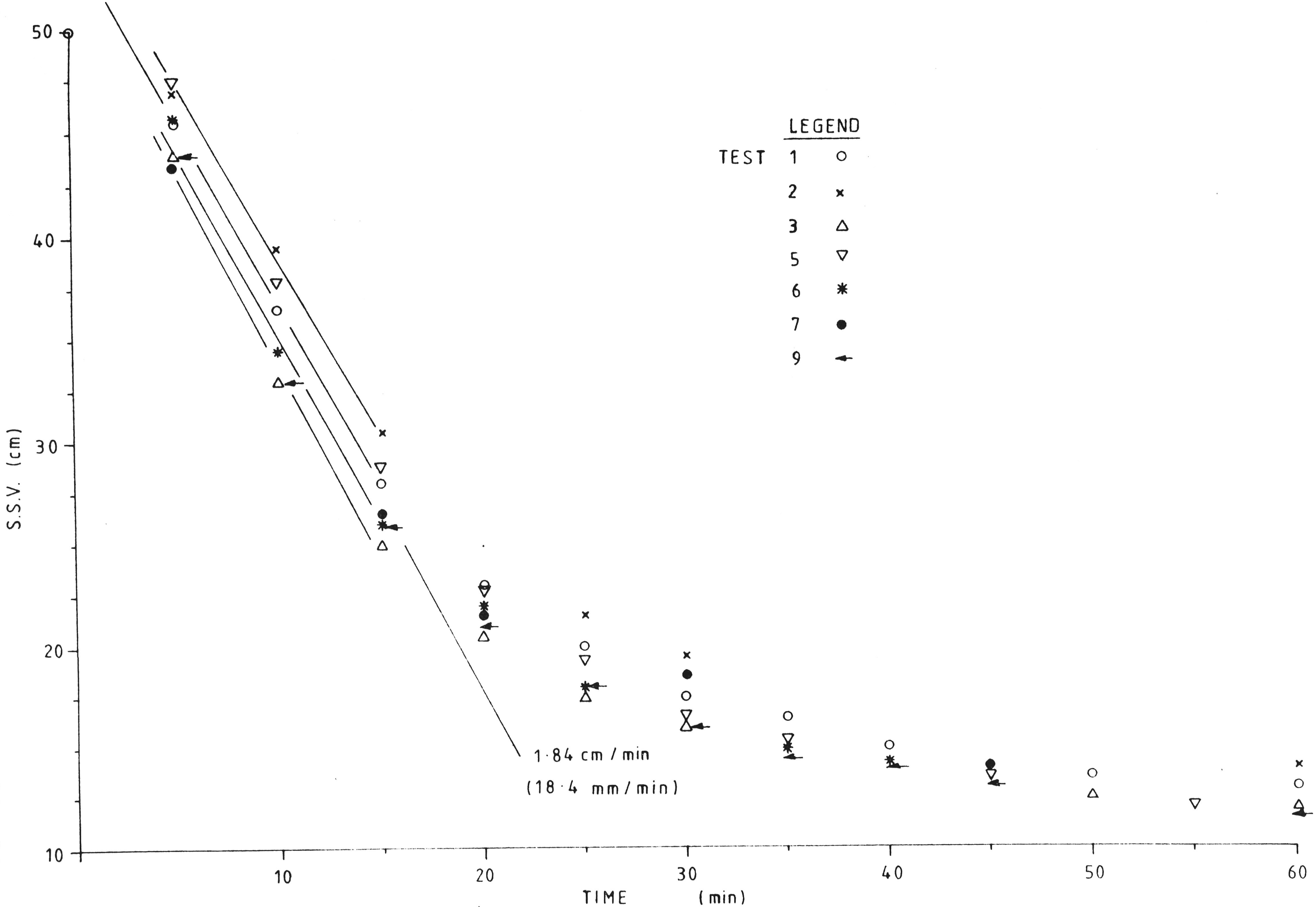


FIGURE 23

LOCK EXCHANGE RESULTS : PORT MACQUARIE 1986

FIGURE 24



STIRRED SETTLEMENT (S.S.V.) TESTS PORT MACQUARIE 1986

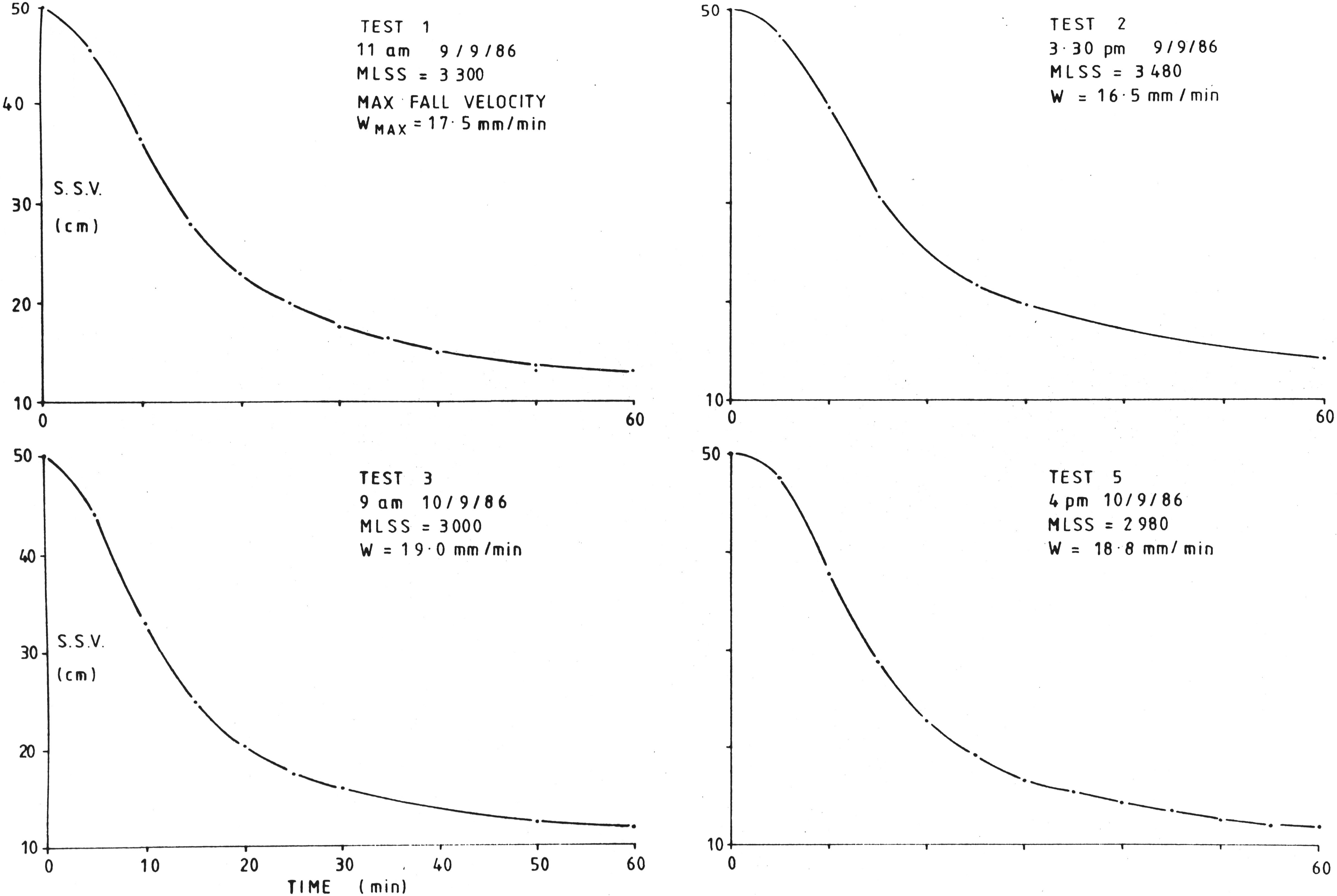
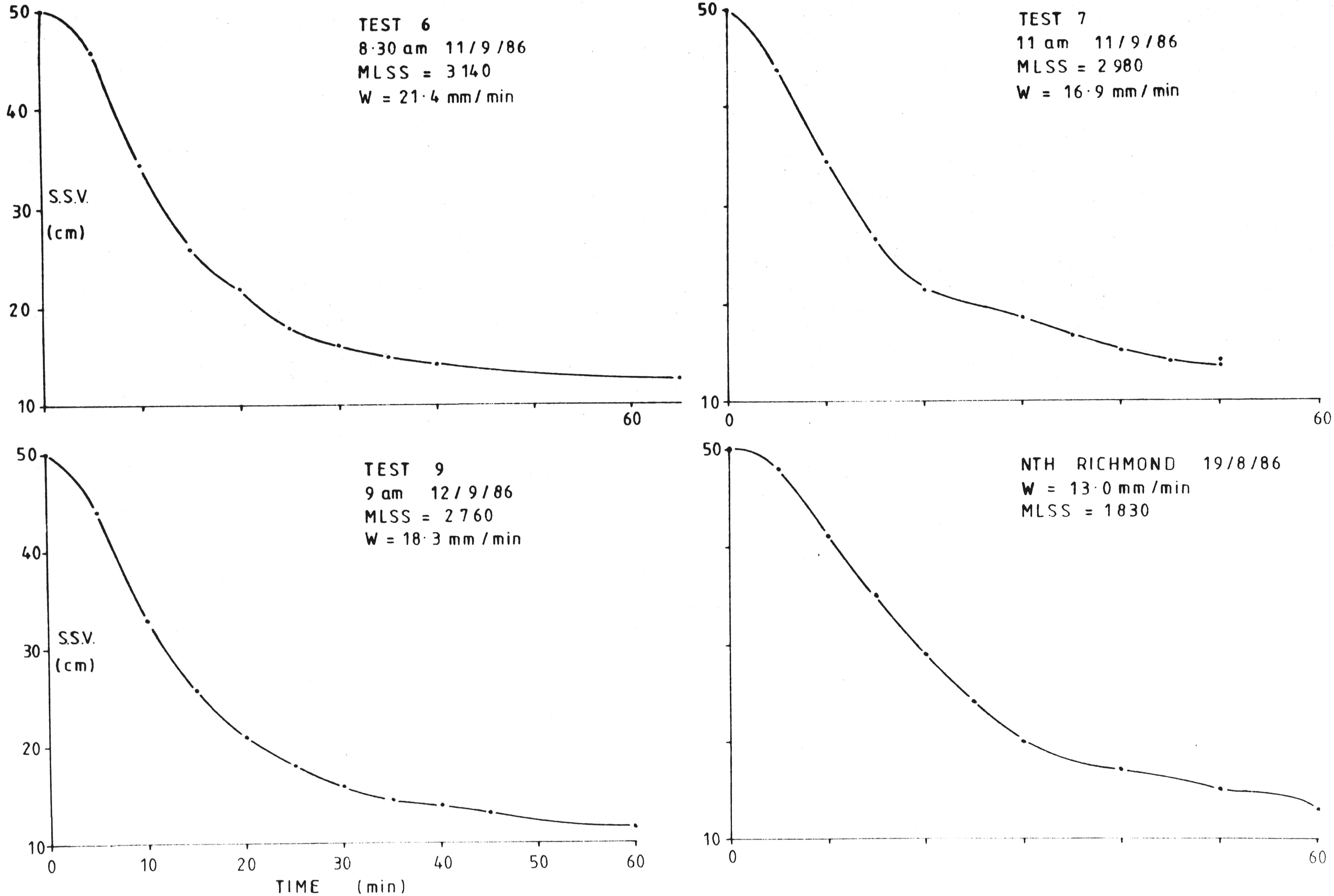
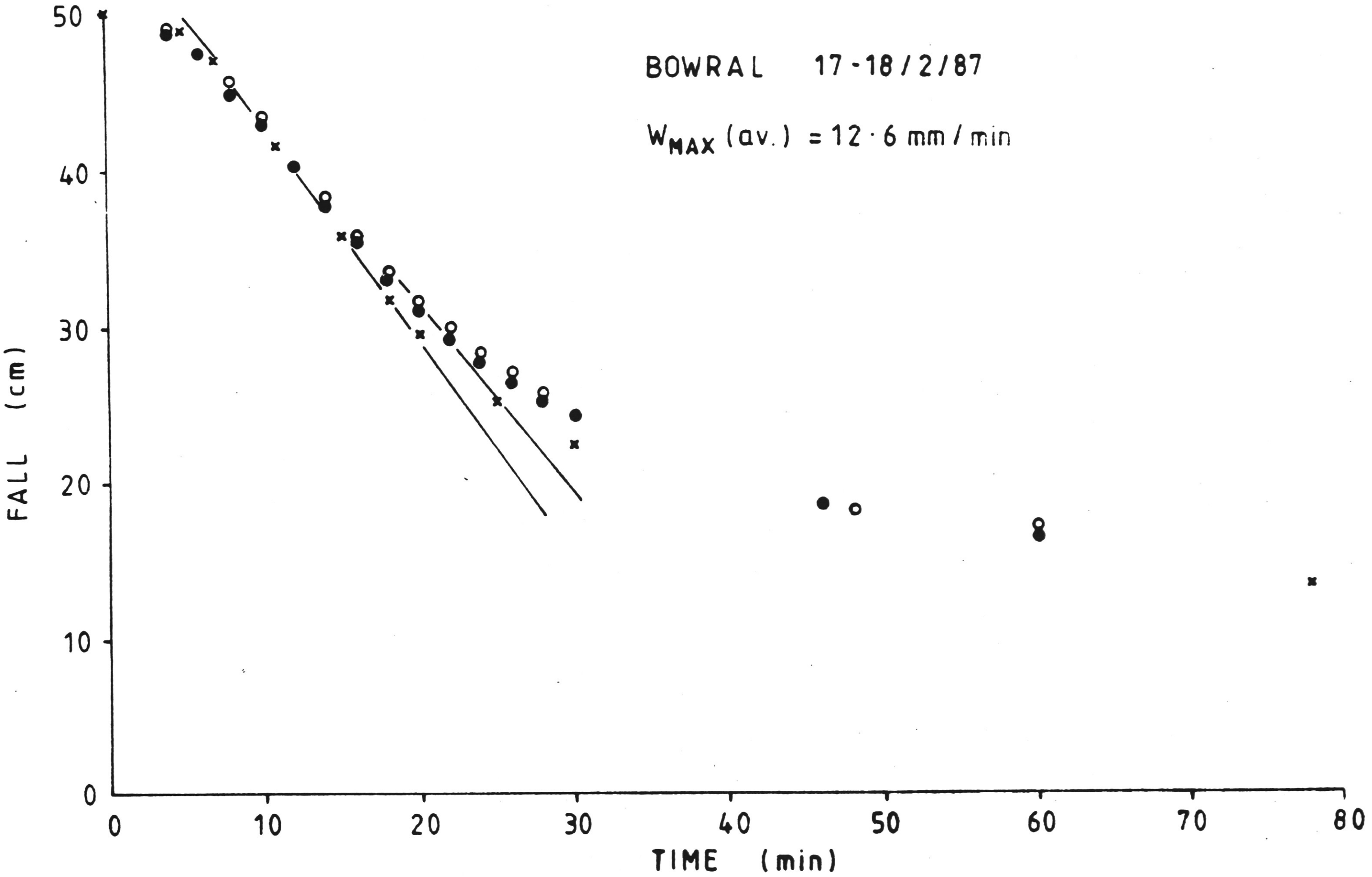


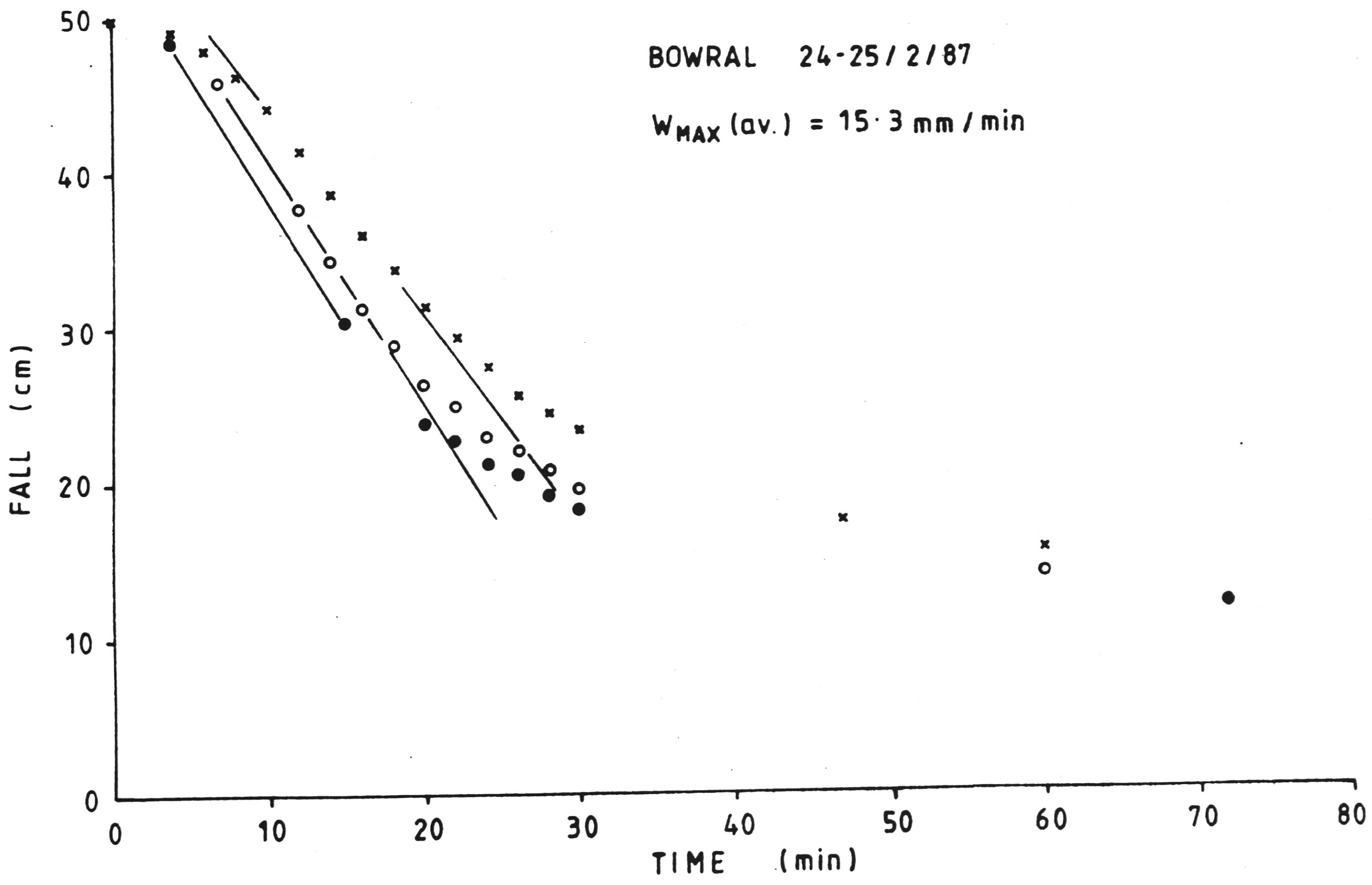
FIGURE 25 PORT MACQUARIE SETTLEMENT TESTS



PORT MACQUARIE SETTLEMENT TESTS

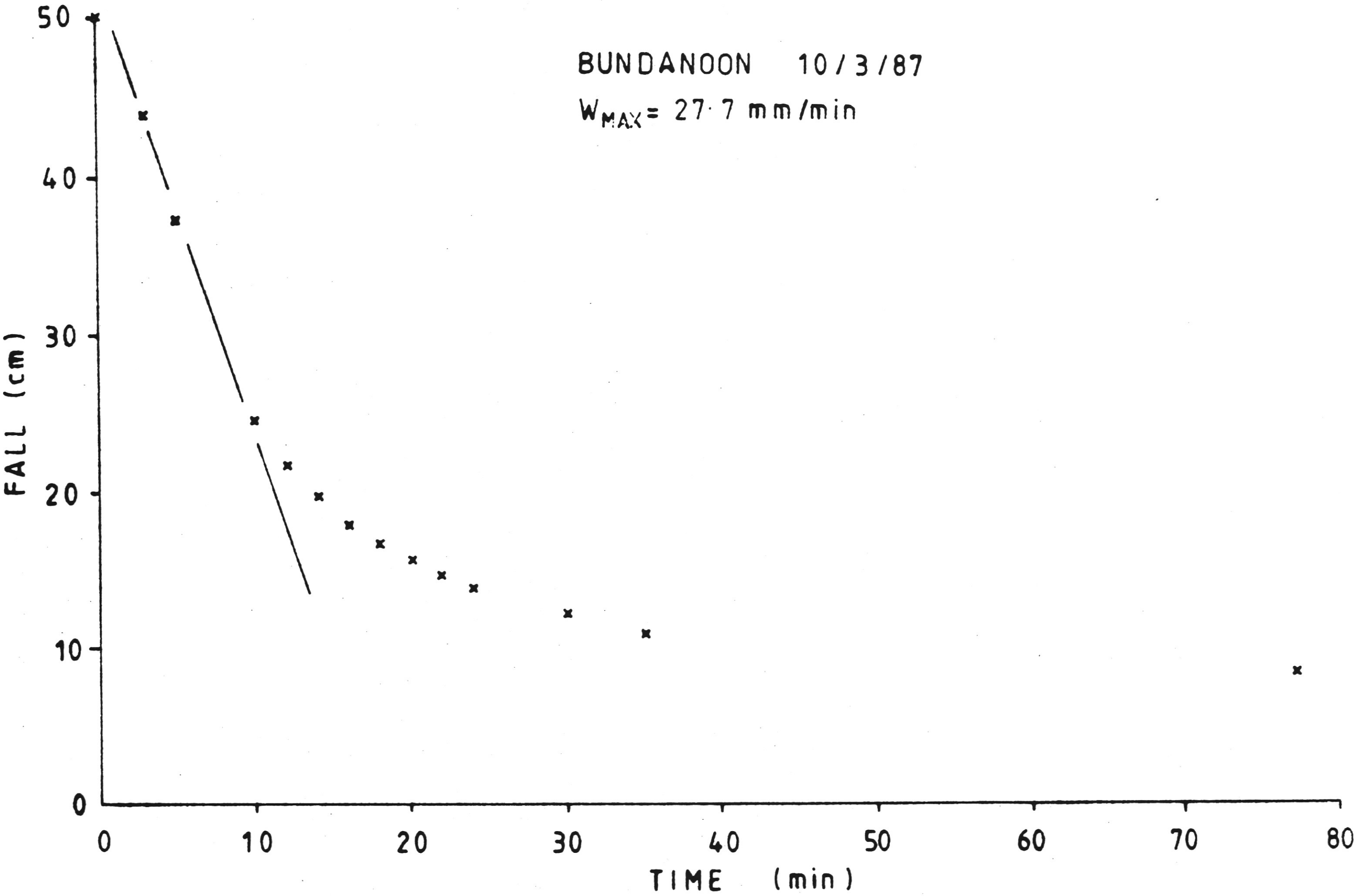
FIGURE 26

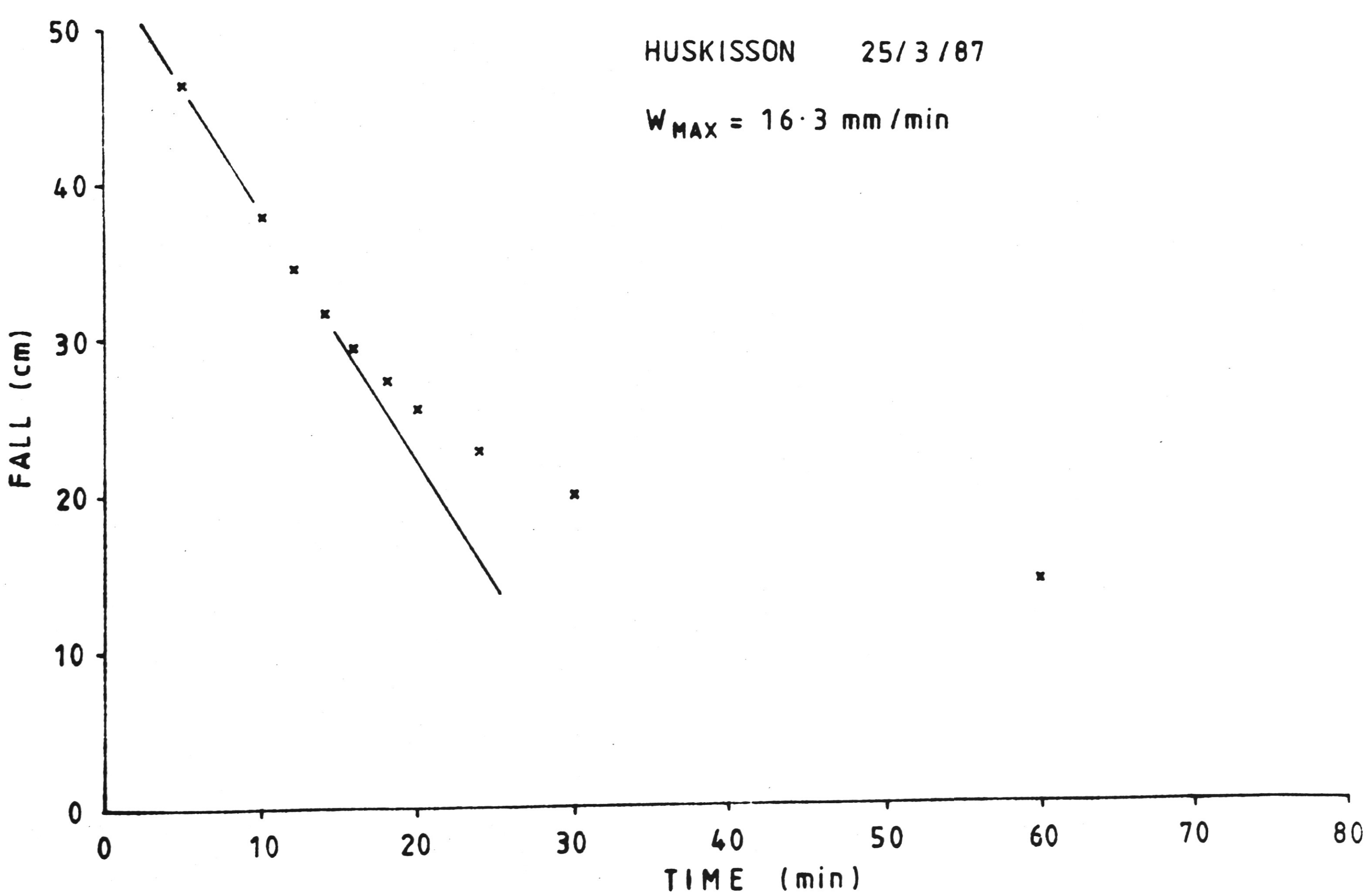




STIRRED SETTLEMENT (S.S.V.) TESTS

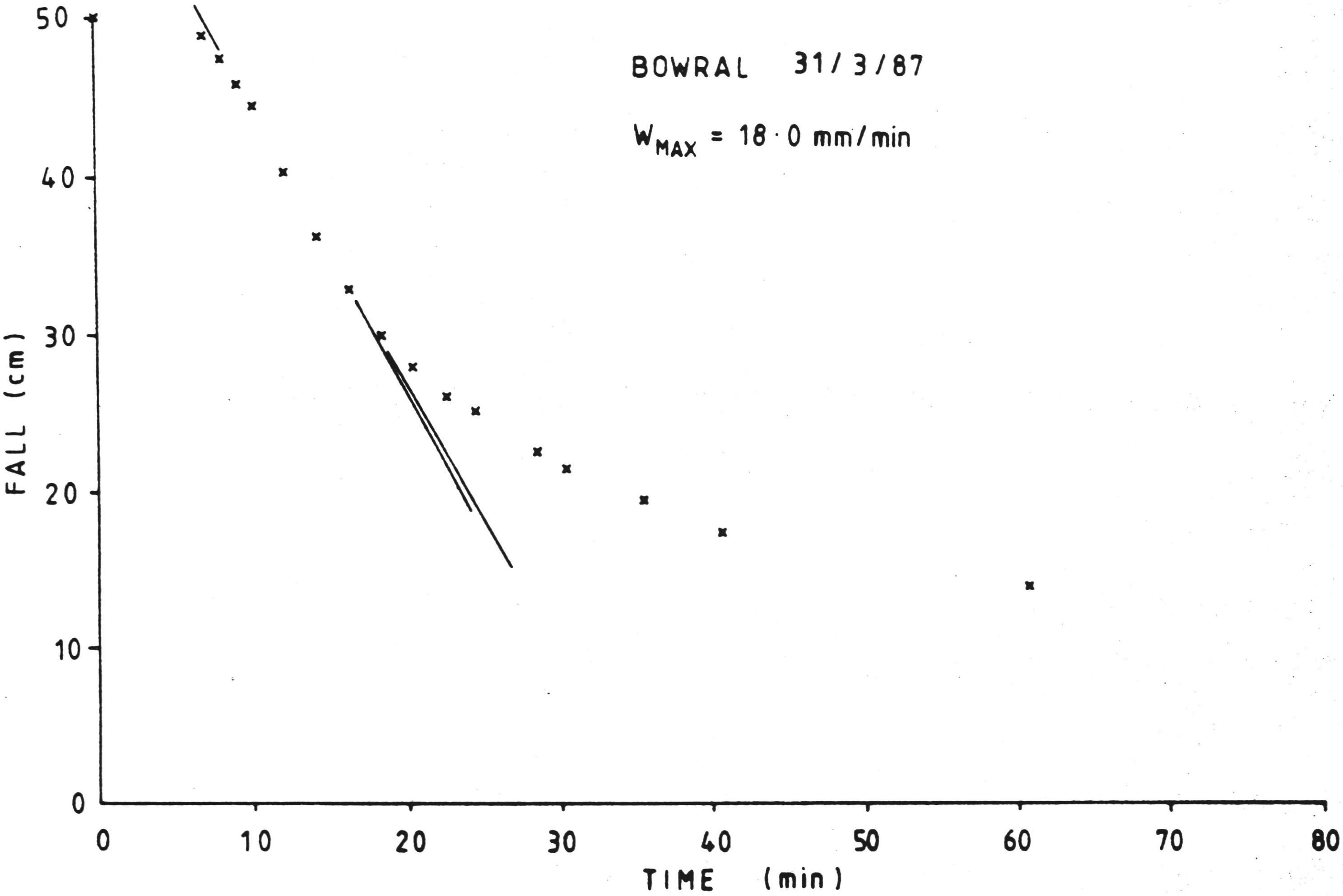
FIGURE 27

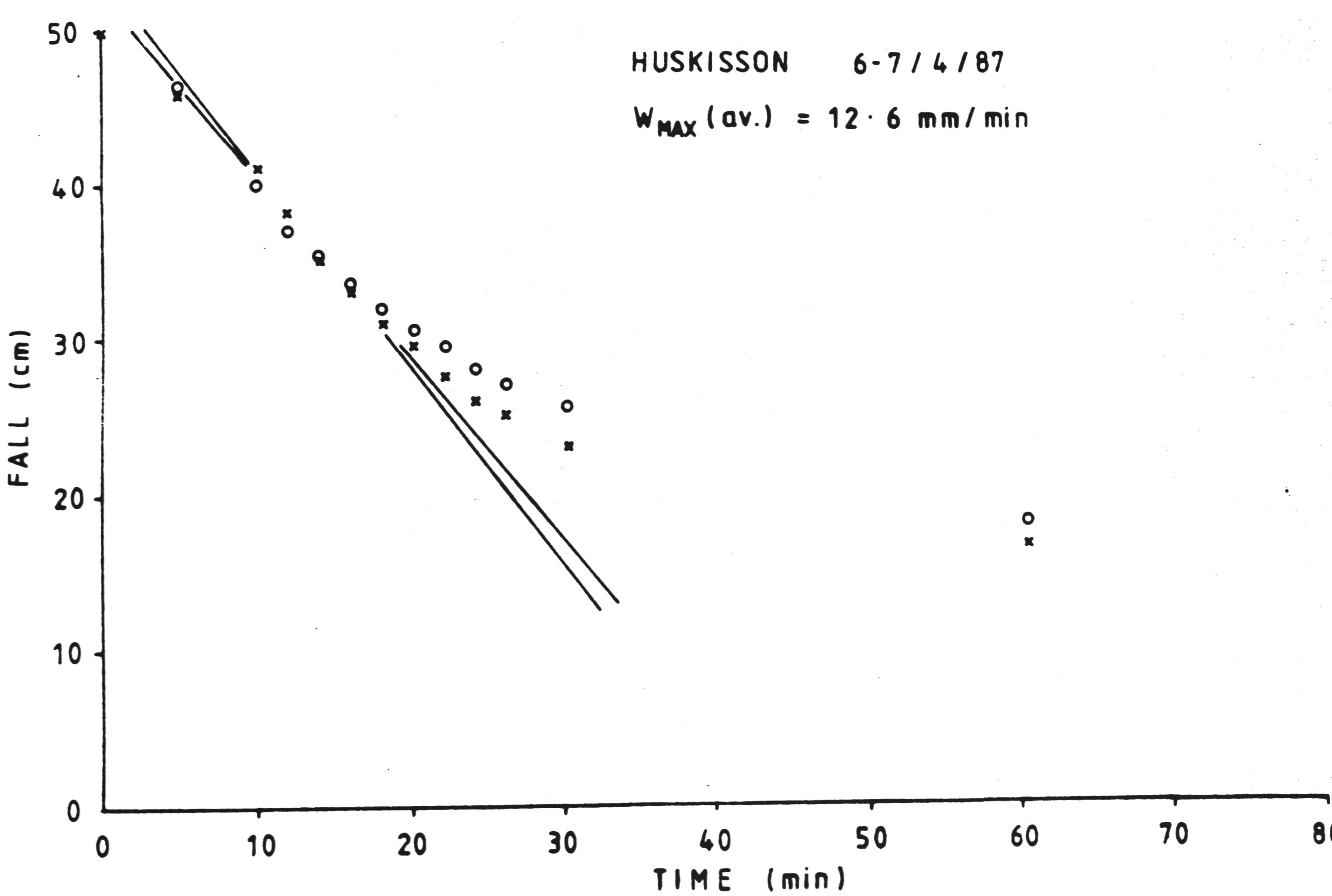




STIRRED SETTLEMENT (S.S.V.) TESTS

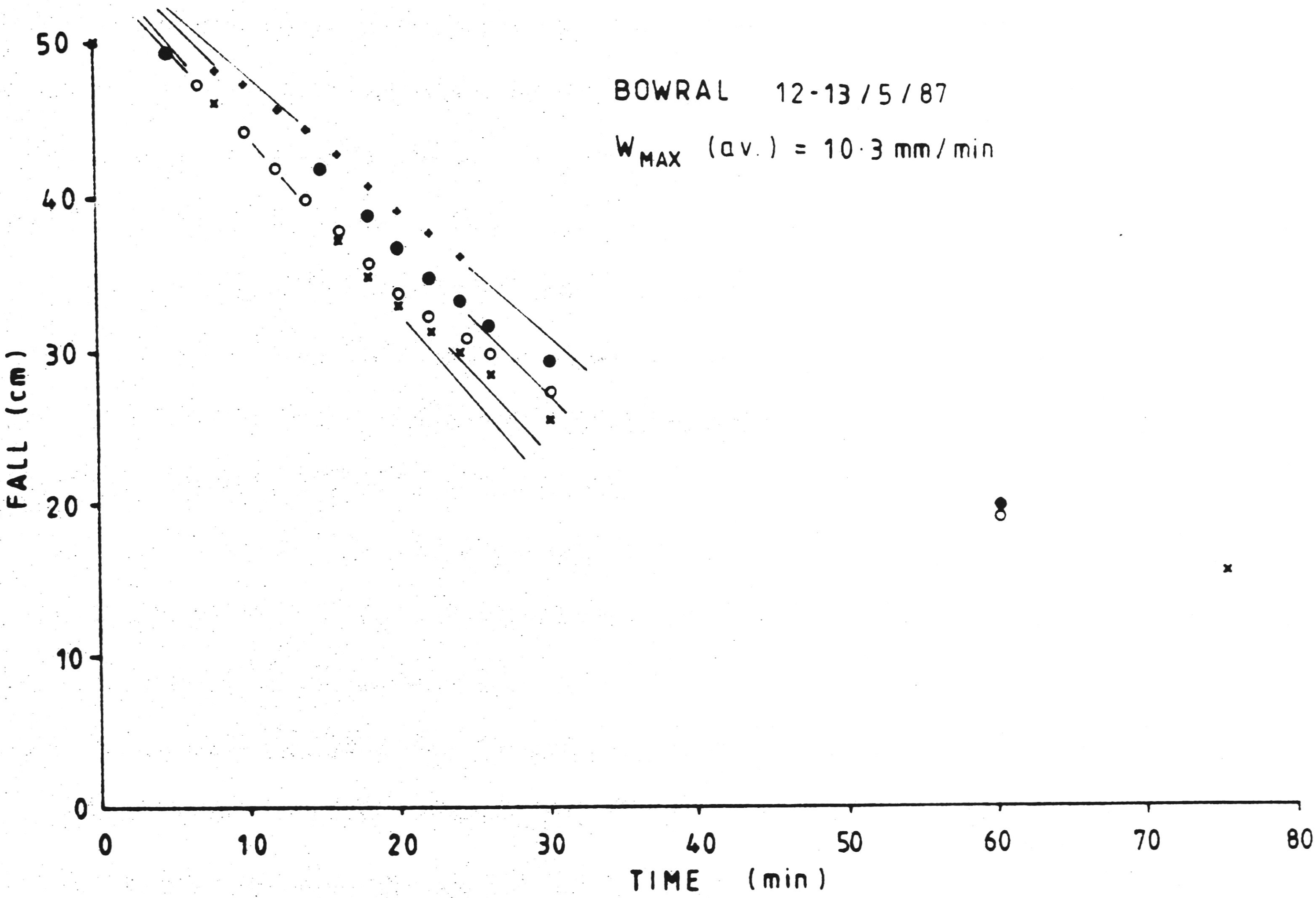
FIGURE 28

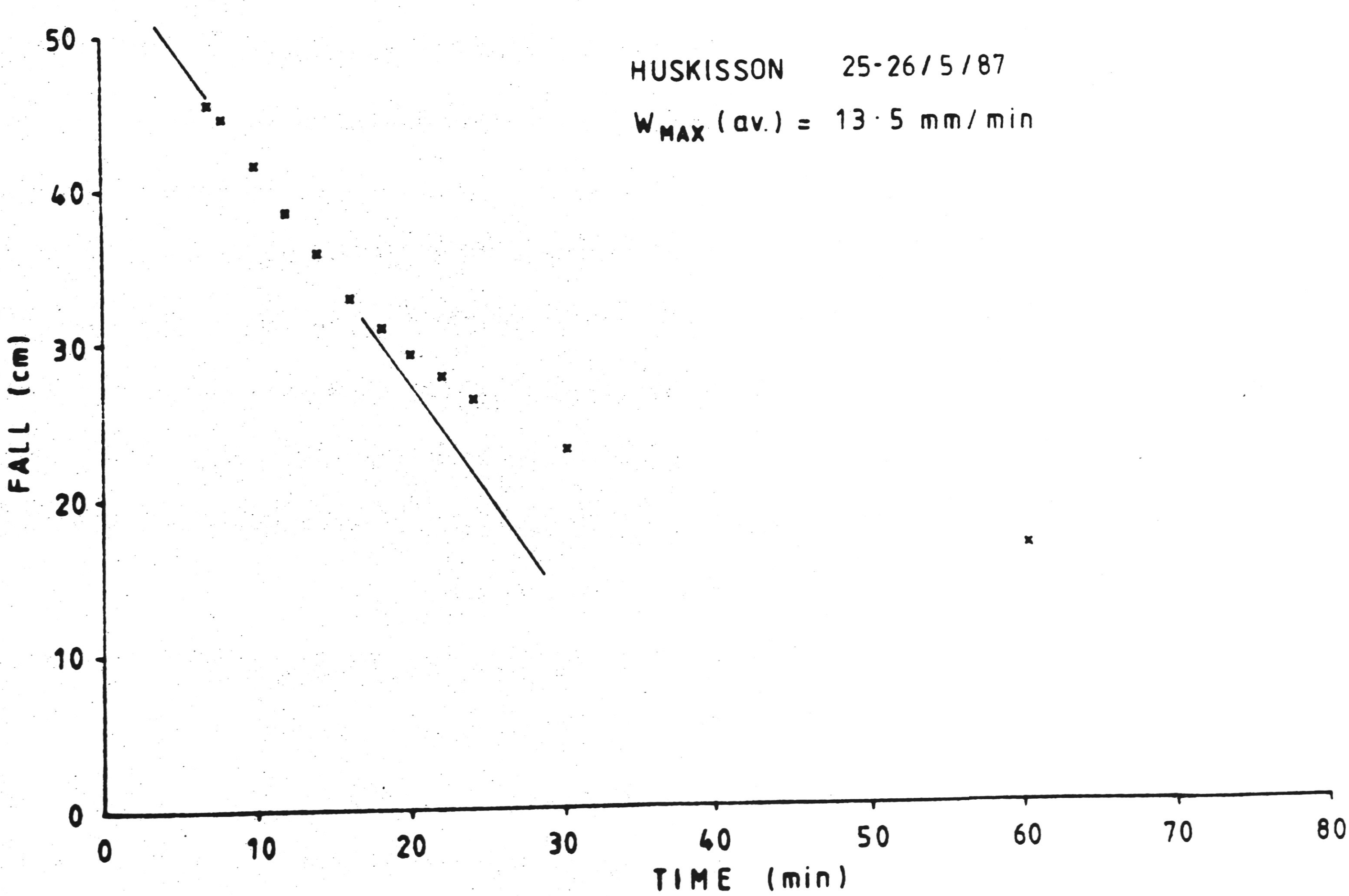




STIRRED SETTLEMENT (S.S.V.) TESTS

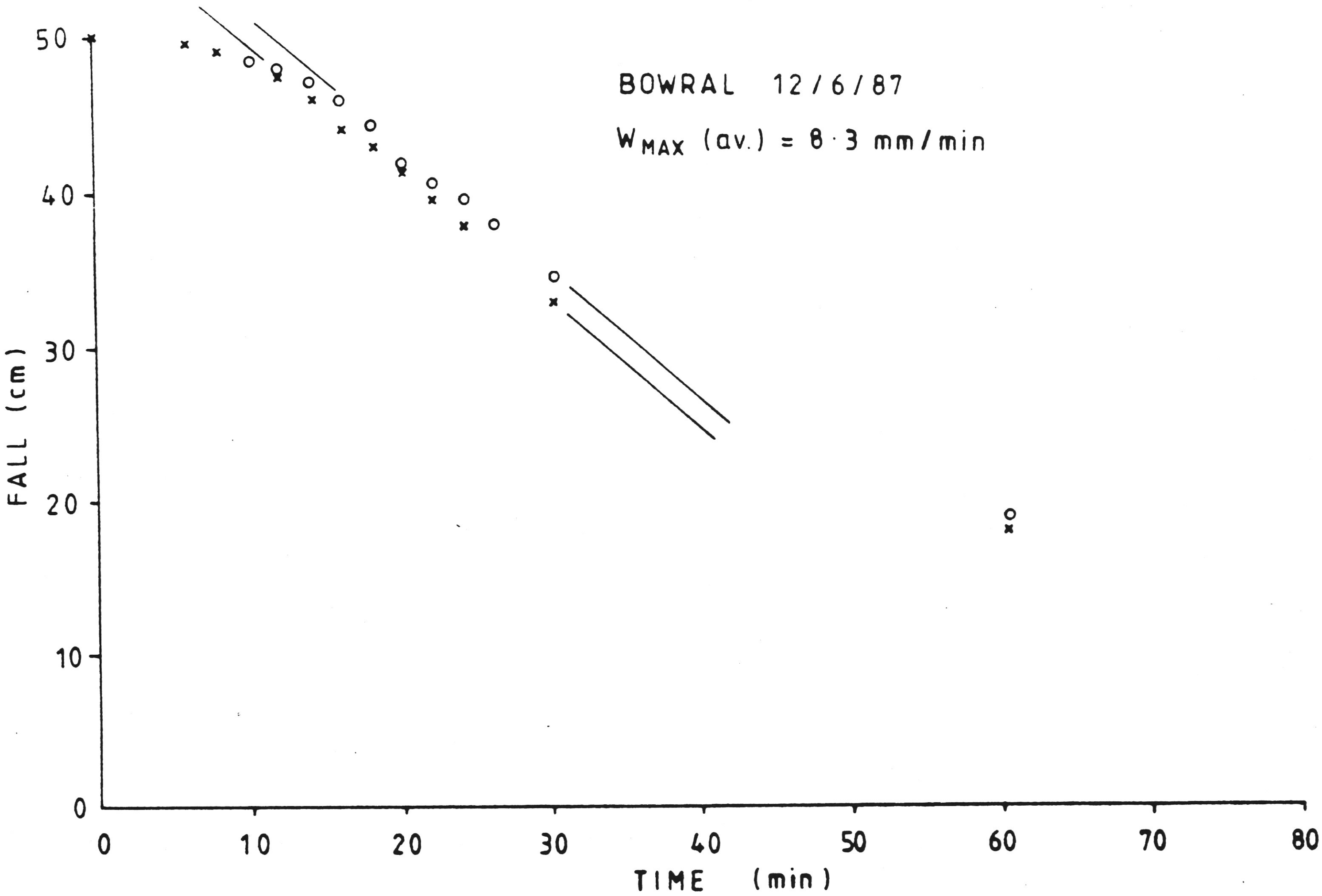
FIGURE 29

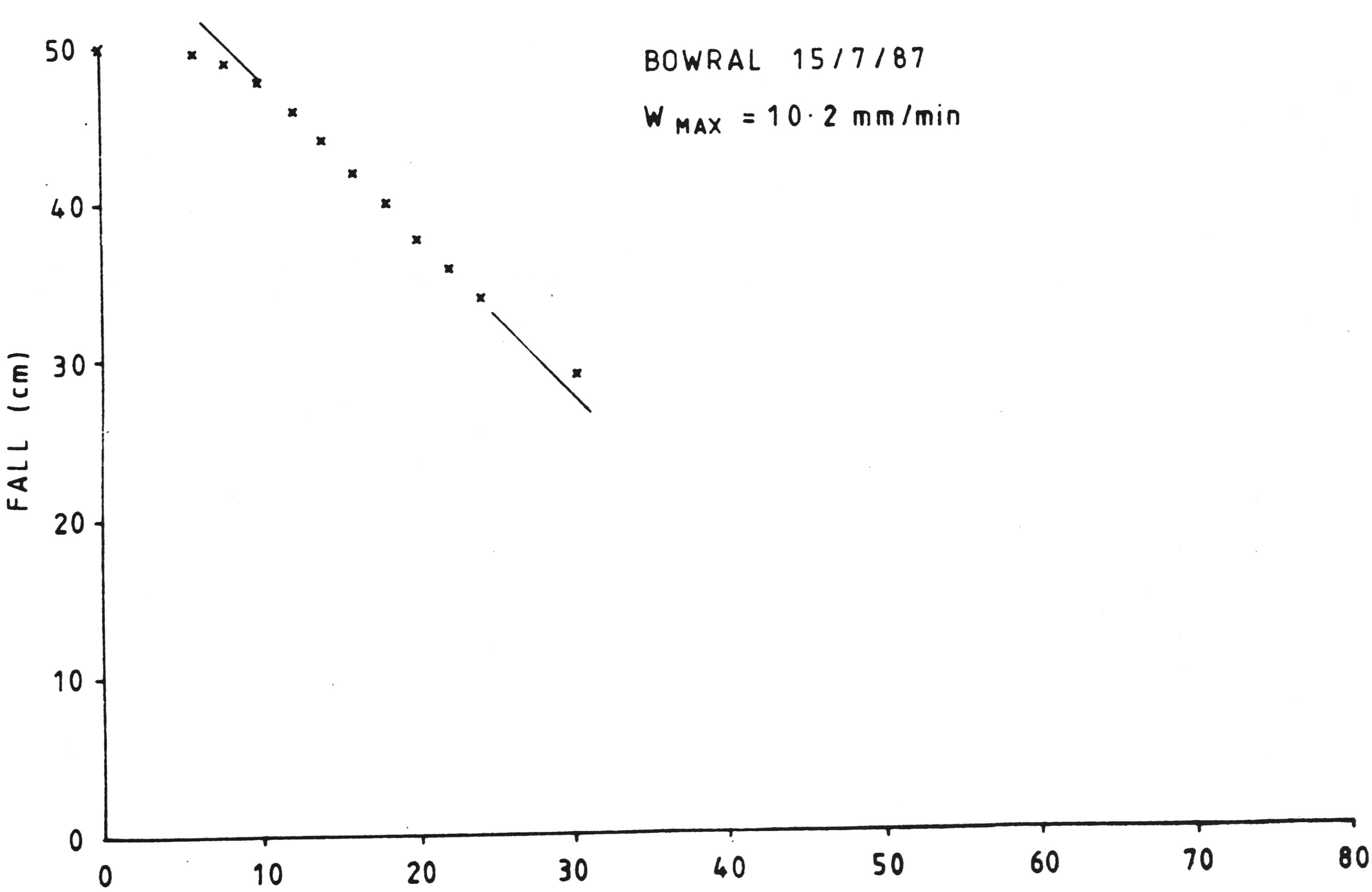




STIRRED SETTLEMENT (S.S.V.) TESTS

FIGURE 30

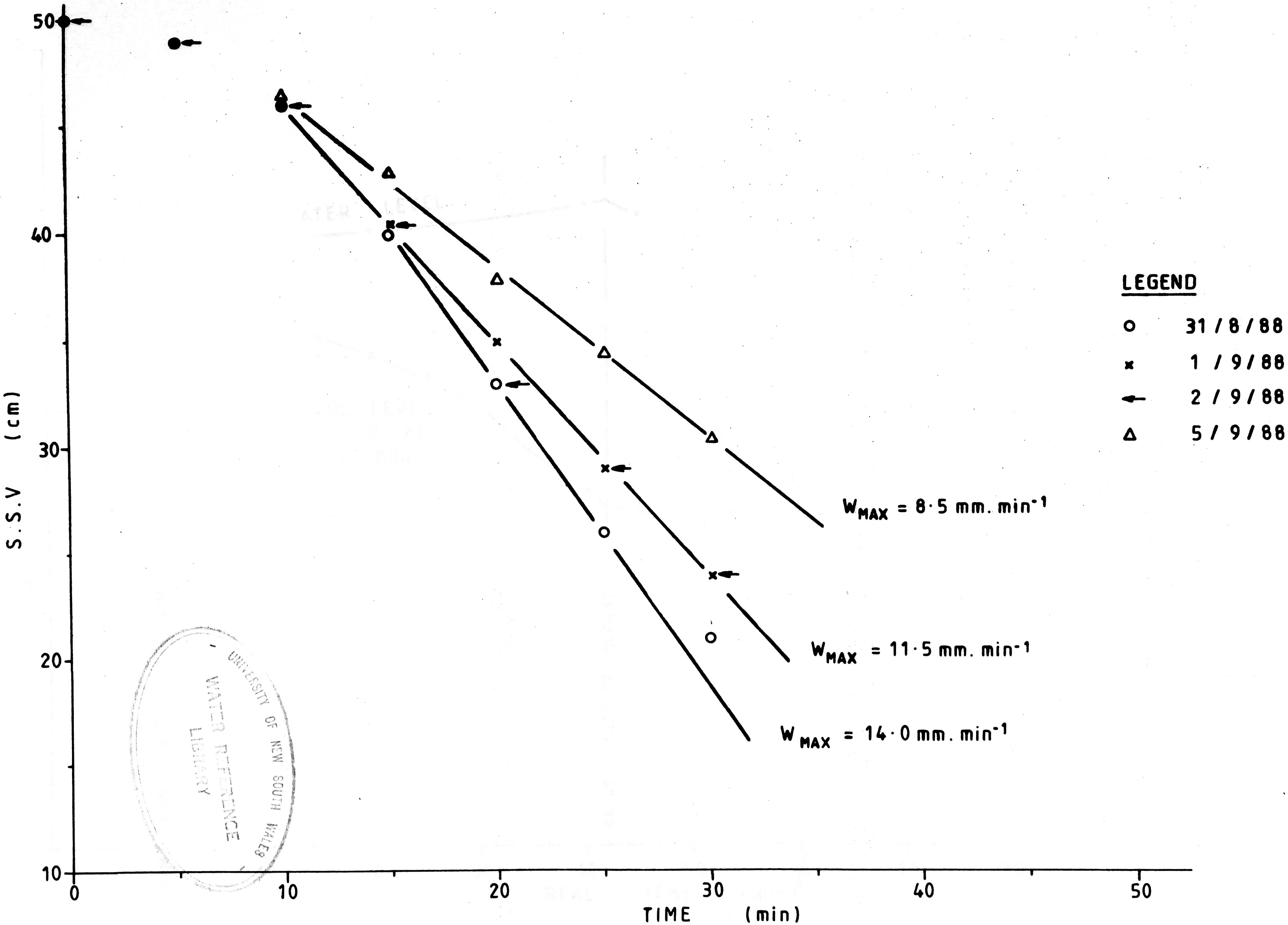




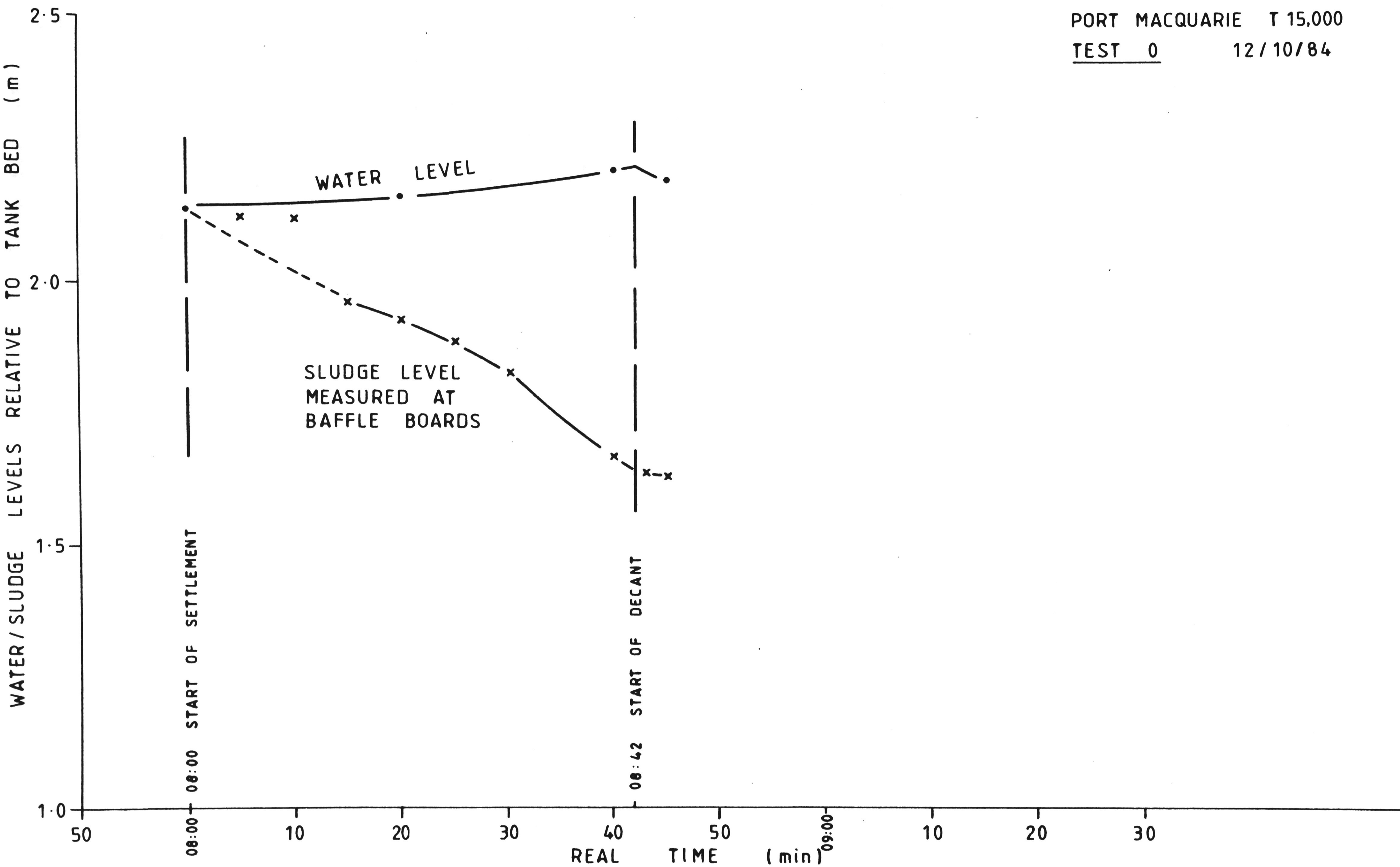
STIRRED SETTLEMENT (S.S.V) TESTS

FIGURE 31

FIGURE 32

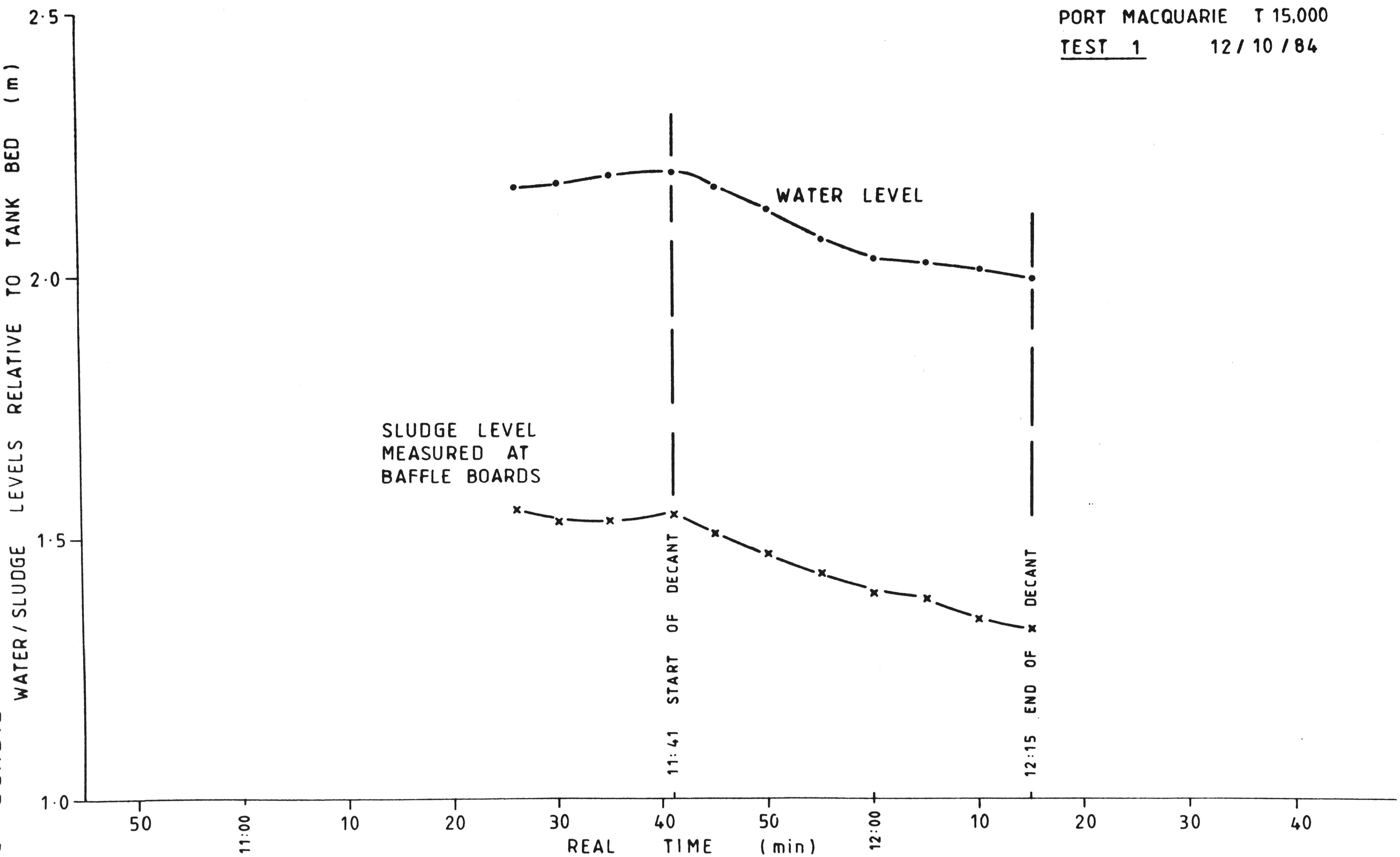


STIRRED SETTLEMENT (S.S.V) TESTS PORT MACQUARIE 1988



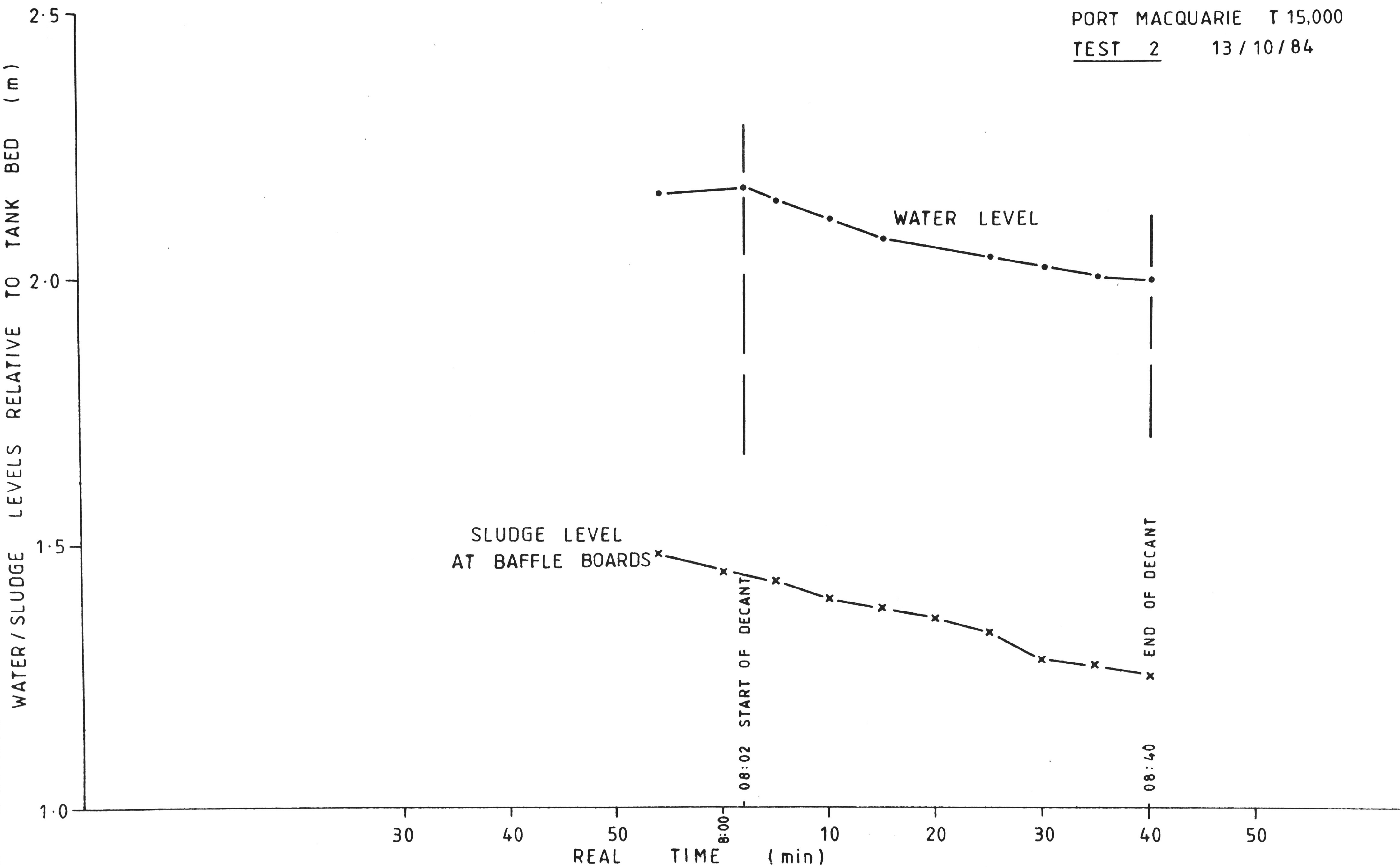
IN - TANK SLUDGE SETTLEMENT

FIGURE 33



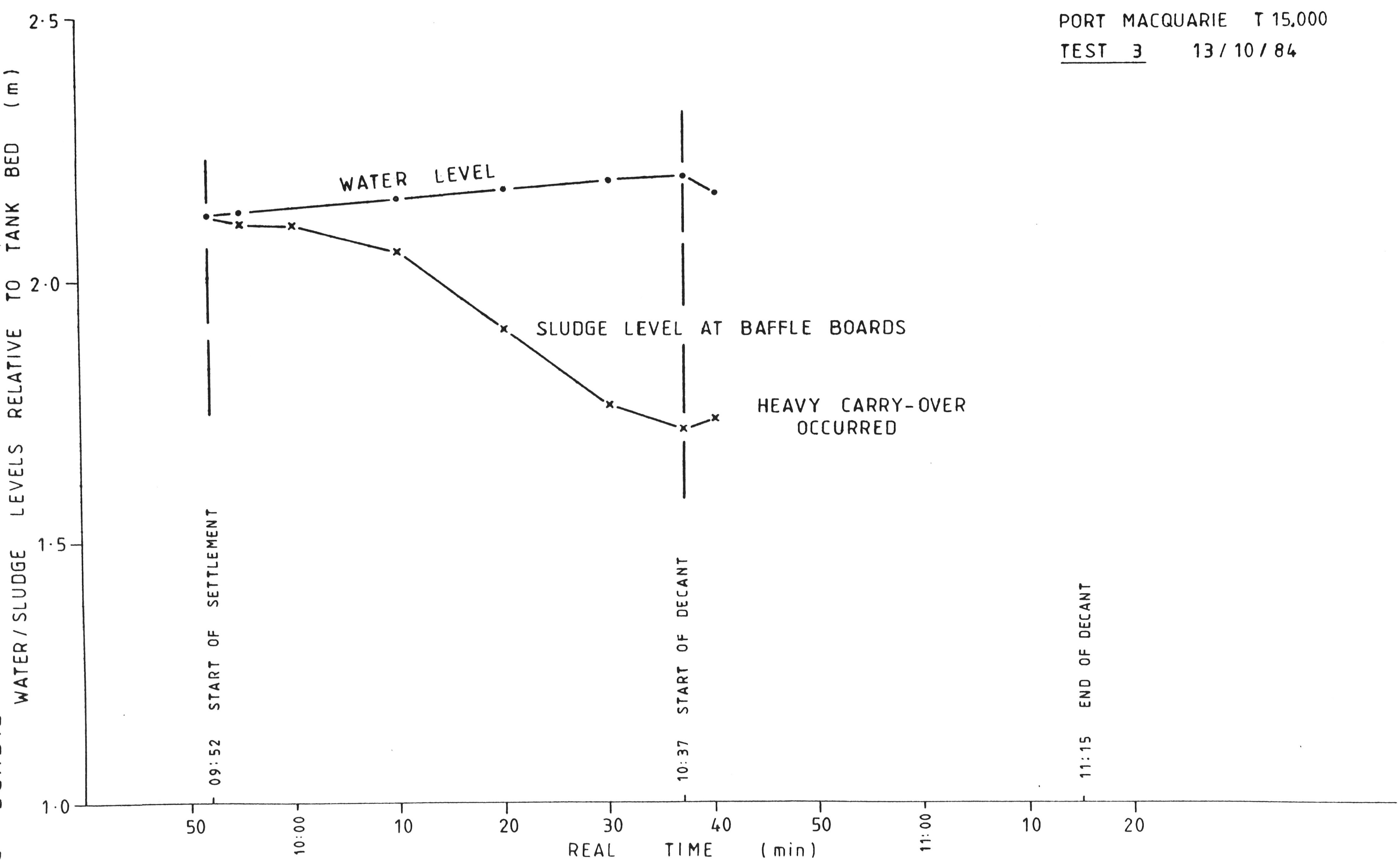
IN - TANK SLUDGE SETTLEMENT

FIGURE 34



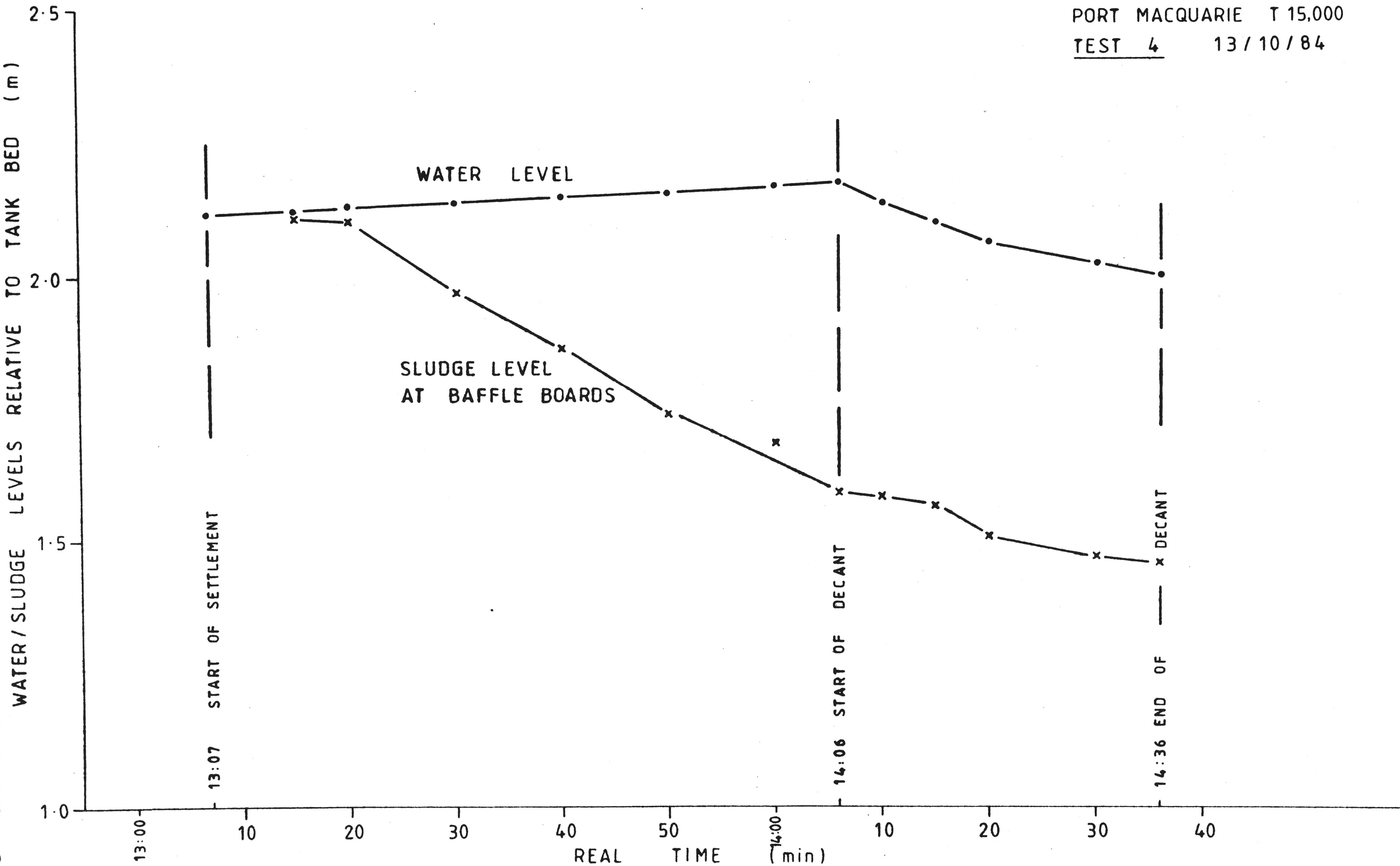
IN - TANK SLUDGE SETTLEMENT

FIGURE 35



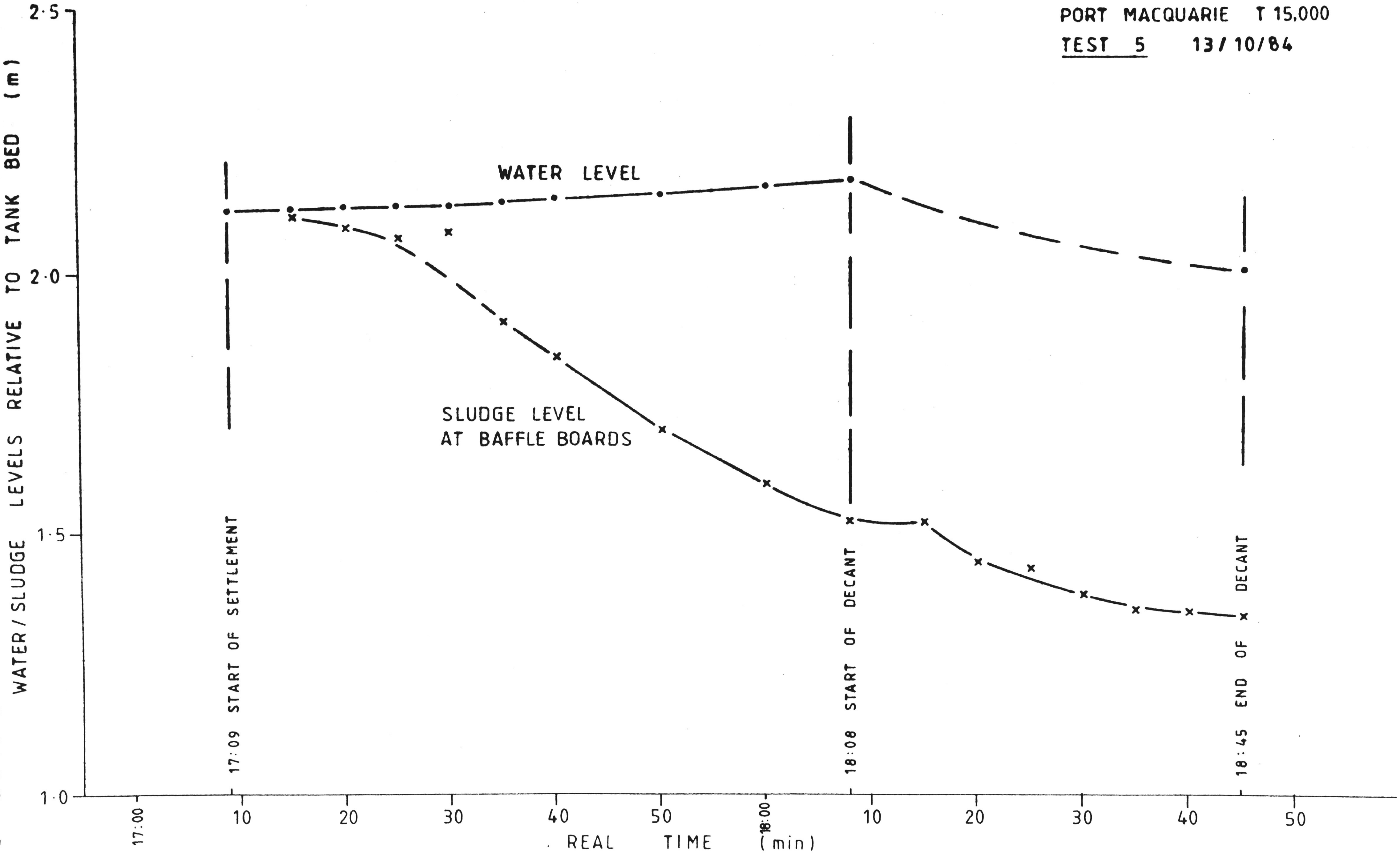
IN - TANK SLUDGE SETTLEMENT

FIGURE 36



IN - TANK SLUDGE SETTLEMENT

FIGURE 37



IN - TANK SLUDGE SETTLEMENT

FIGURE 38

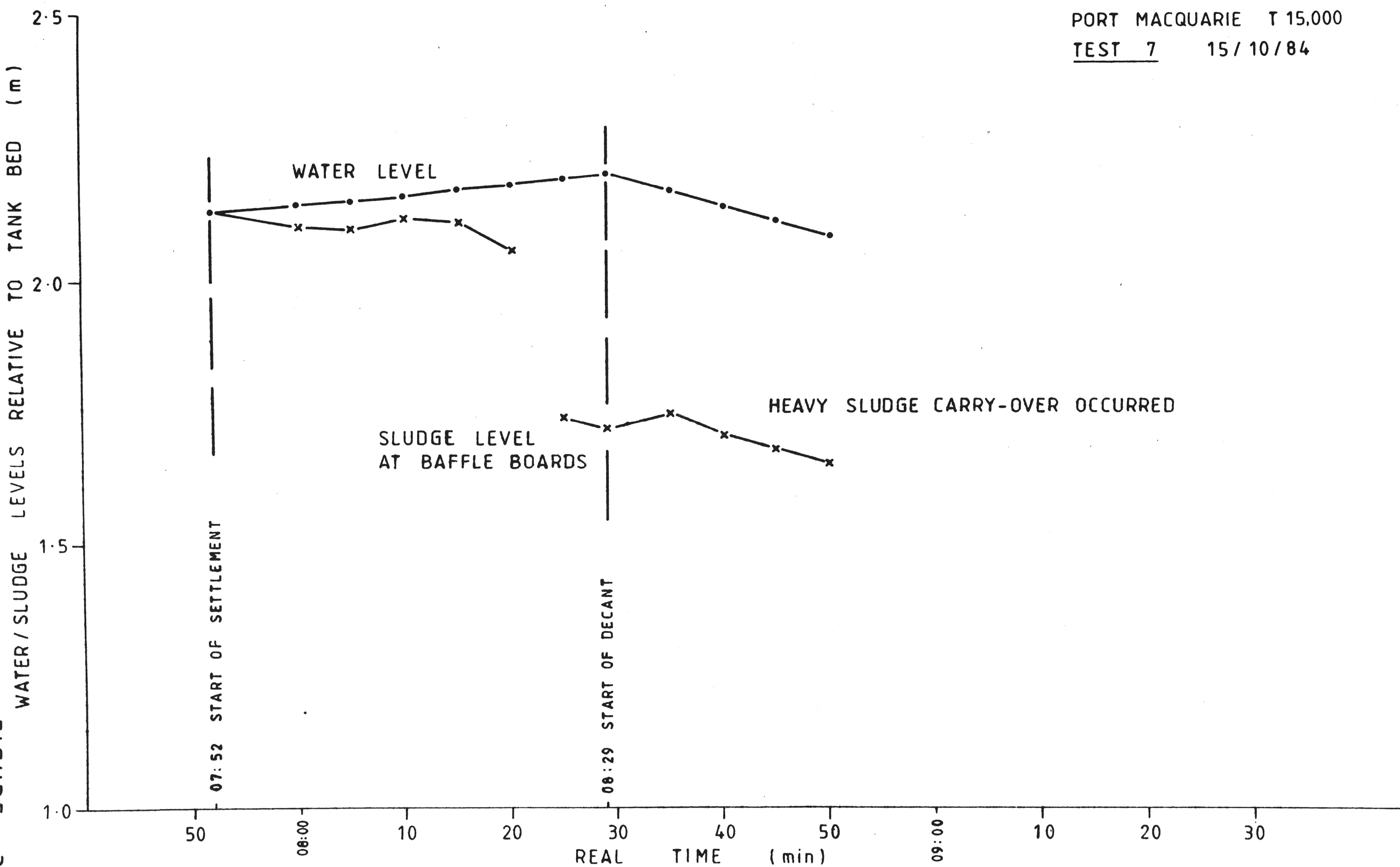


FIGURE 39

IN - TANK SLUDGE SETTLEMENT

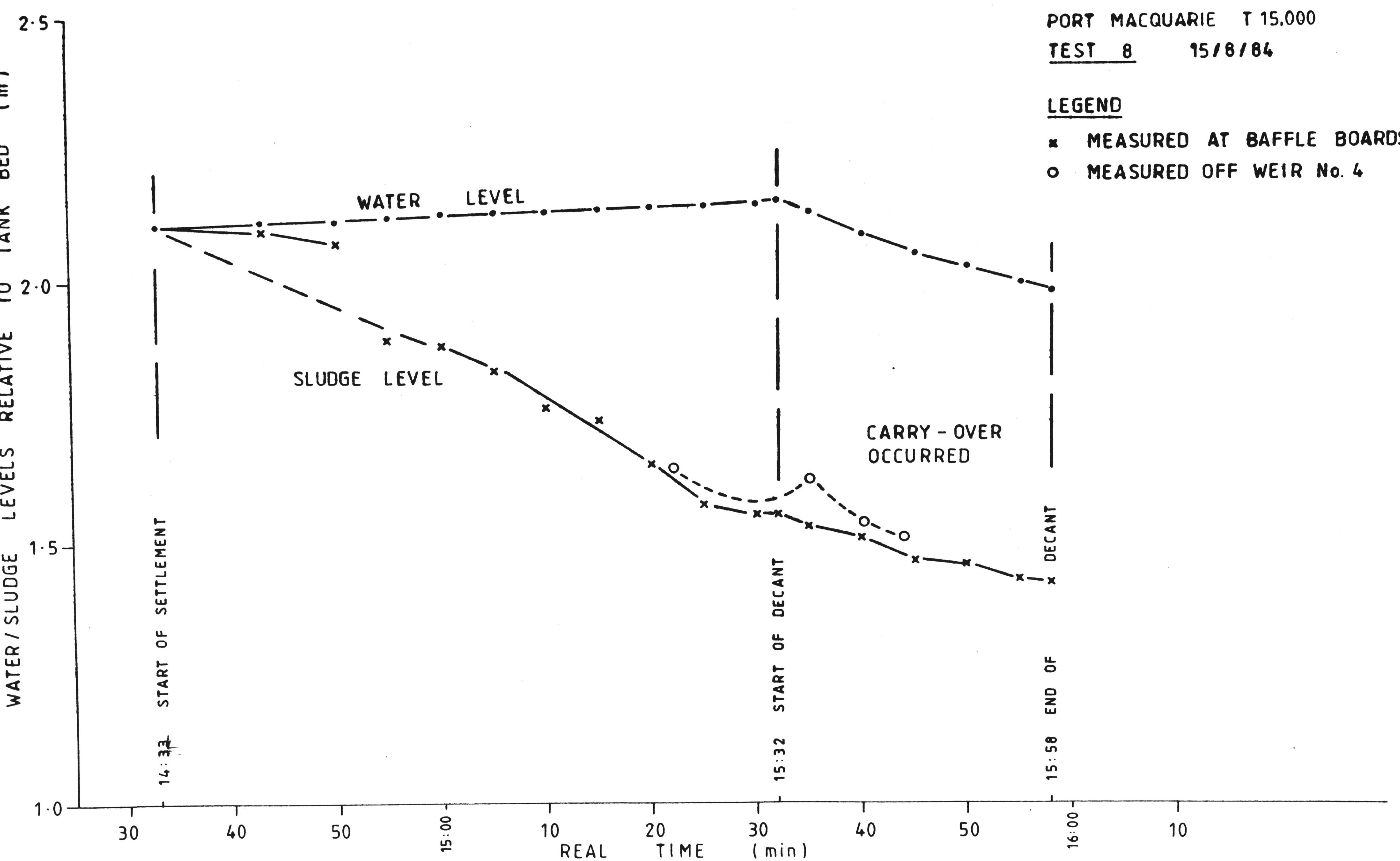


FIGURE 40

IN - TANK SLUDGE SETTLEMENT

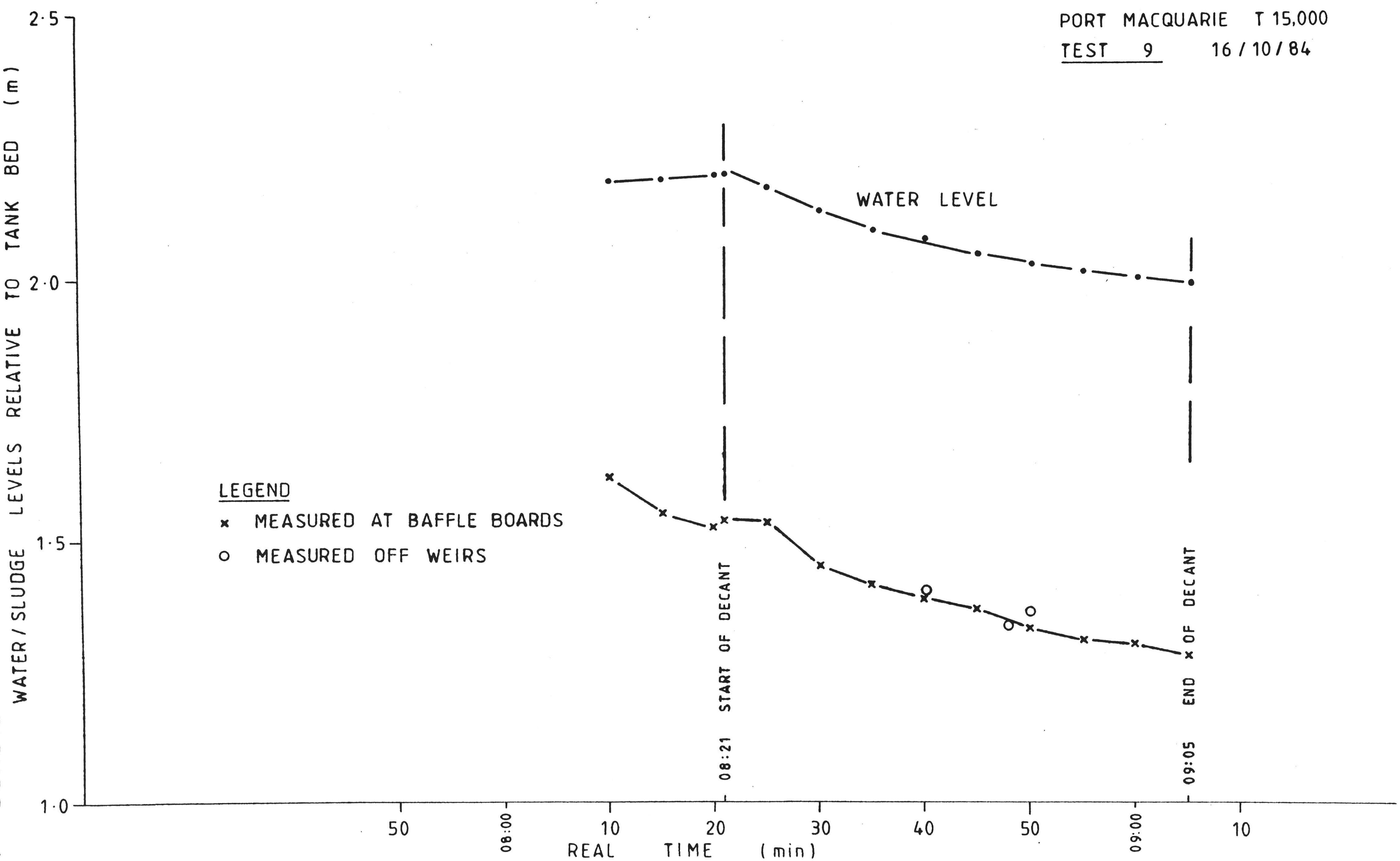
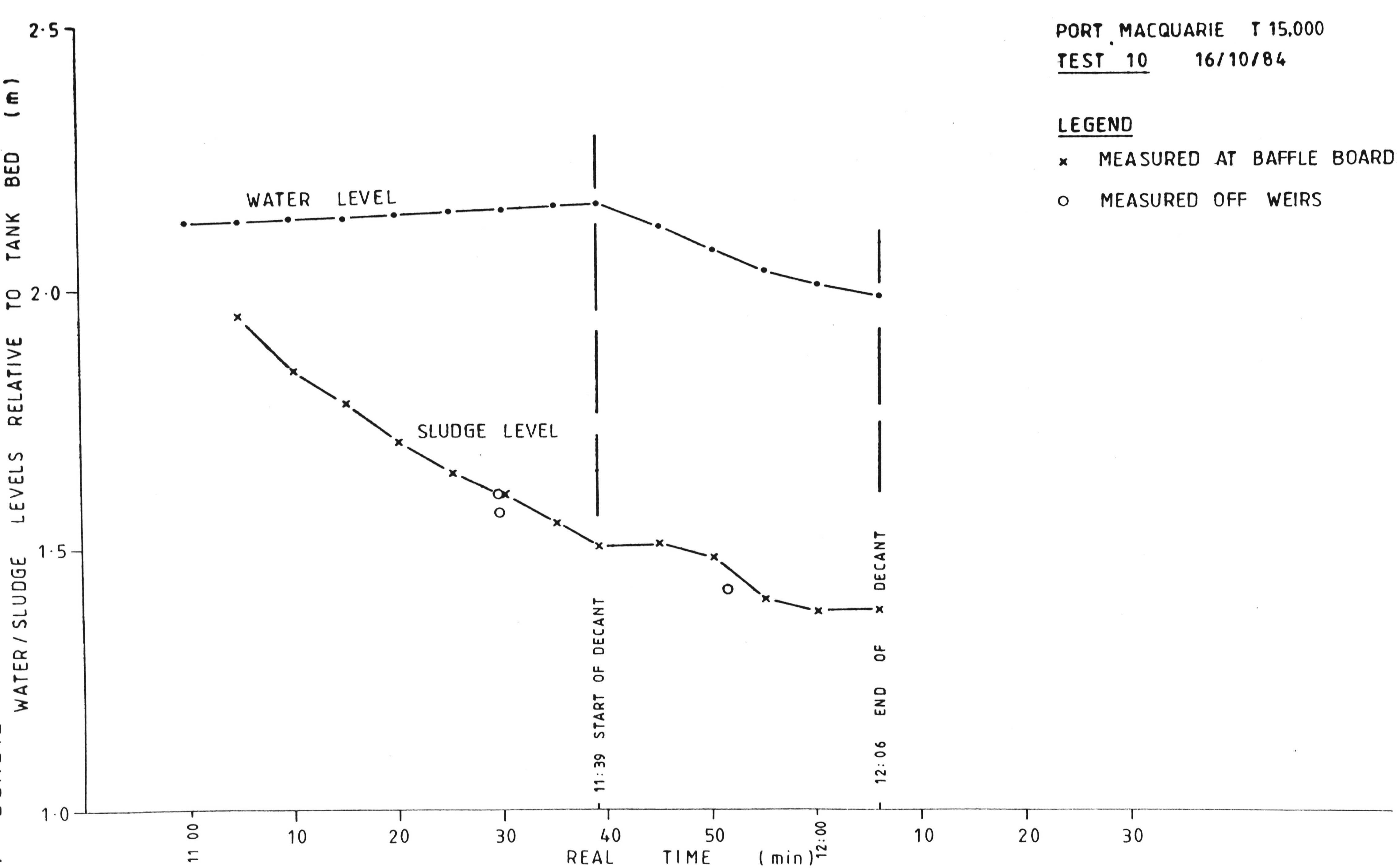


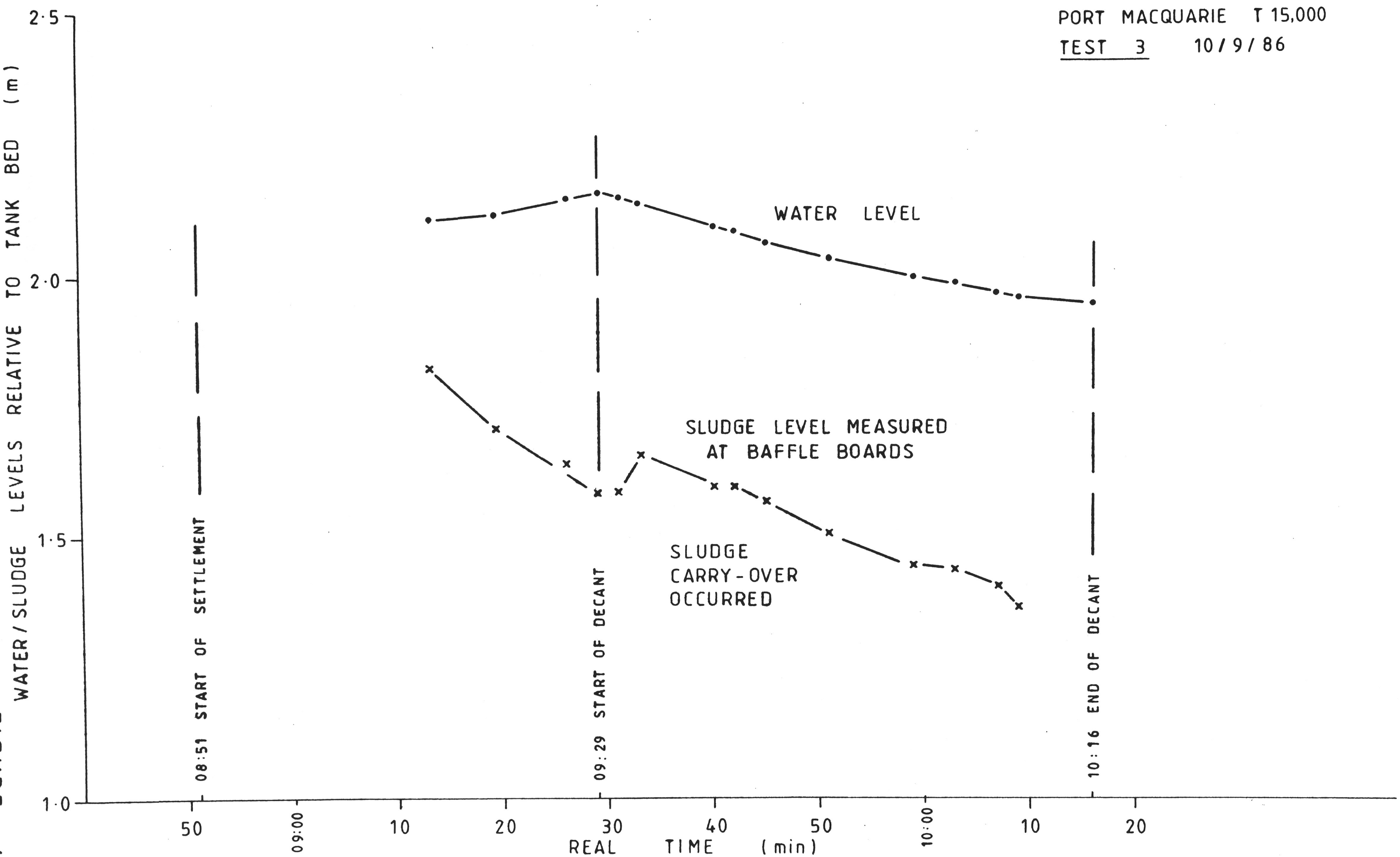
FIGURE 41

IN - TANK SLUDGE SETTLEMENT



IN - TANK SLUDGE SETTLEMENT

FIGURE 42



IN - TANK SLUDGE SETTLEMENT

FIGURE 43

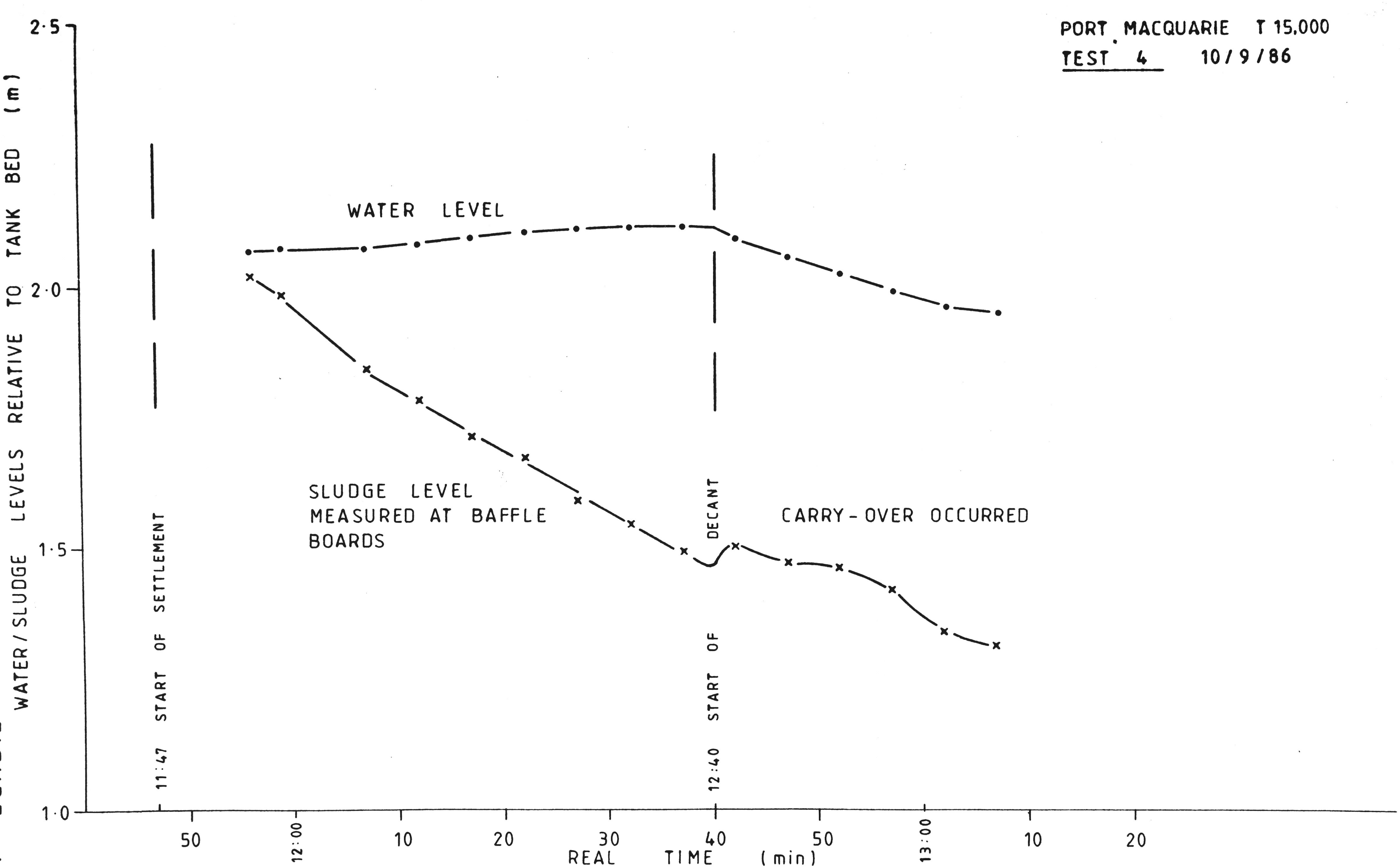
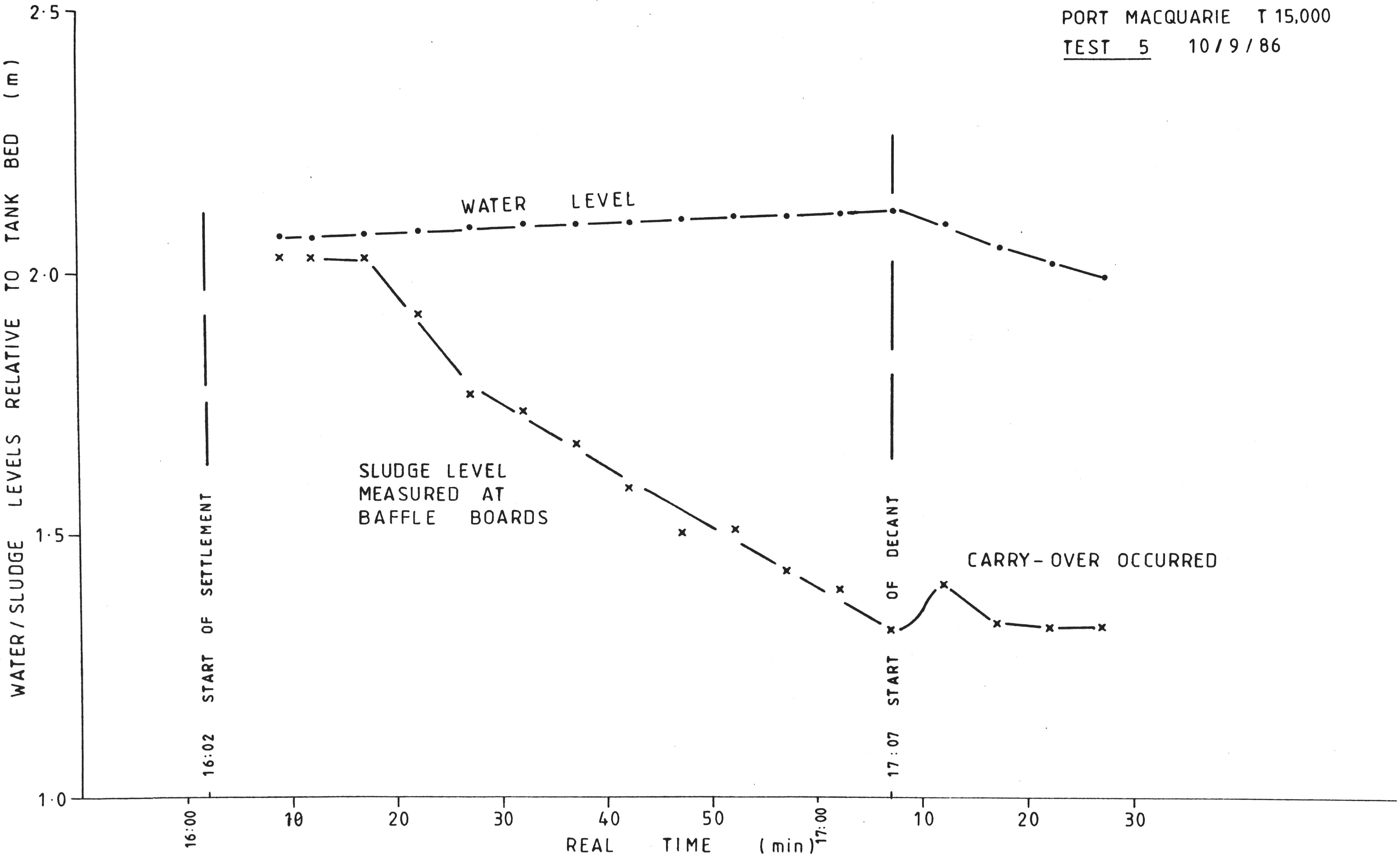


FIGURE 44

IN - TANK SLUDGE SETTLEMENT



IN - TANK SLUDGE SETTLEMENT

FIGURE 4.5

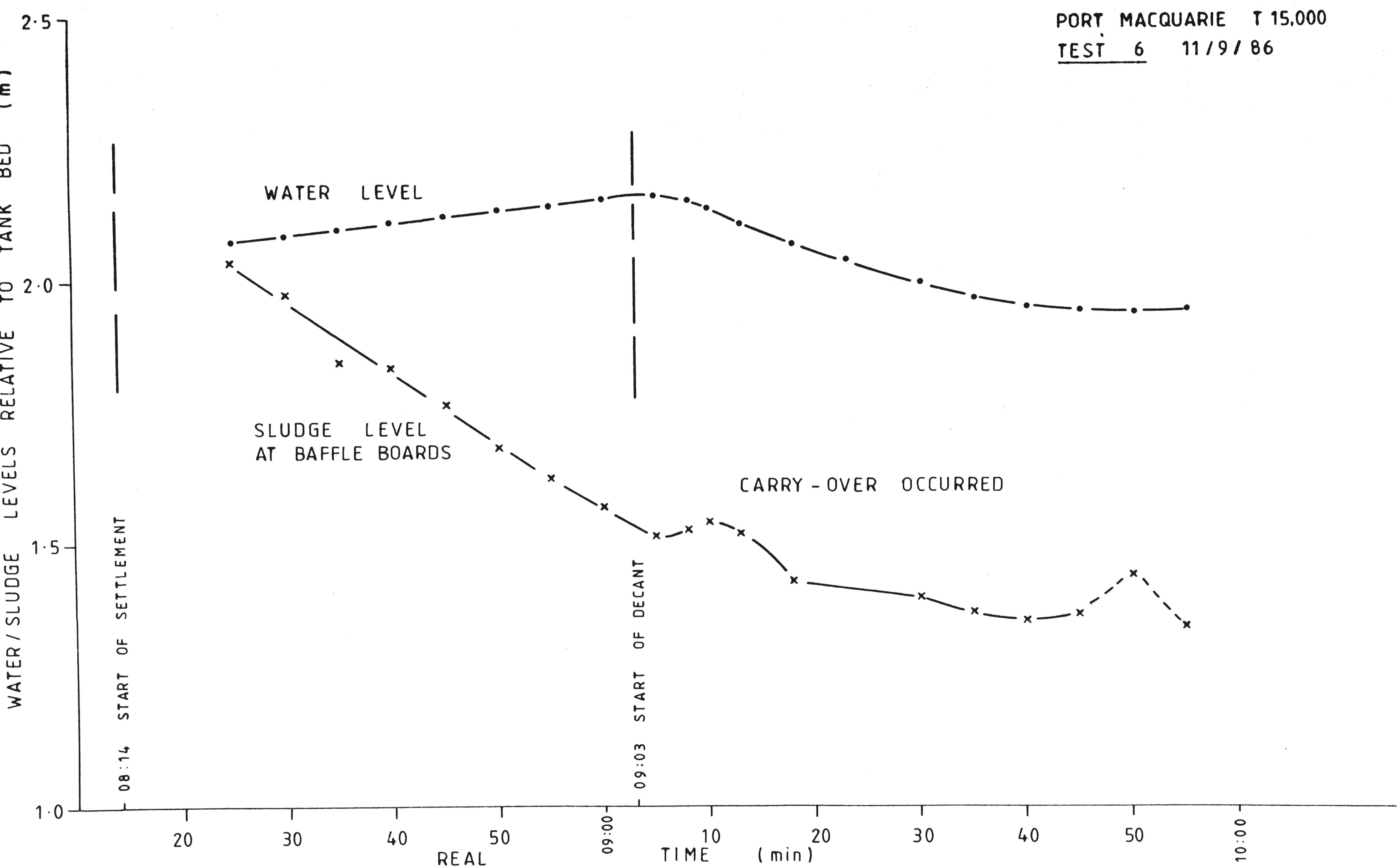


FIGURE 46

IN - TANK SLUDGE SETTLEMENT

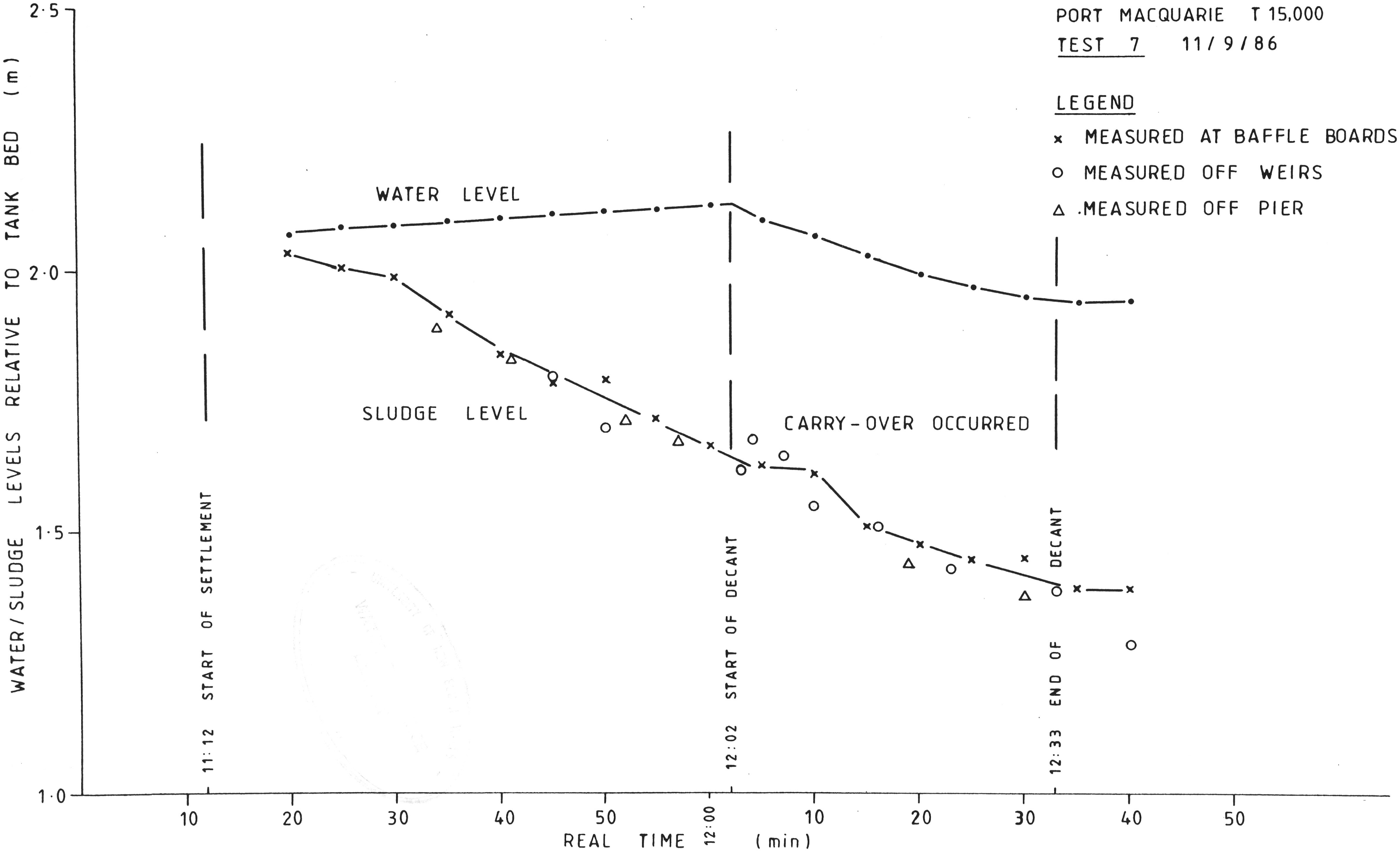


FIGURE 47

IN - TANK SLUDGE SETTLEMENT

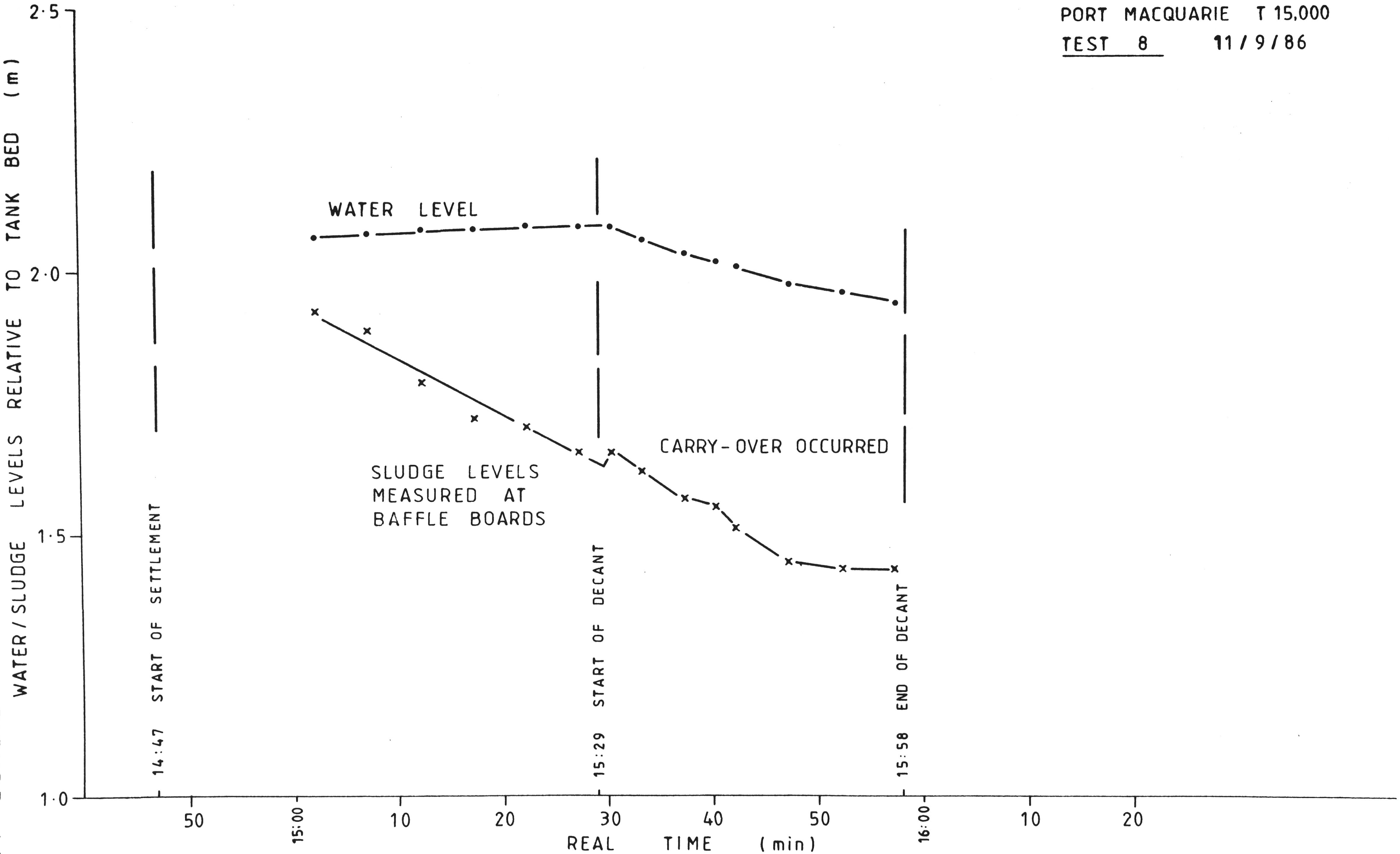
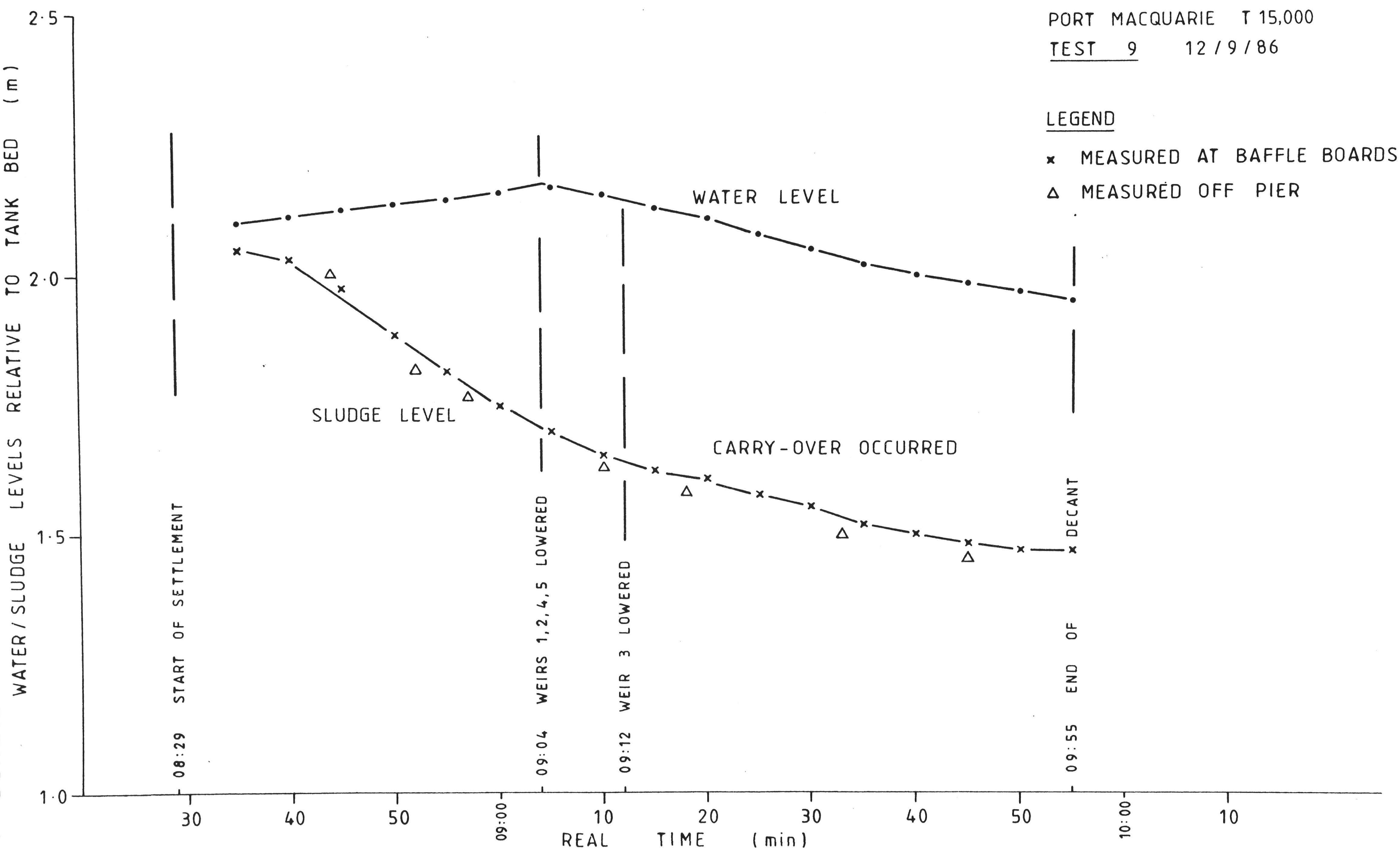


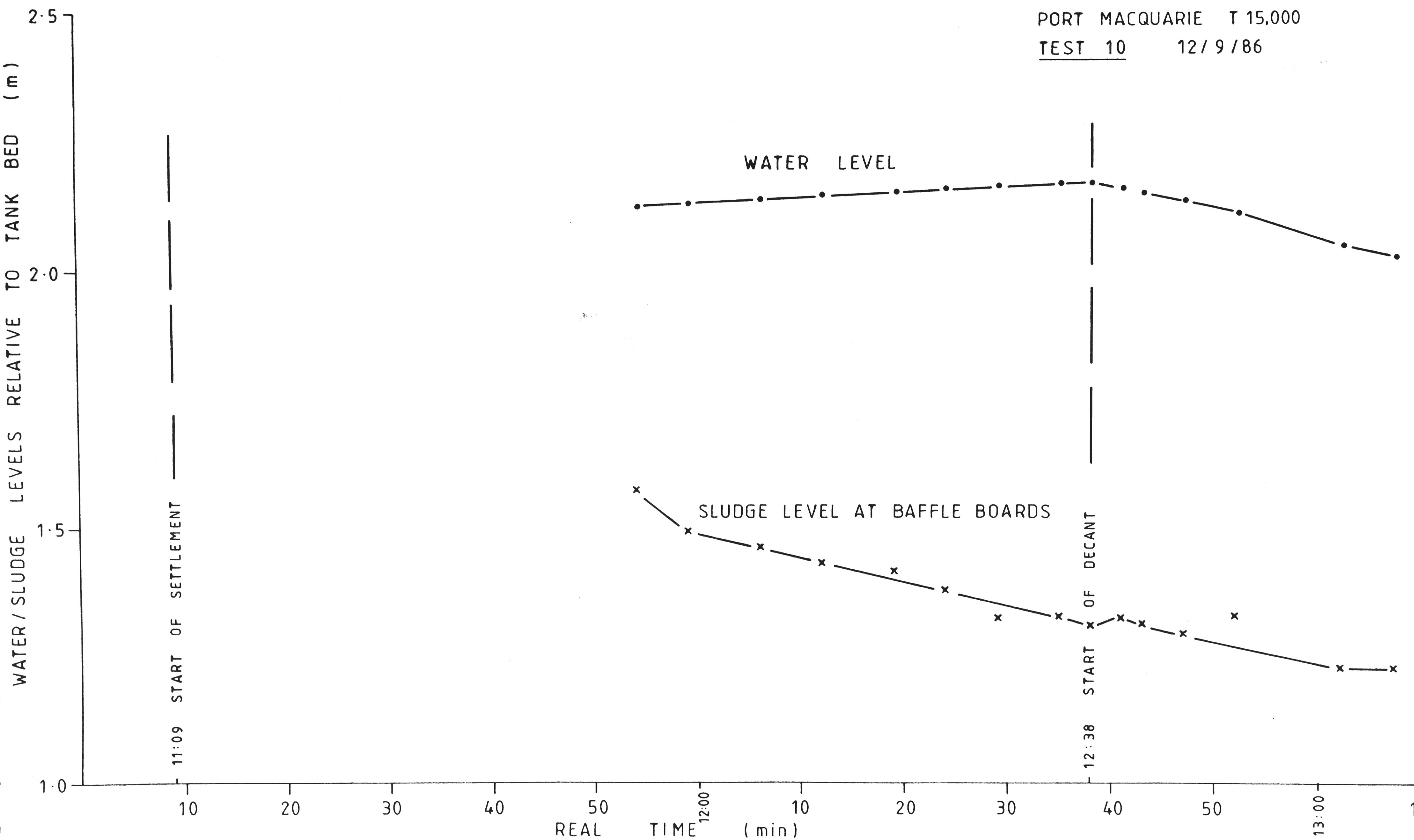
FIGURE 48

IN - TANK SLUDGE SETTLEMENT



IN - TANK SLUDGE SETTLEMENT

FIGURE 49



IN - TANK SLUDGE SETTLEMENT

FIGURE 50

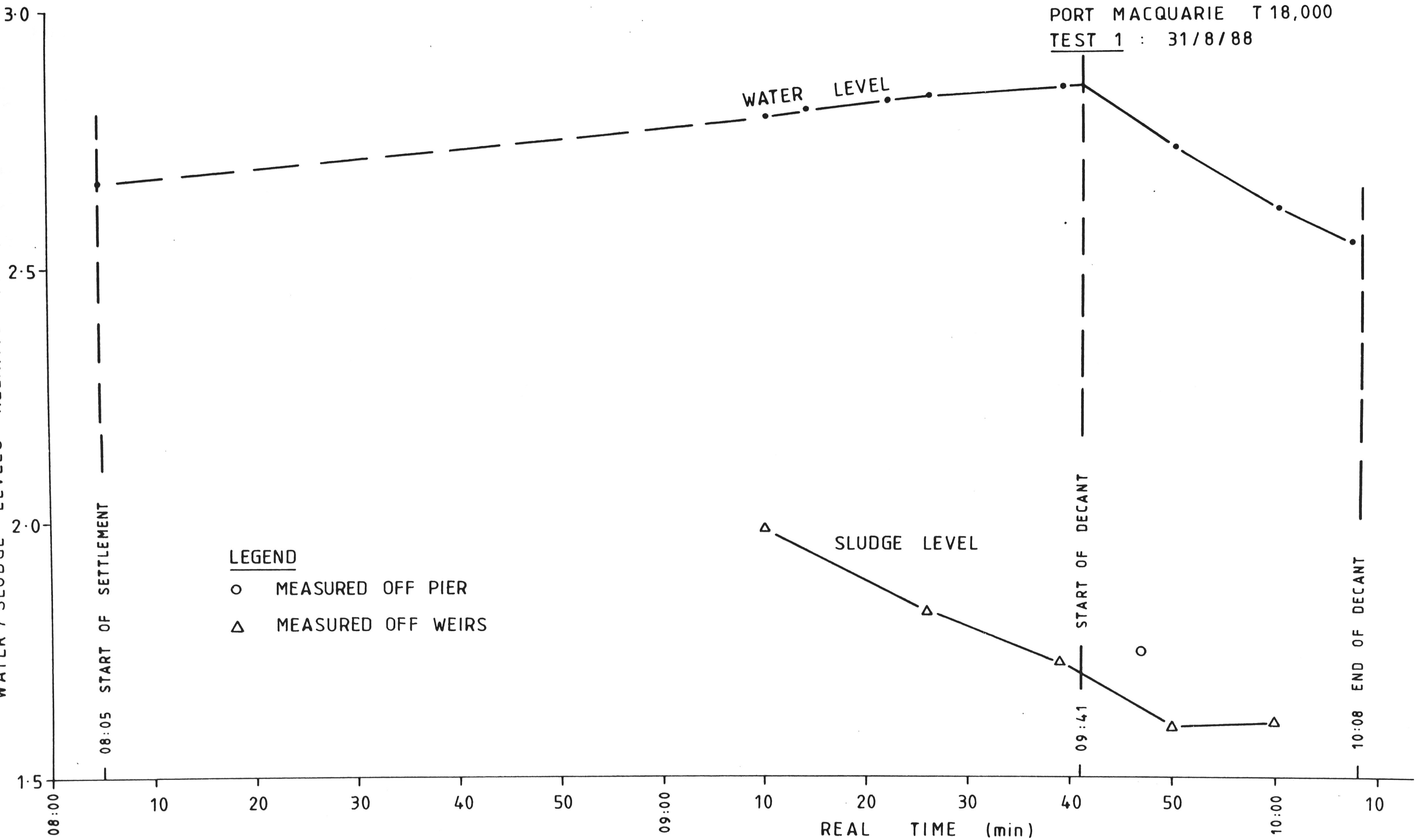


FIGURE 51

IN-TANK SLUDGE SETTLEMENT

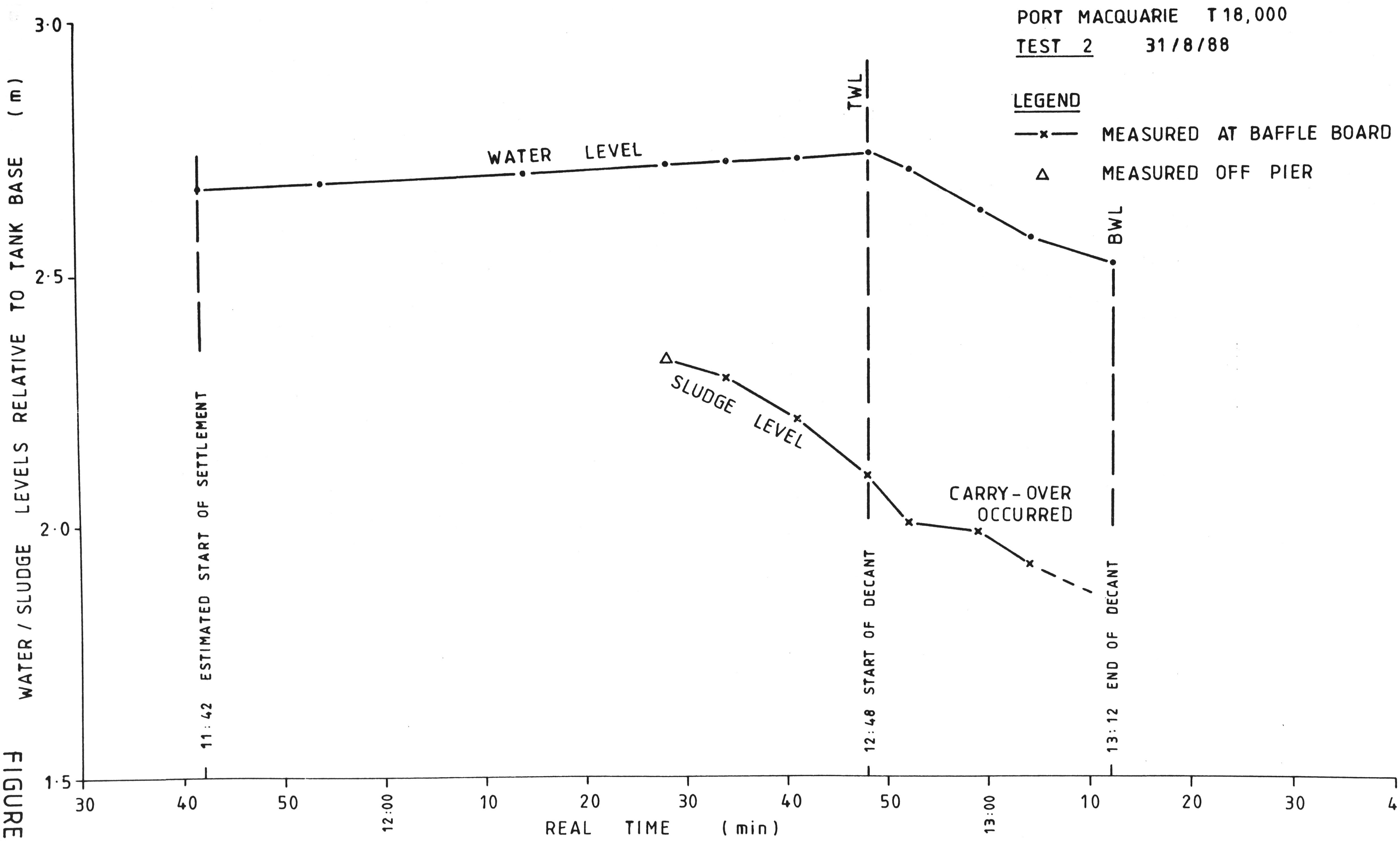
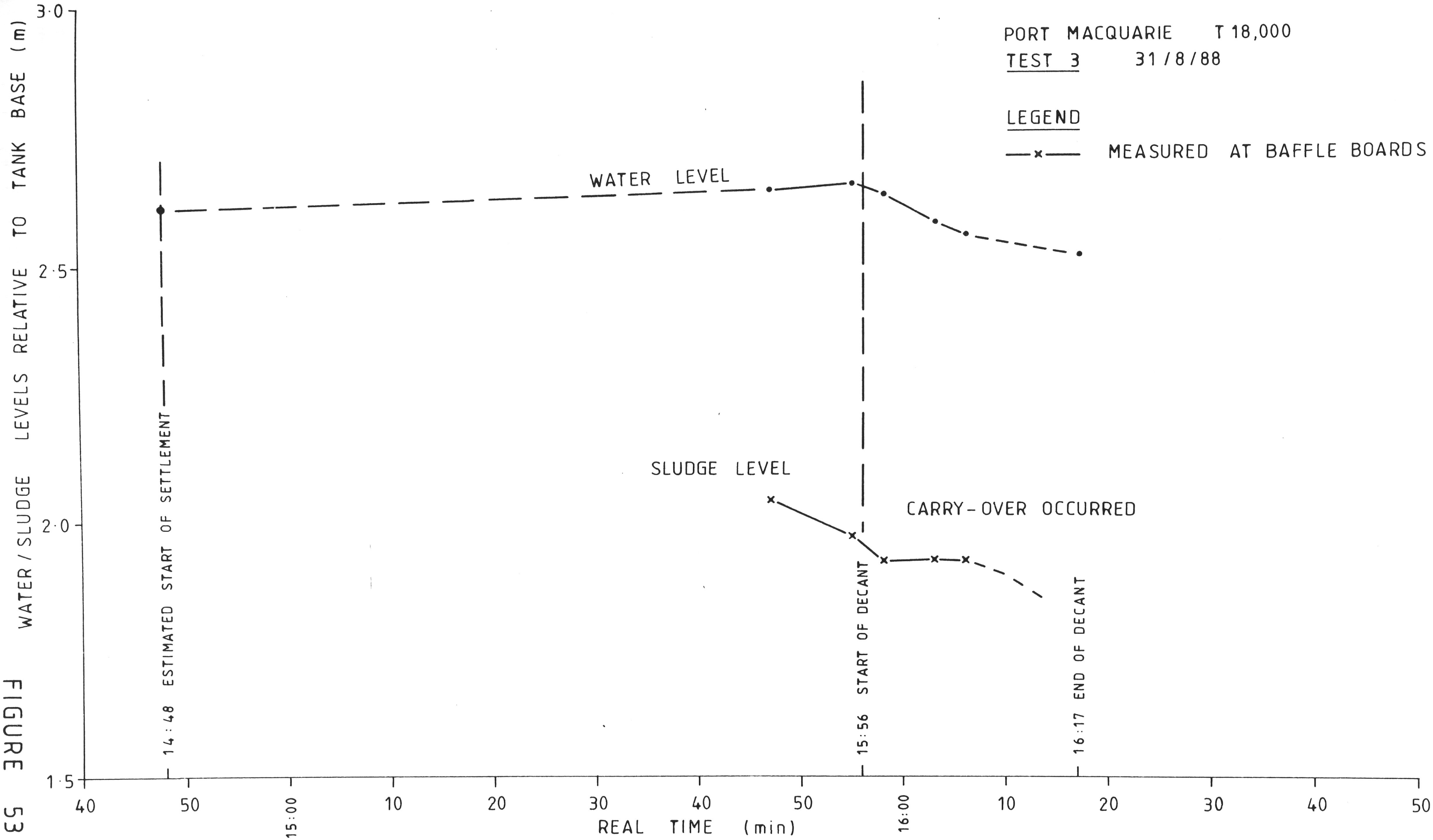


FIGURE 52

IN TANK SLUDGE SETTLEMENT



IN TANK SLUDGE SETTLEMENT

FIGURE 53

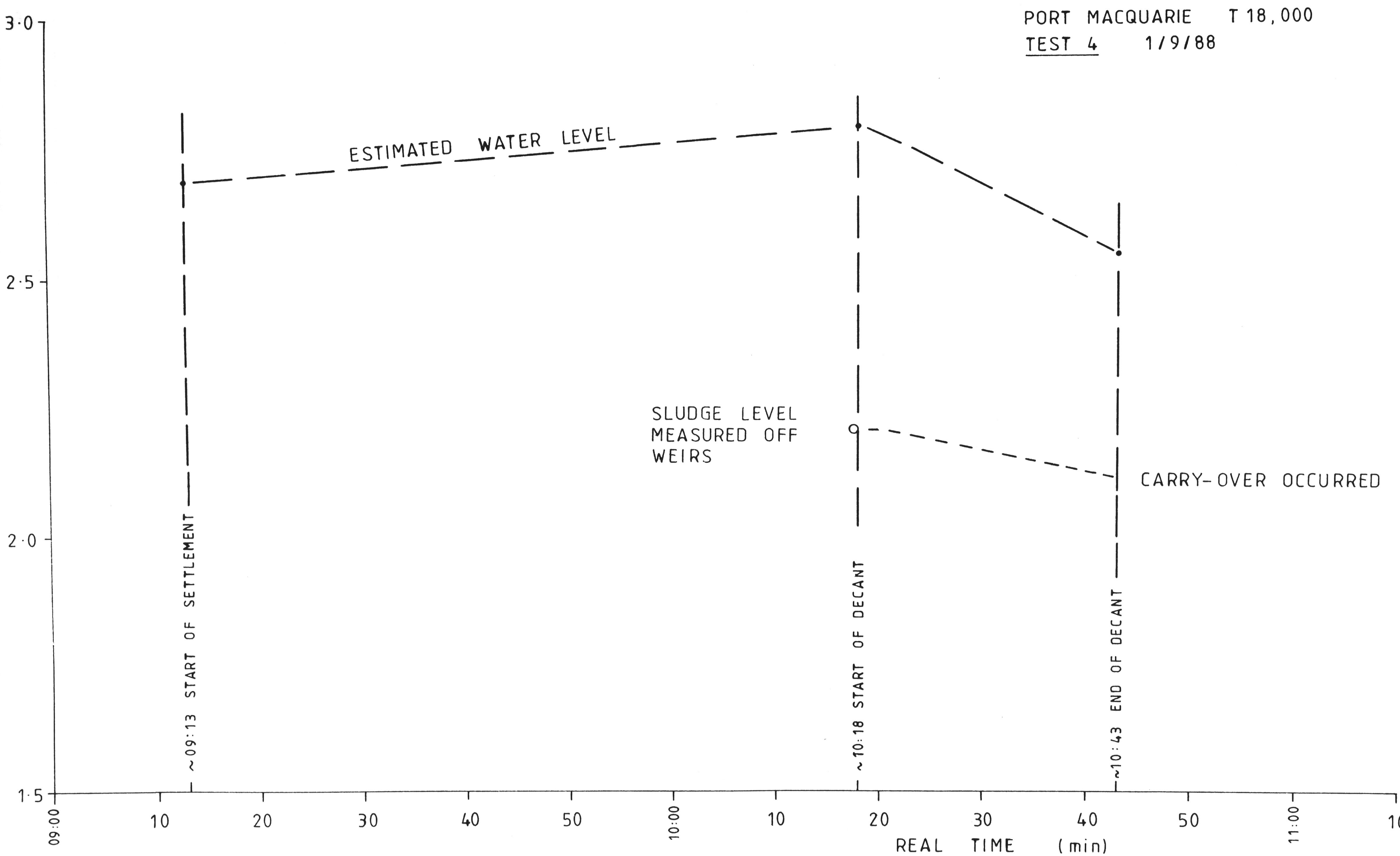
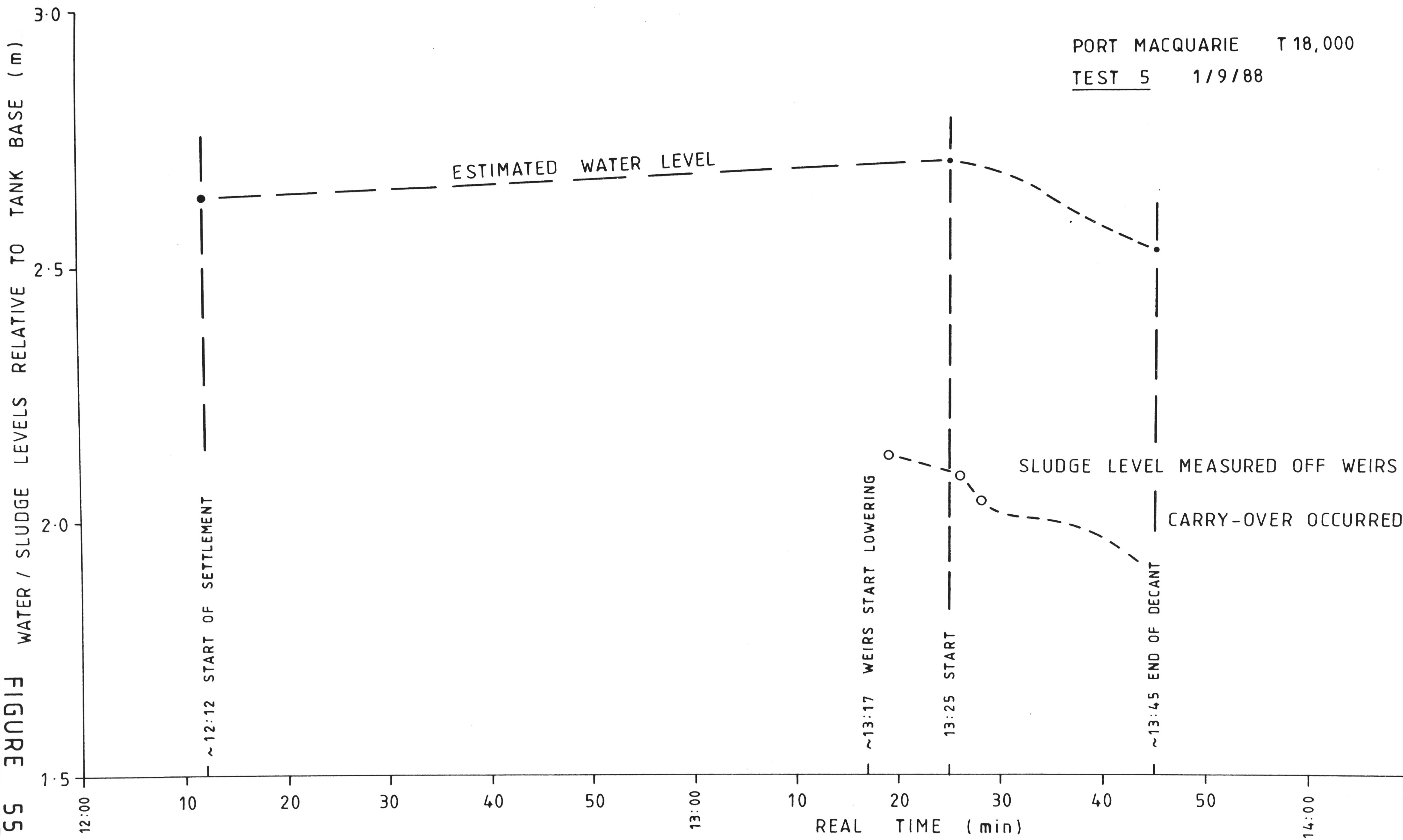


FIGURE 54

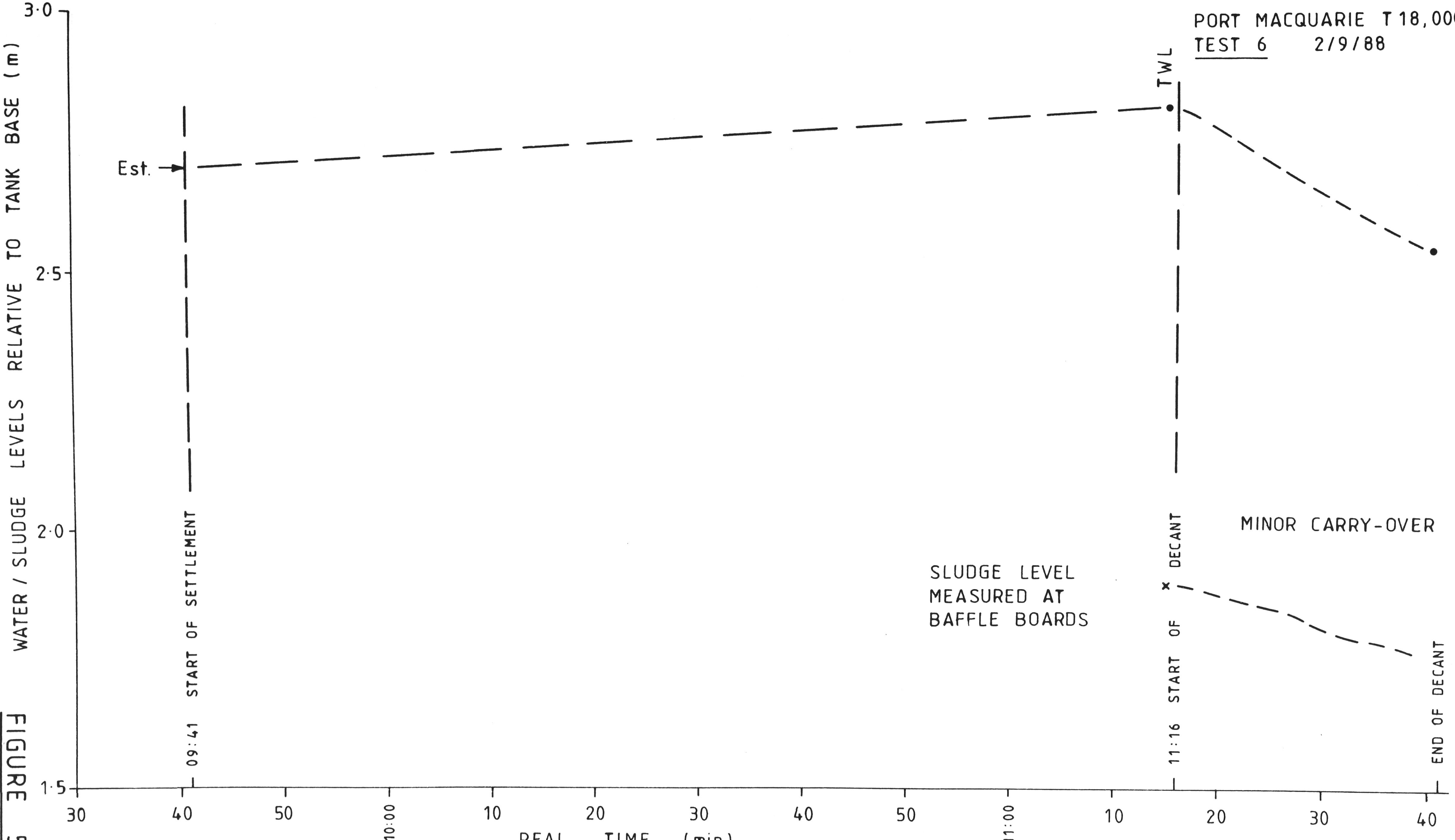
IN-TANK SLUDGE SETTLEMENT



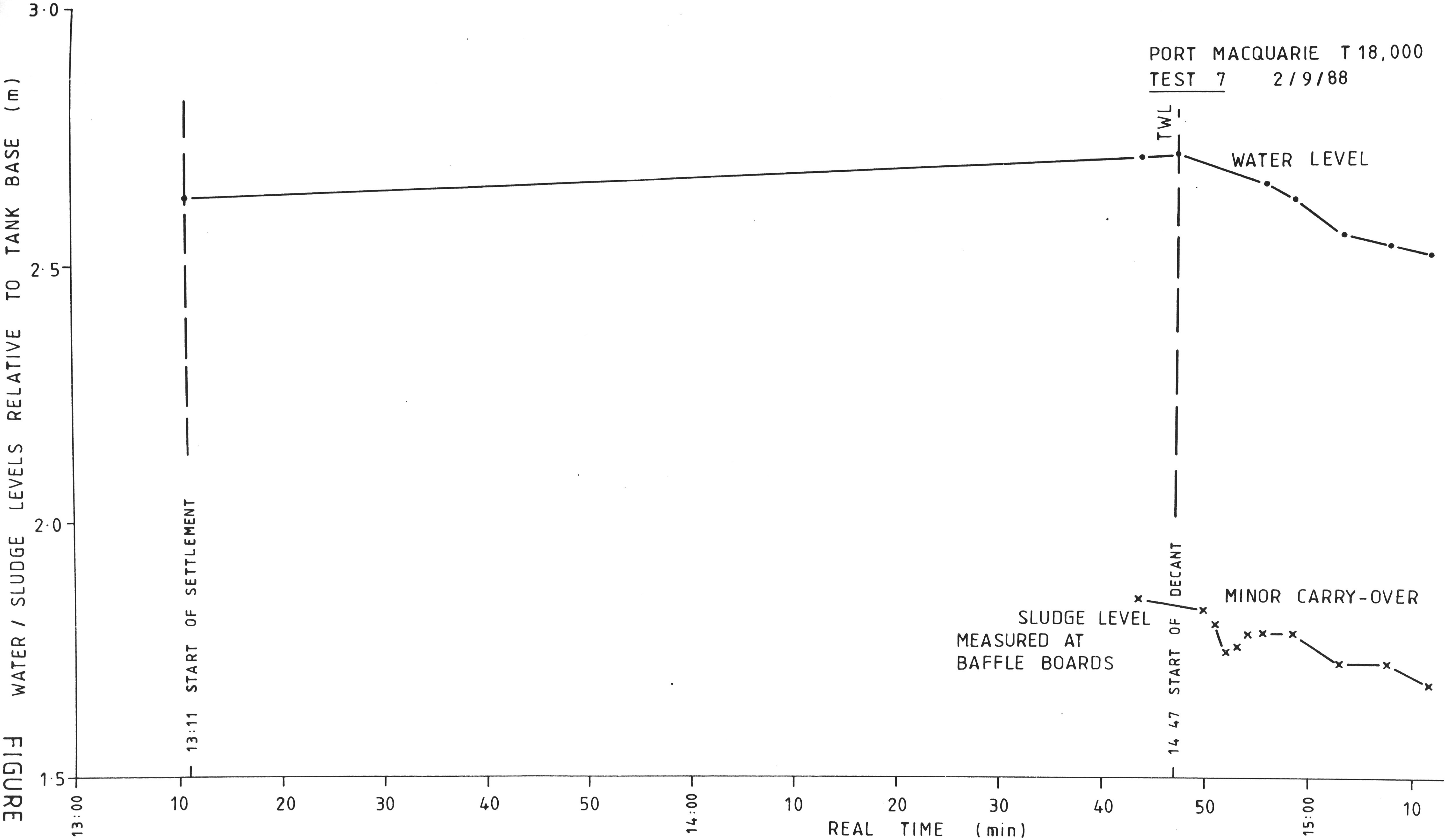
IN TANK SLUDGE SETTLEMENT

FIGURE 55

FIGURE 56

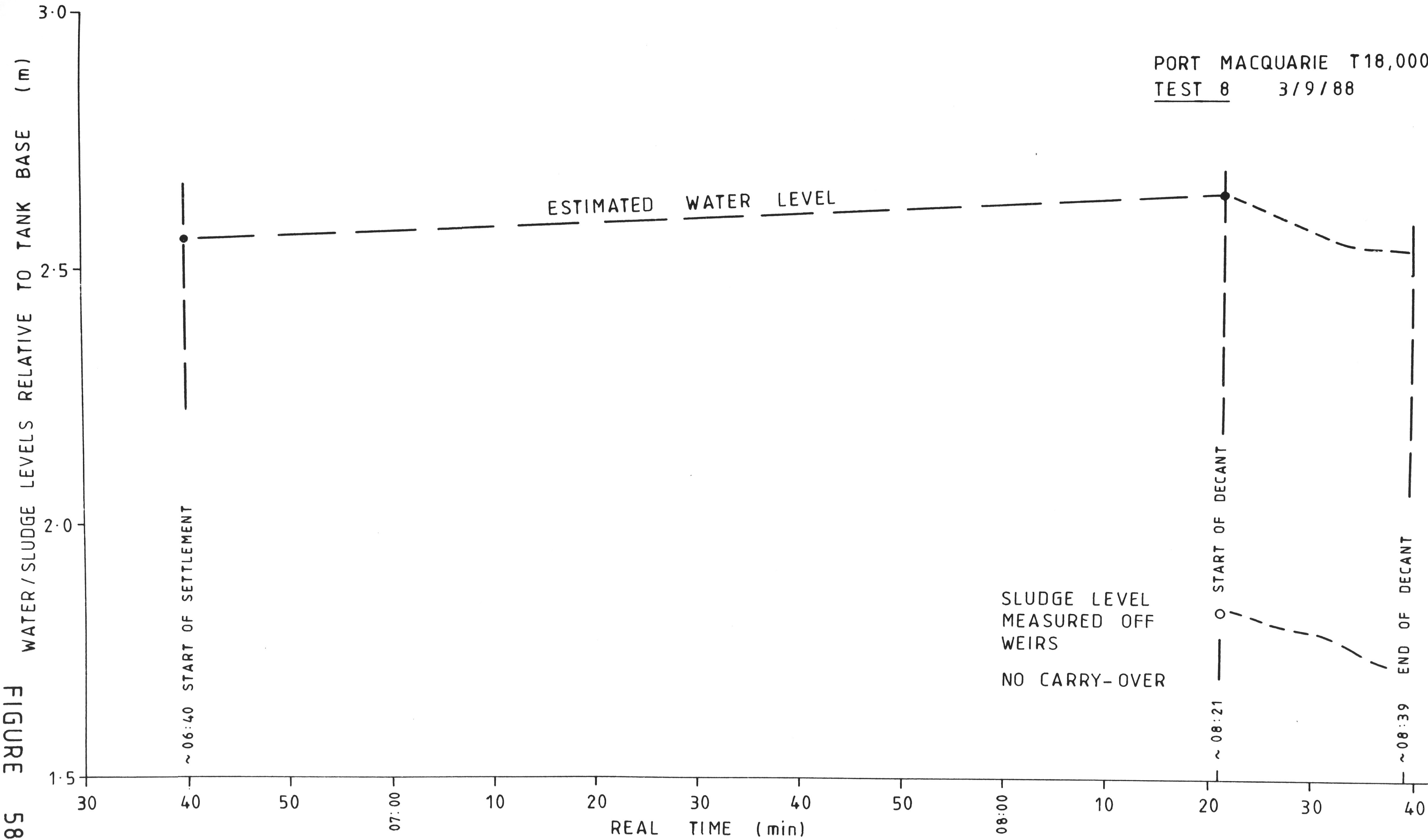


IN-TANK SLUDGE SETTLEMENT



IN-TANK SLUDGE SETTLEMENT

FIGURE 57



IN-TANK SLUDGE SETTLEMENT

FIGURE 58

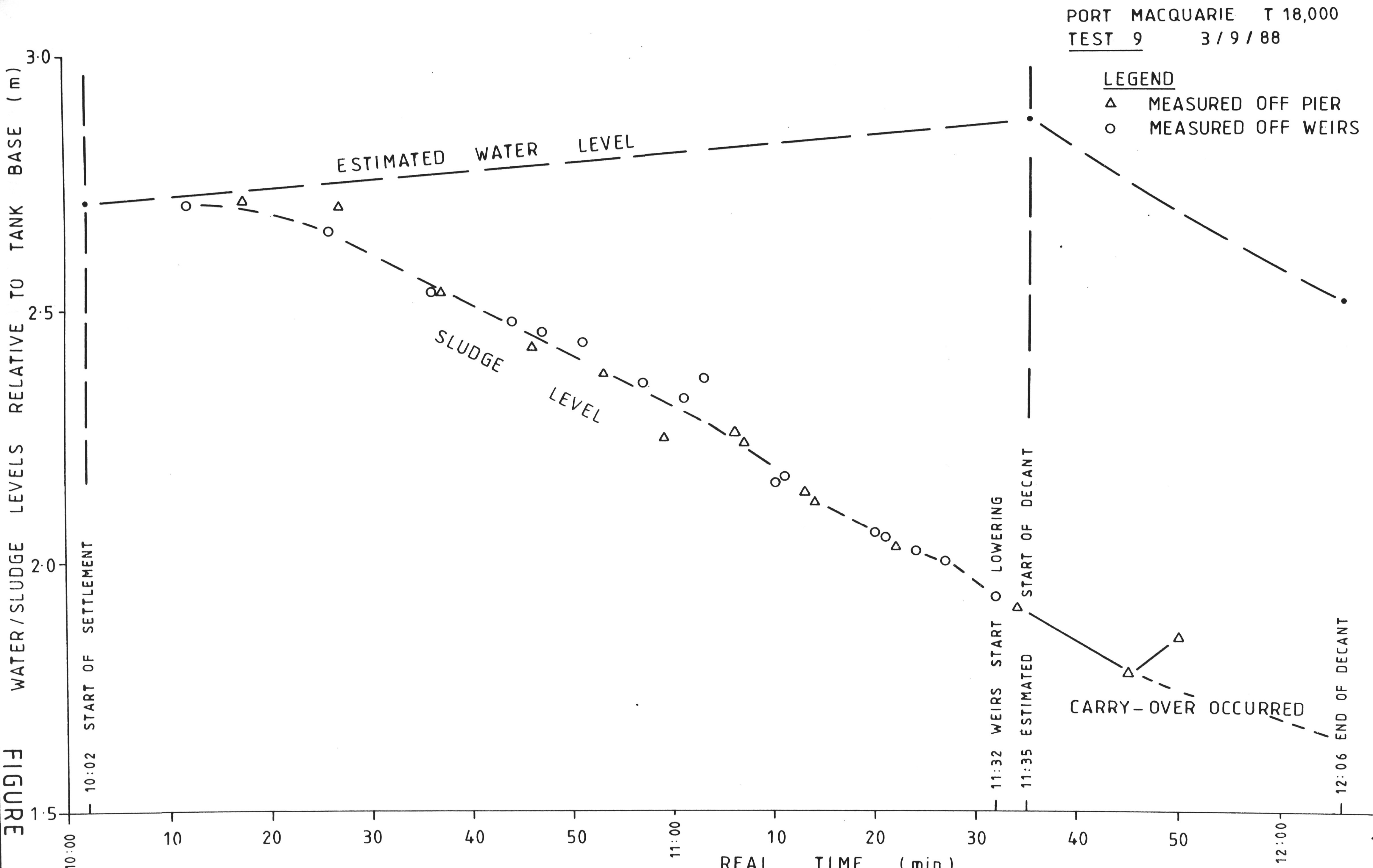


FIGURE 59

IN-TANK SLUDGE SETTLEMENT

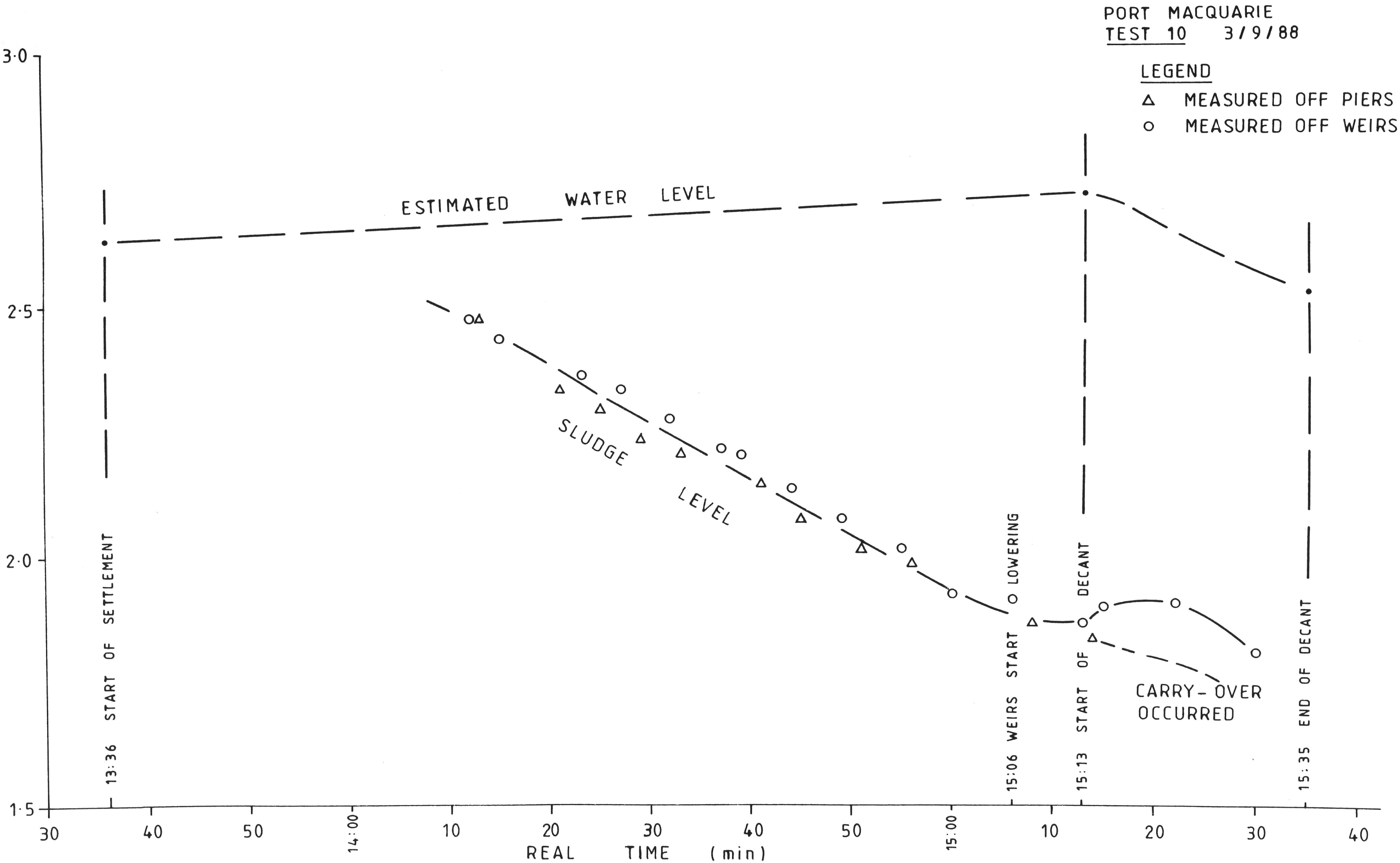
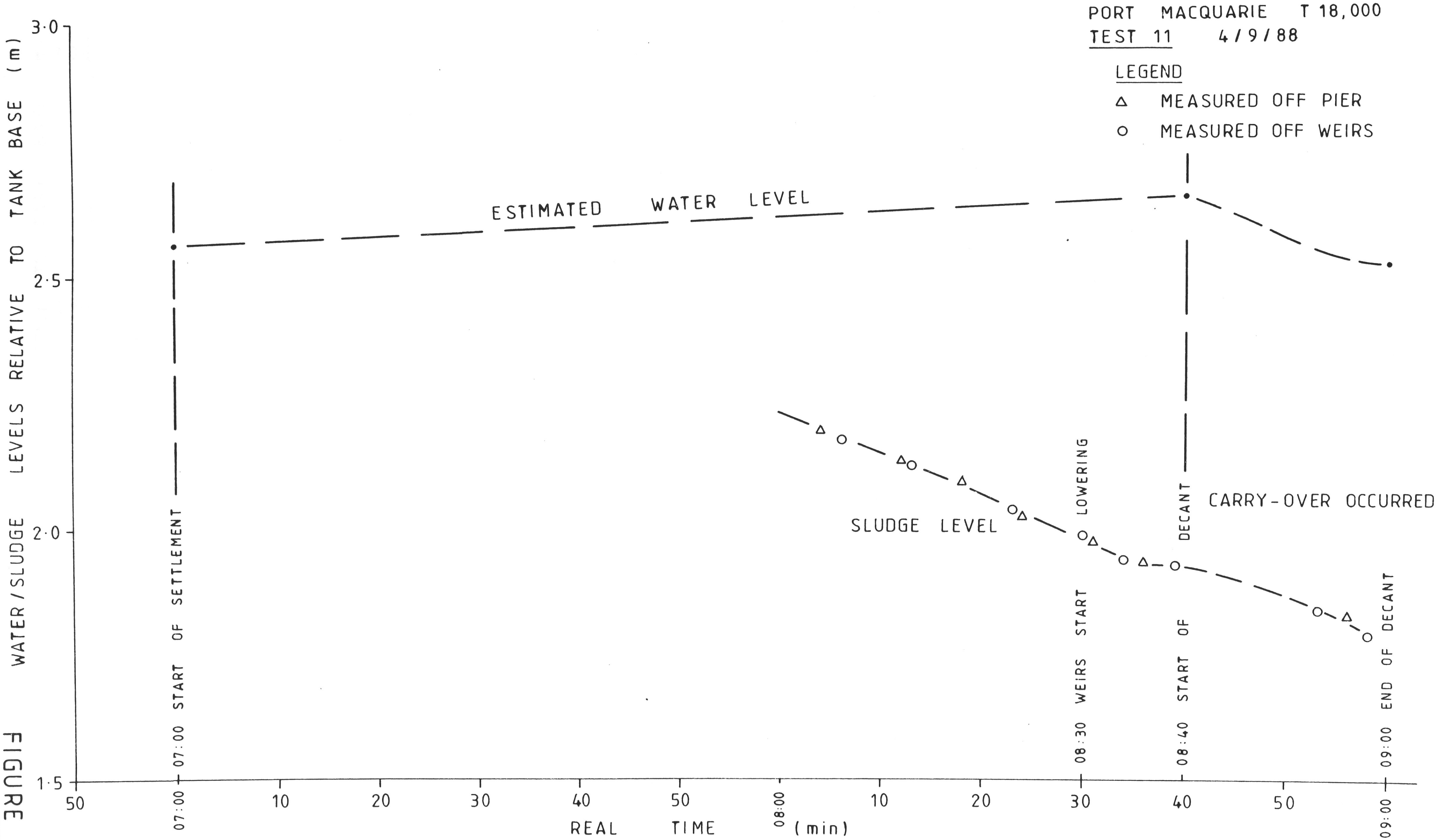


FIGURE 60

IN TANK SLUDGE SETTLEMENT



IN - TANK SLUDGE SETTLEMENT

FIGURE 61

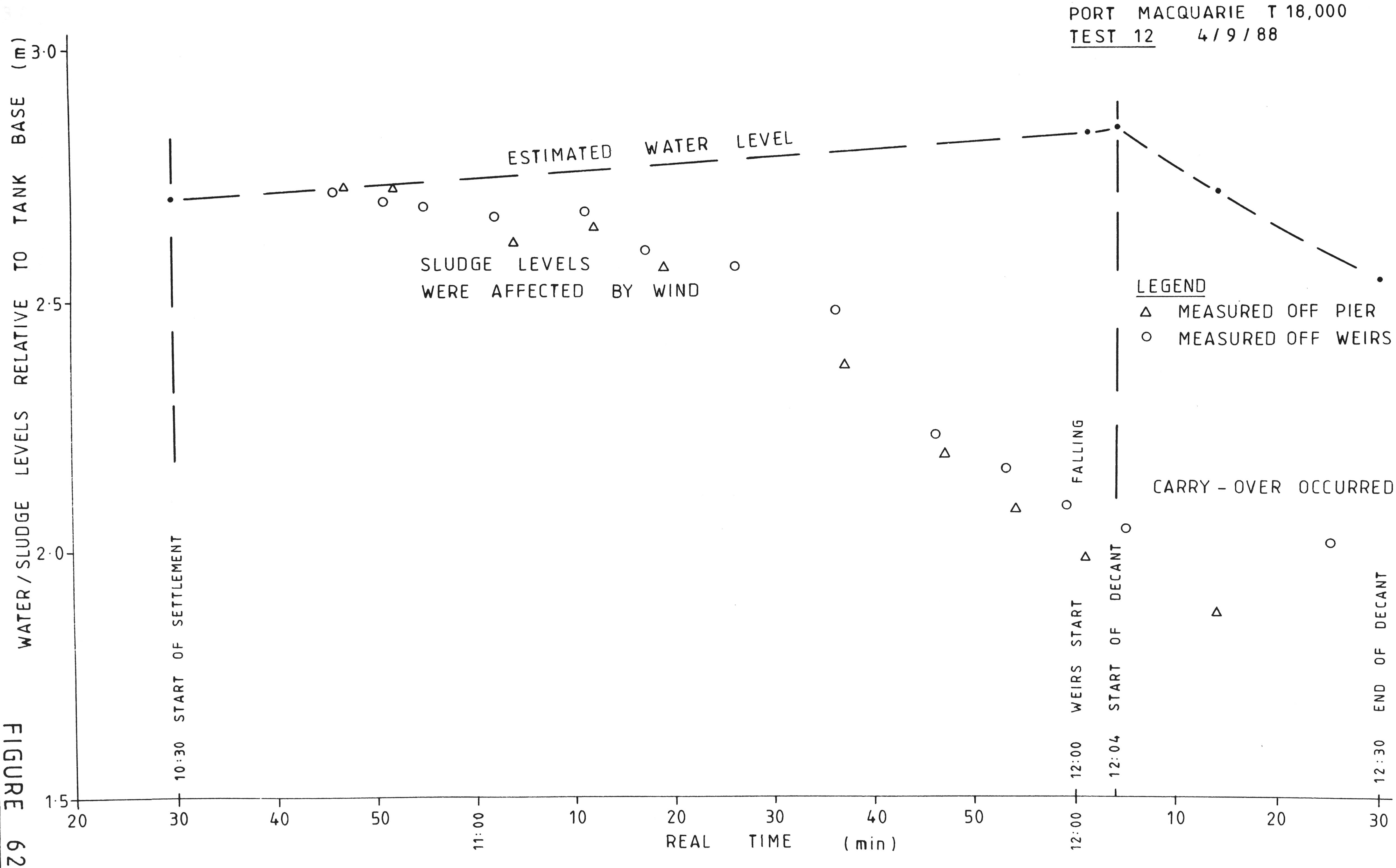


FIGURE 62

IN - TANK SLUDGE SETTLEMENT

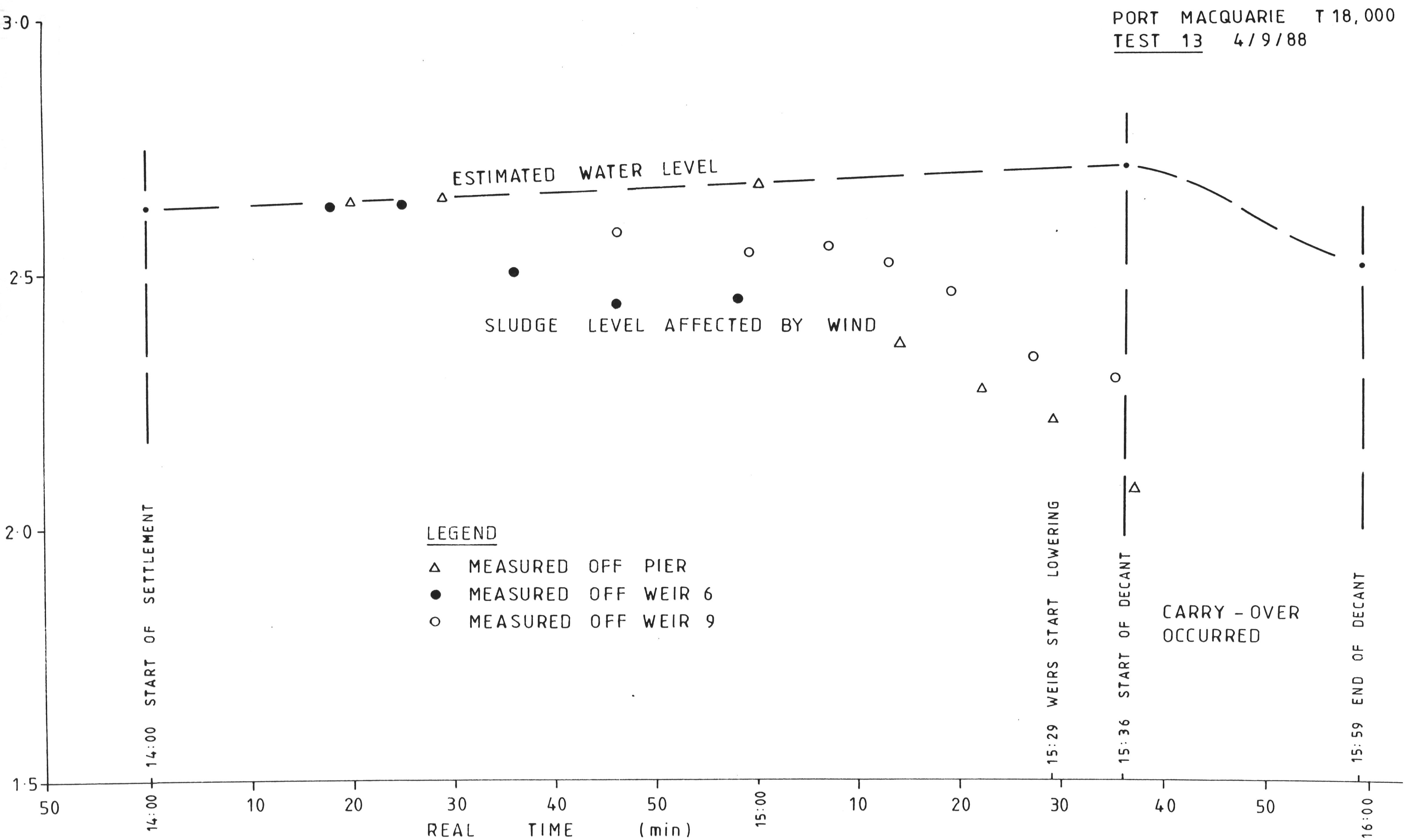


FIGURE 63

IN - TANK SLUDGE SETTLEMENT

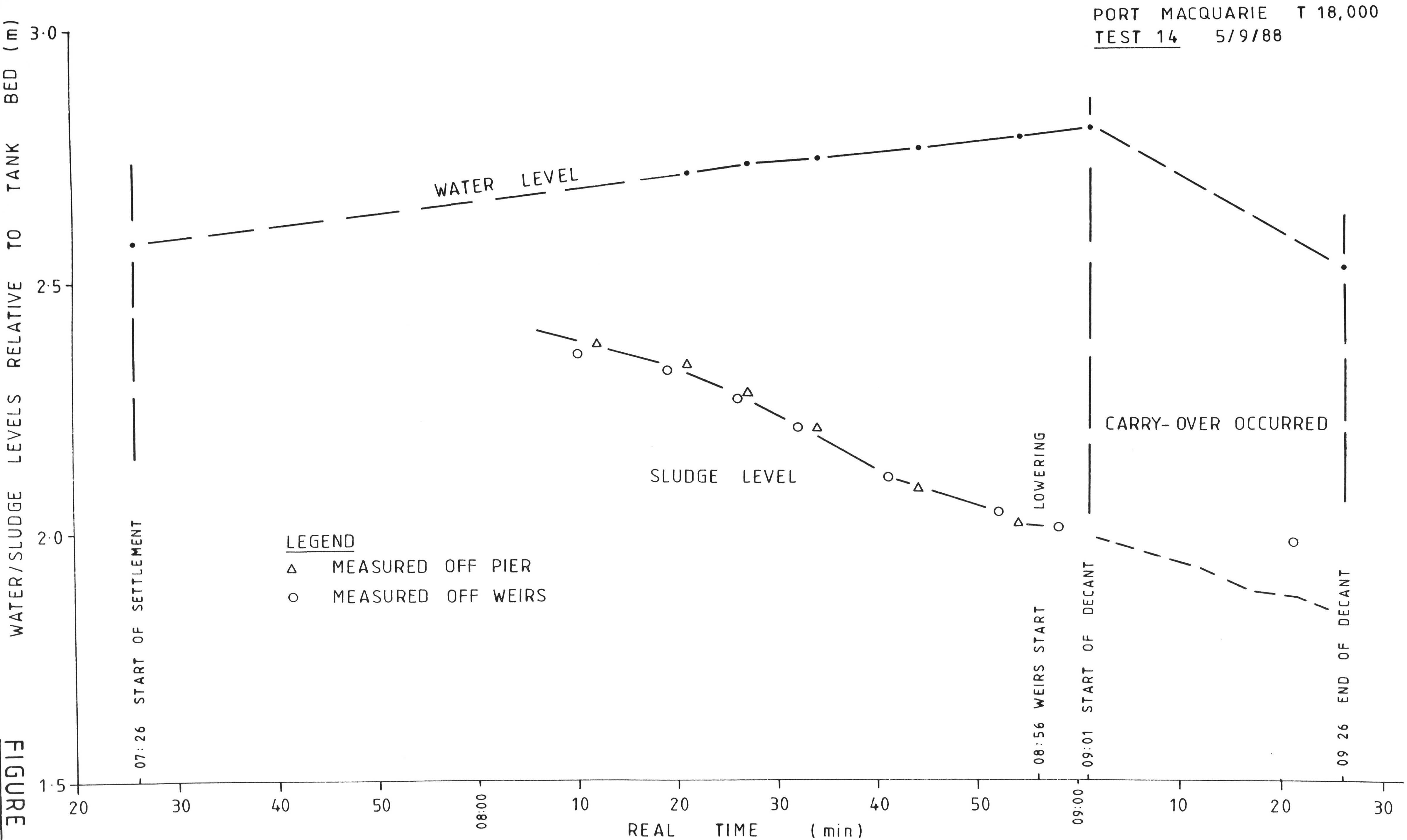


FIGURE 64

IN - TANK SLUDGE SETTLEMENT

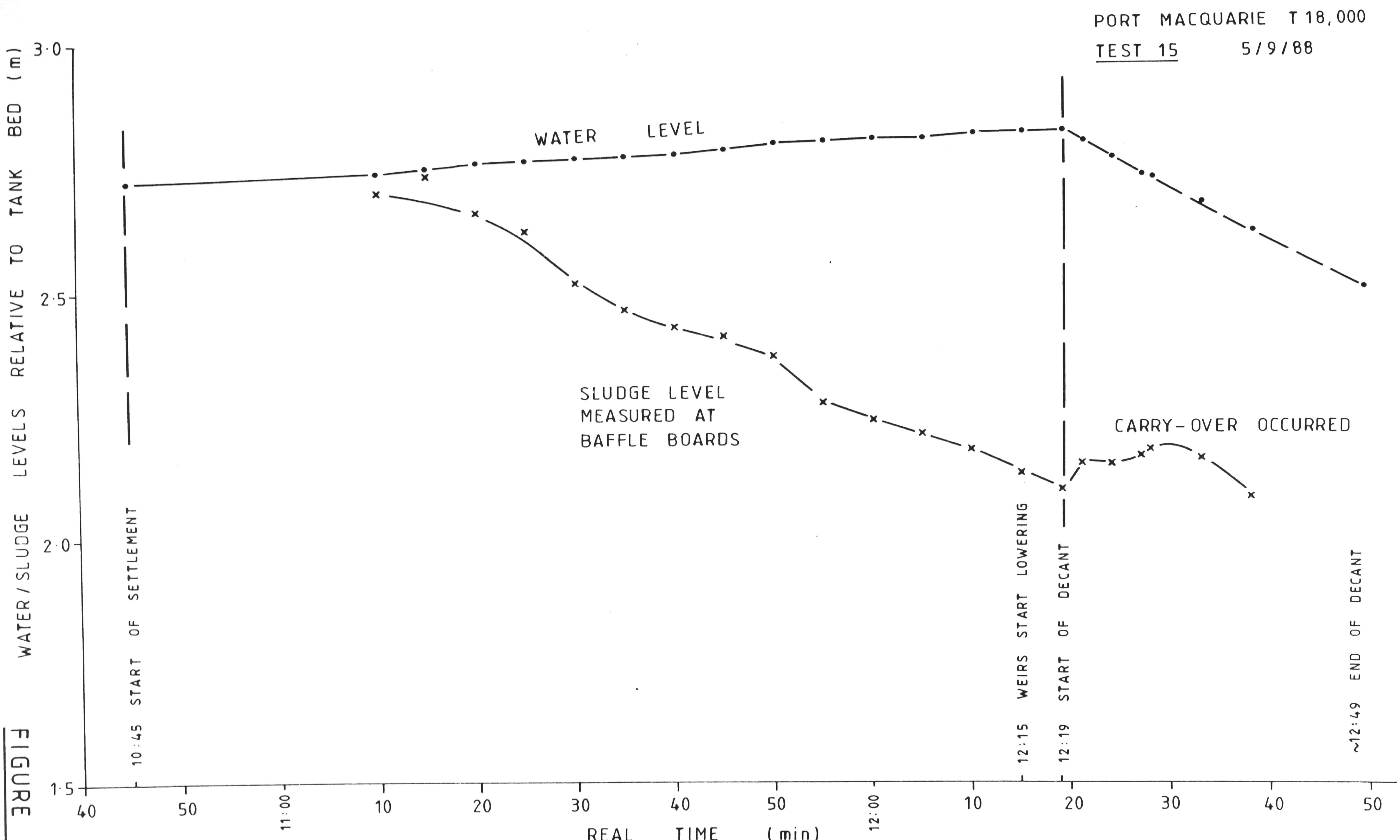


FIGURE 65

IN - TANK SLUDGE SETTLEMENT

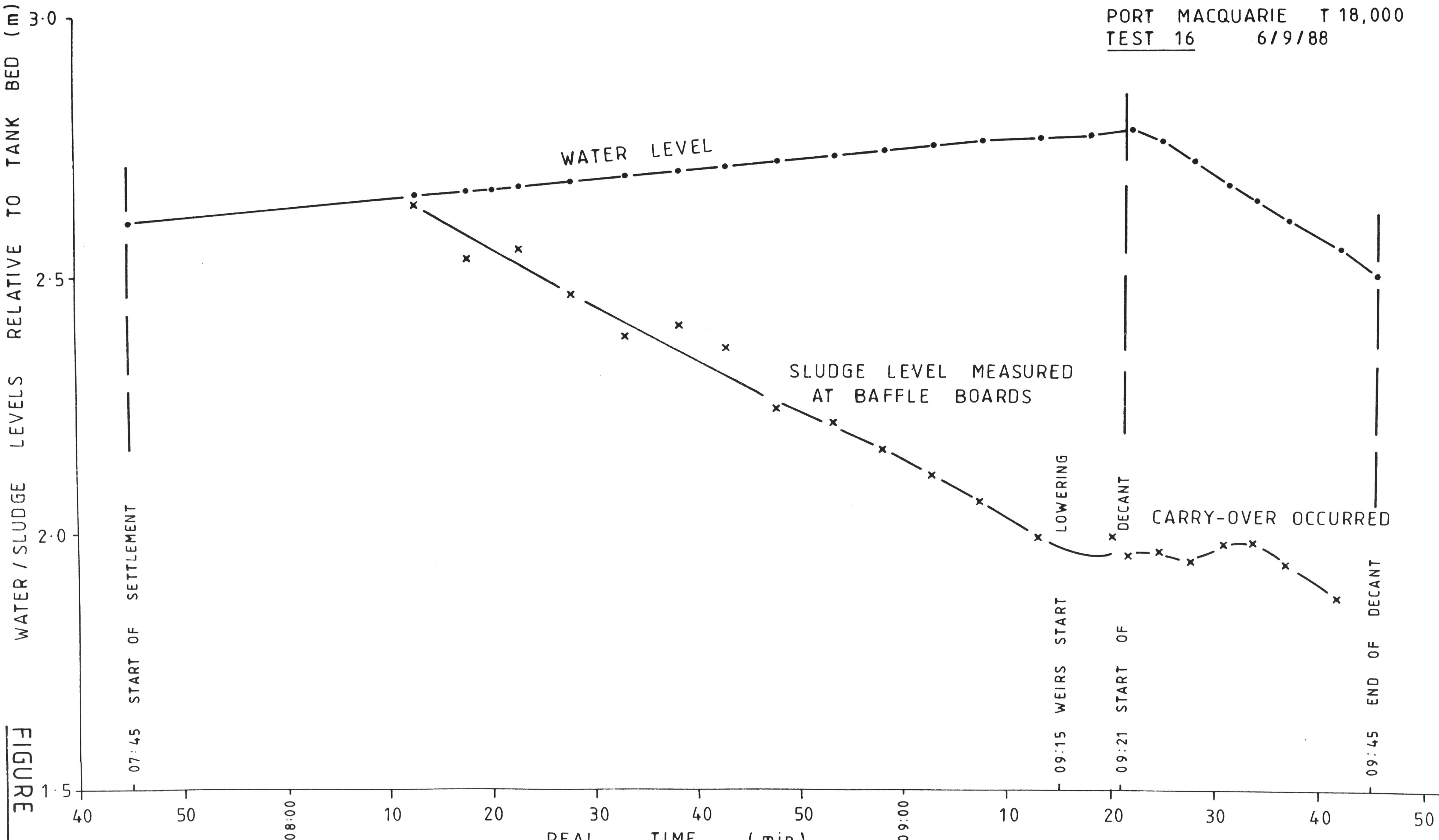


FIGURE 66

IN-TANK SLUDGE SETTLEMENT

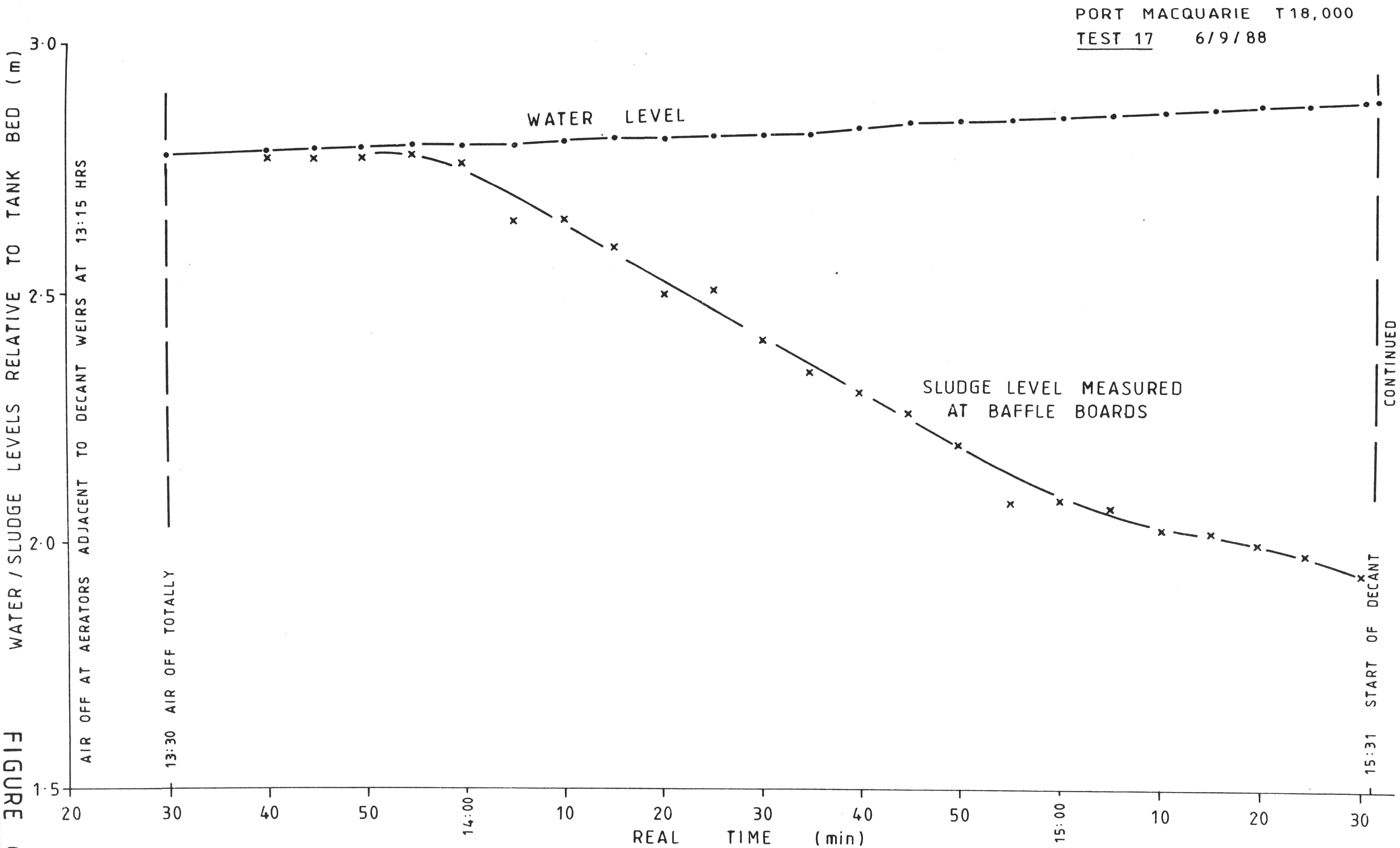


FIGURE 67

IN - TANK SLUDGE SETTLEMENT

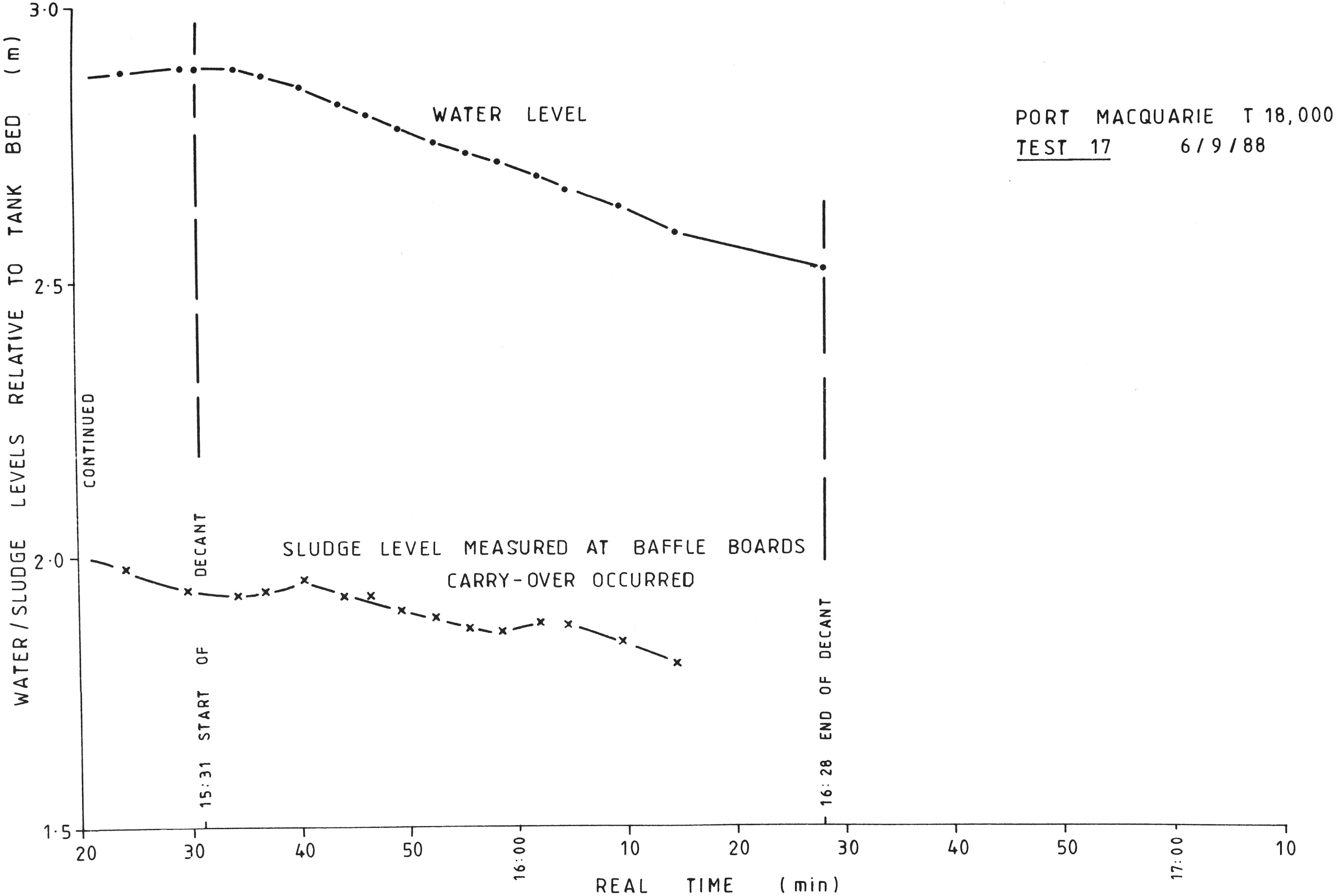


FIGURE 68

IN - TANK SLUDGE SETTLEMENT

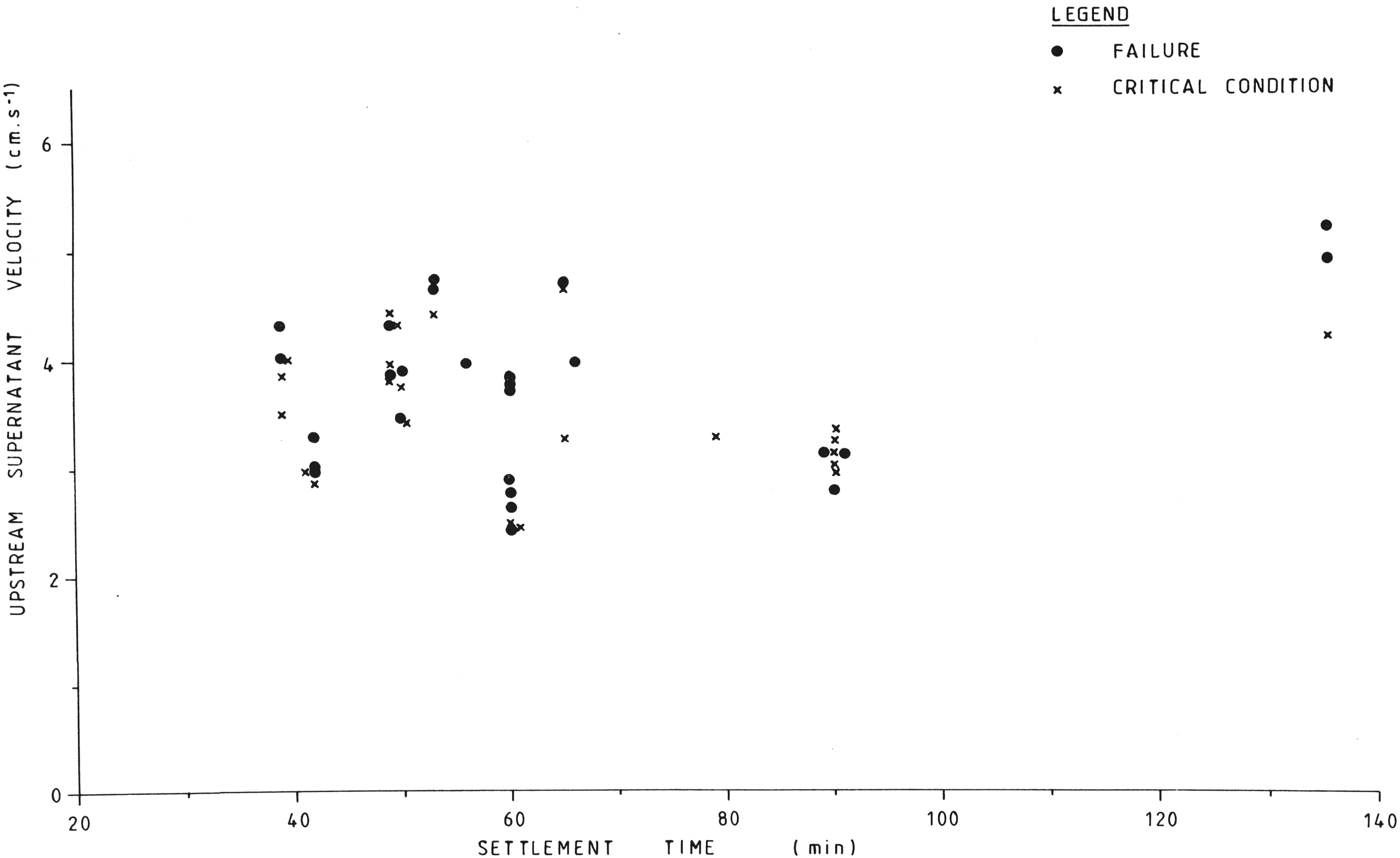
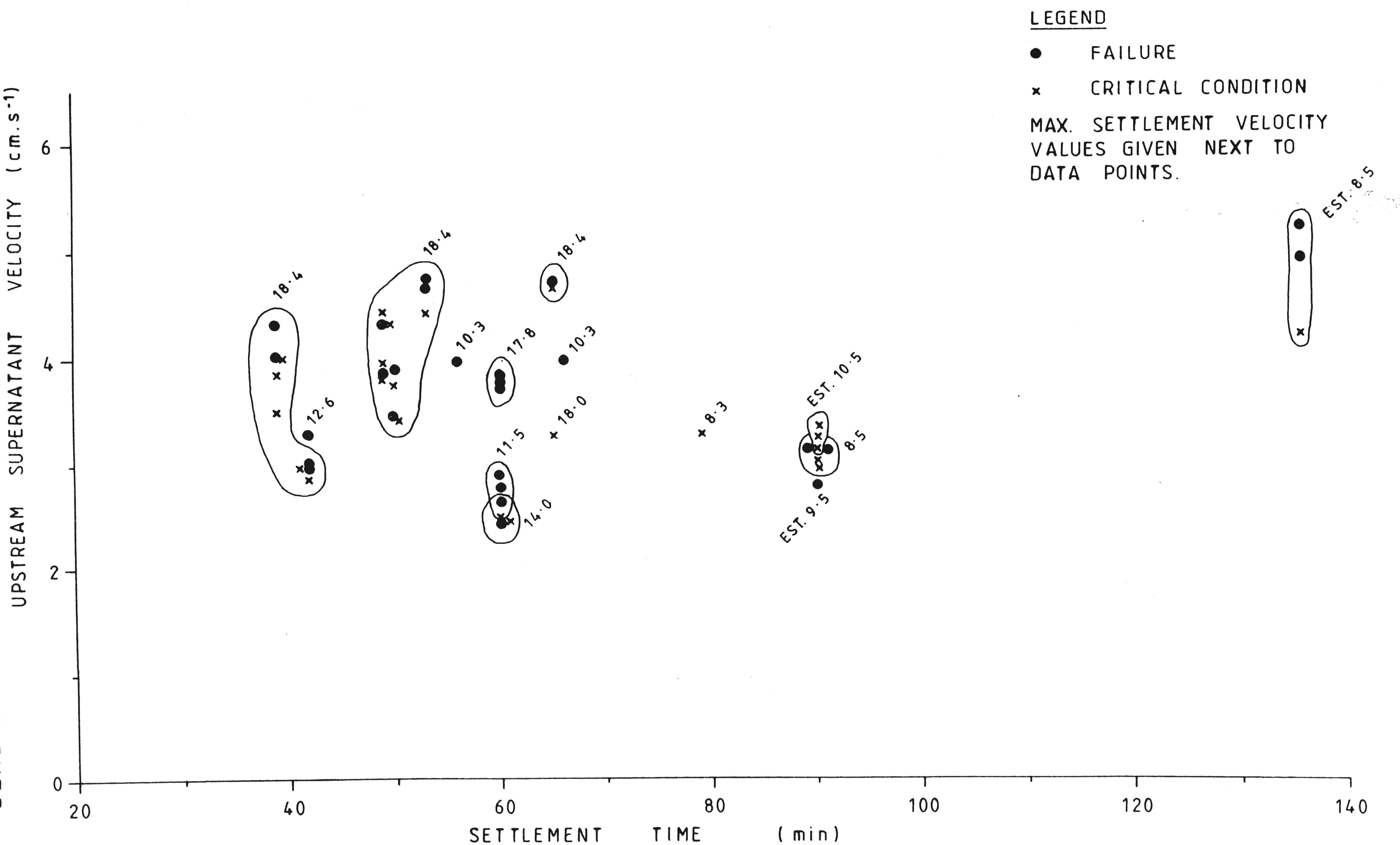


FIGURE 69

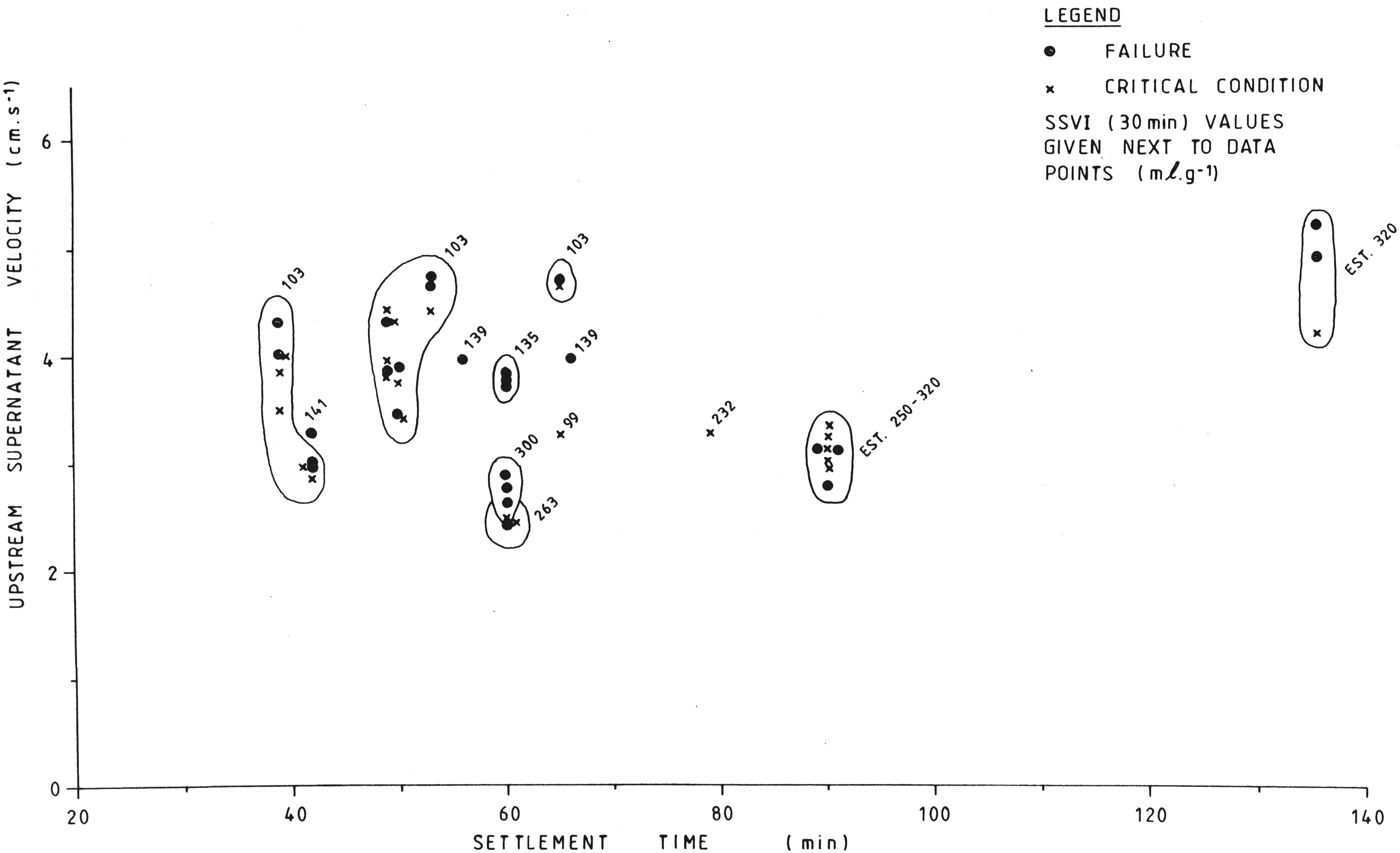
DECANT TEST RESULTS



DECANT TEST RESULTS

FIGURE 70

FIGURE 71



DECANT TEST RESULTS

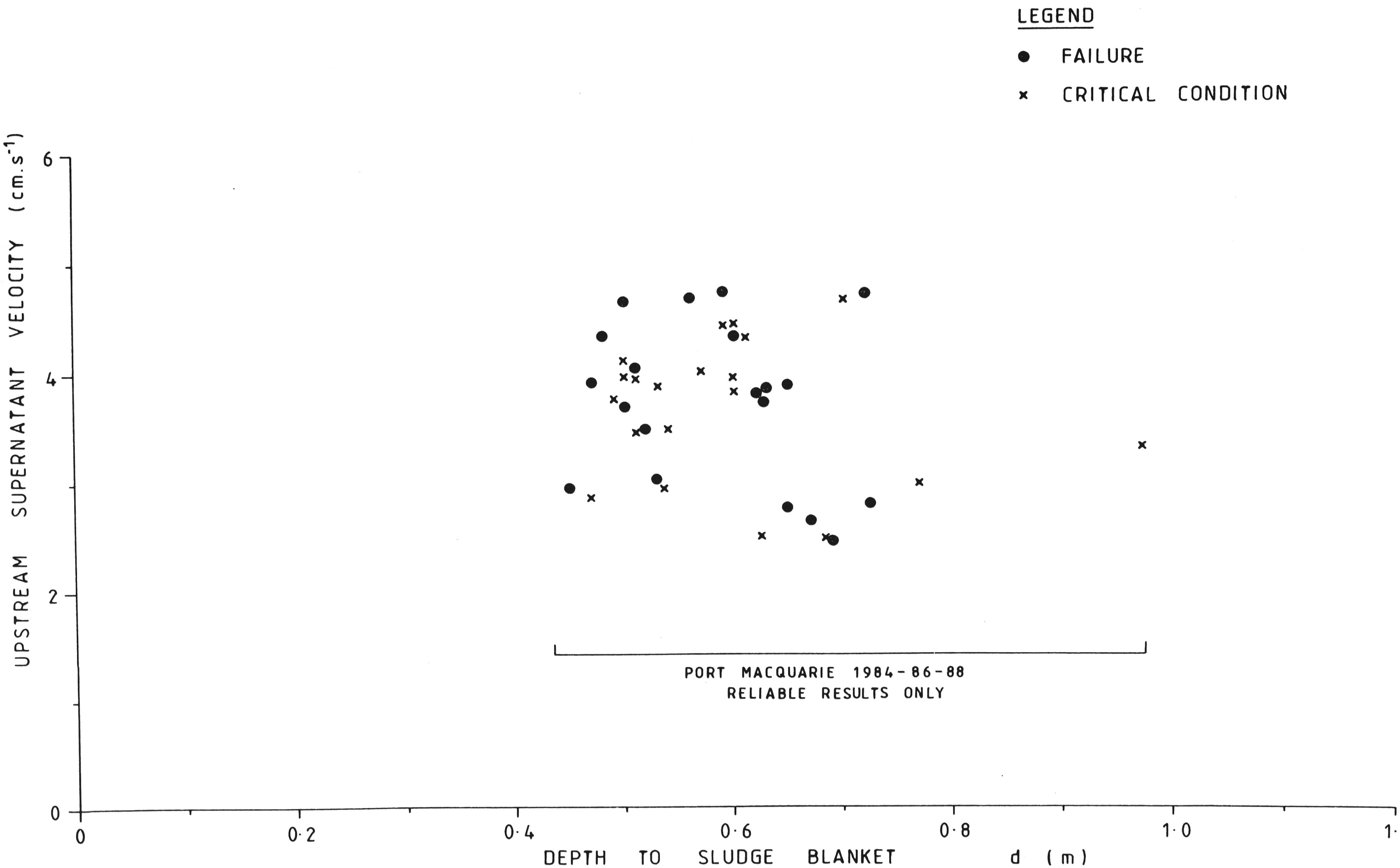


FIGURE 72

DECANT TEST RESULTS

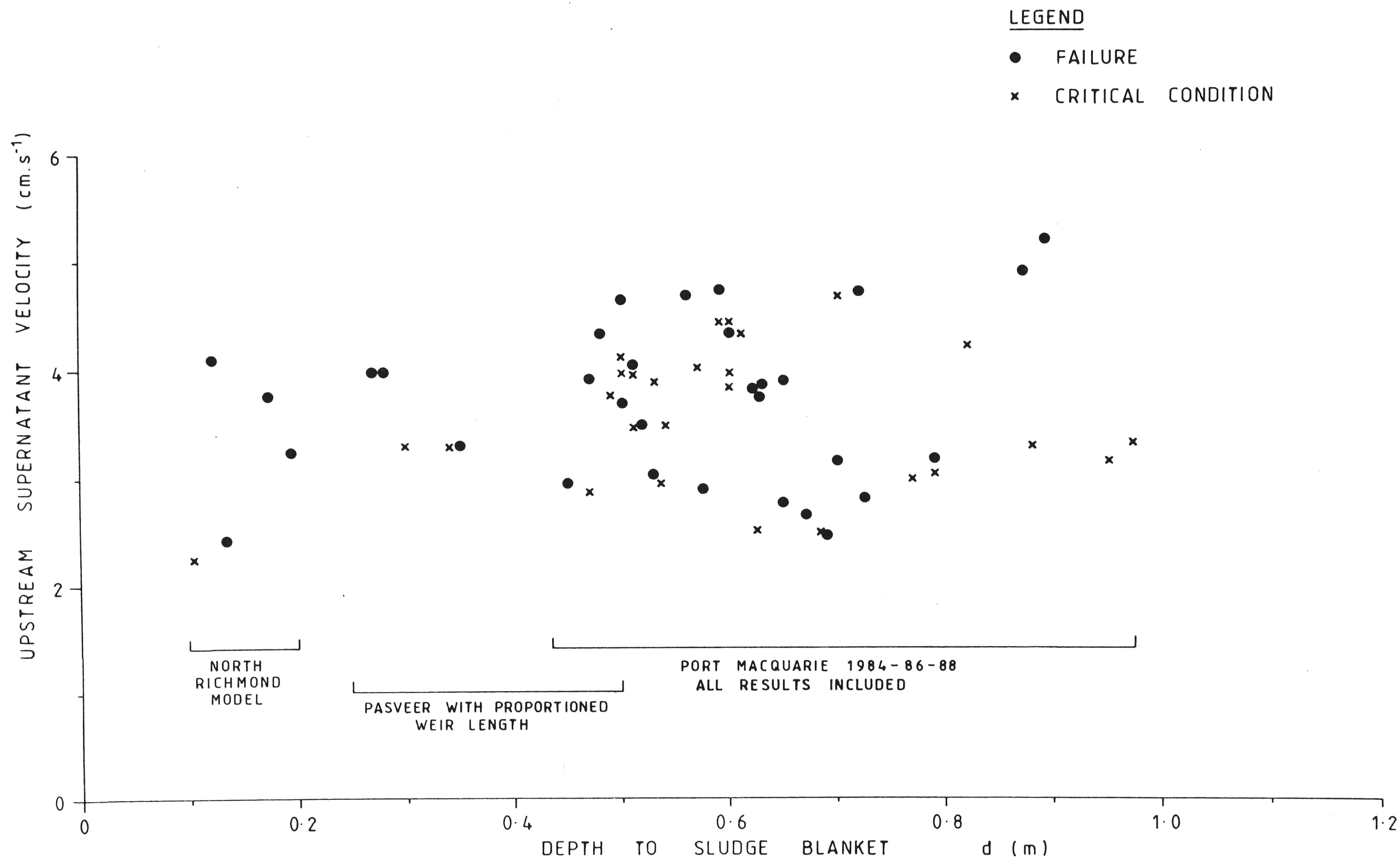


FIGURE 73

DECANT TEST RESULTS

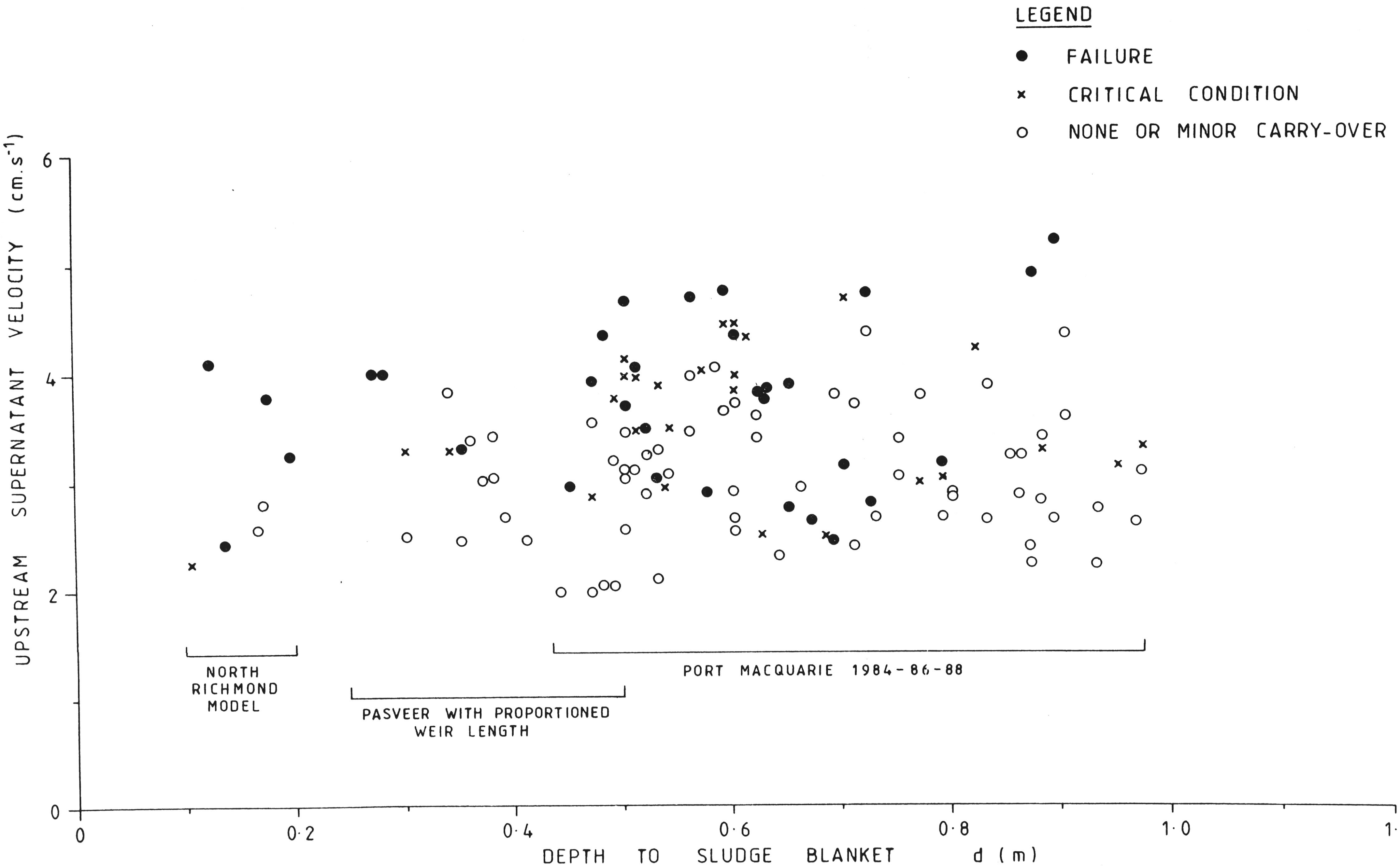


FIGURE 74

DECANT TEST RESULTS

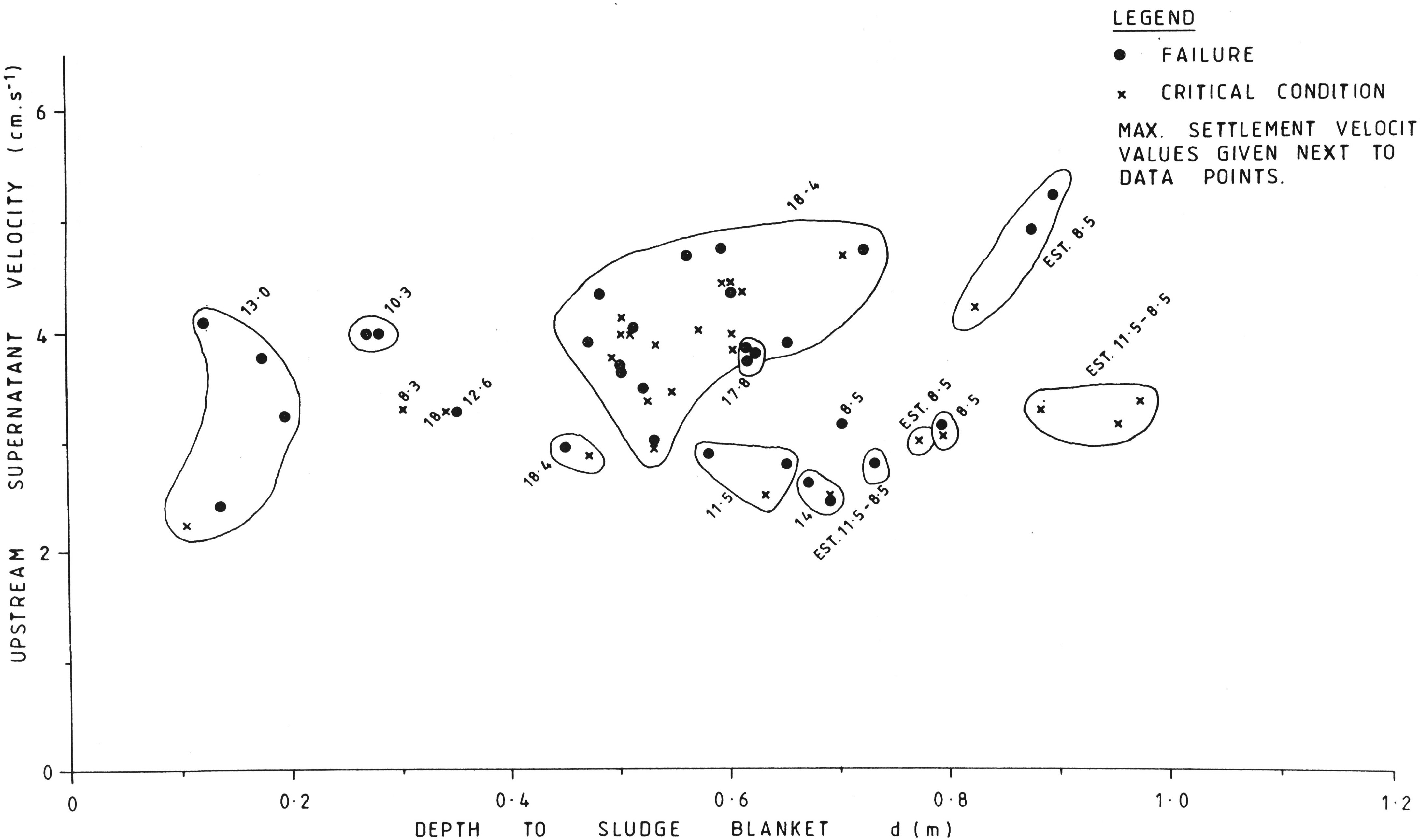
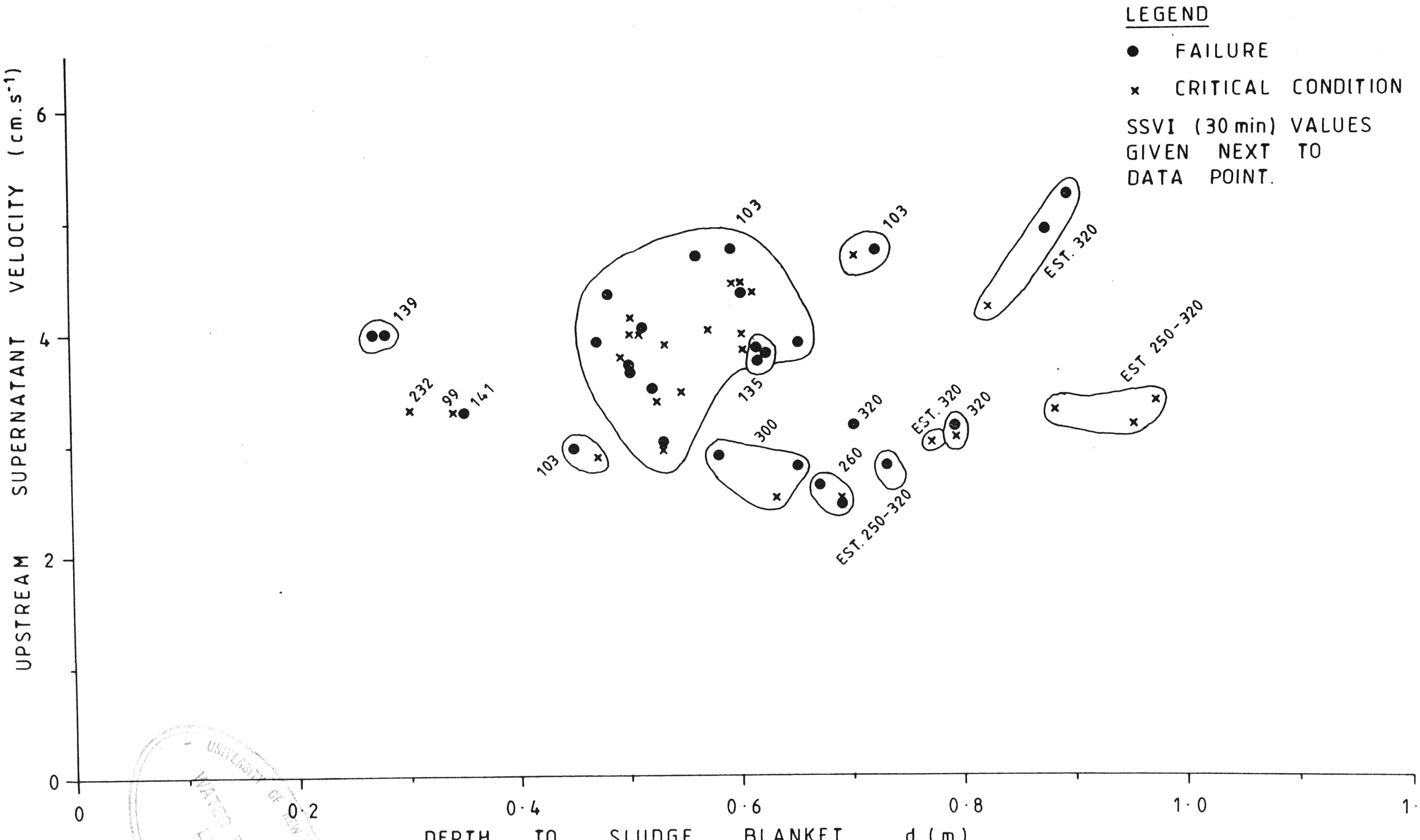


FIGURE 75

DECANT TEST RESULTS



DECANT TEST RESULTS

FIGURE 76

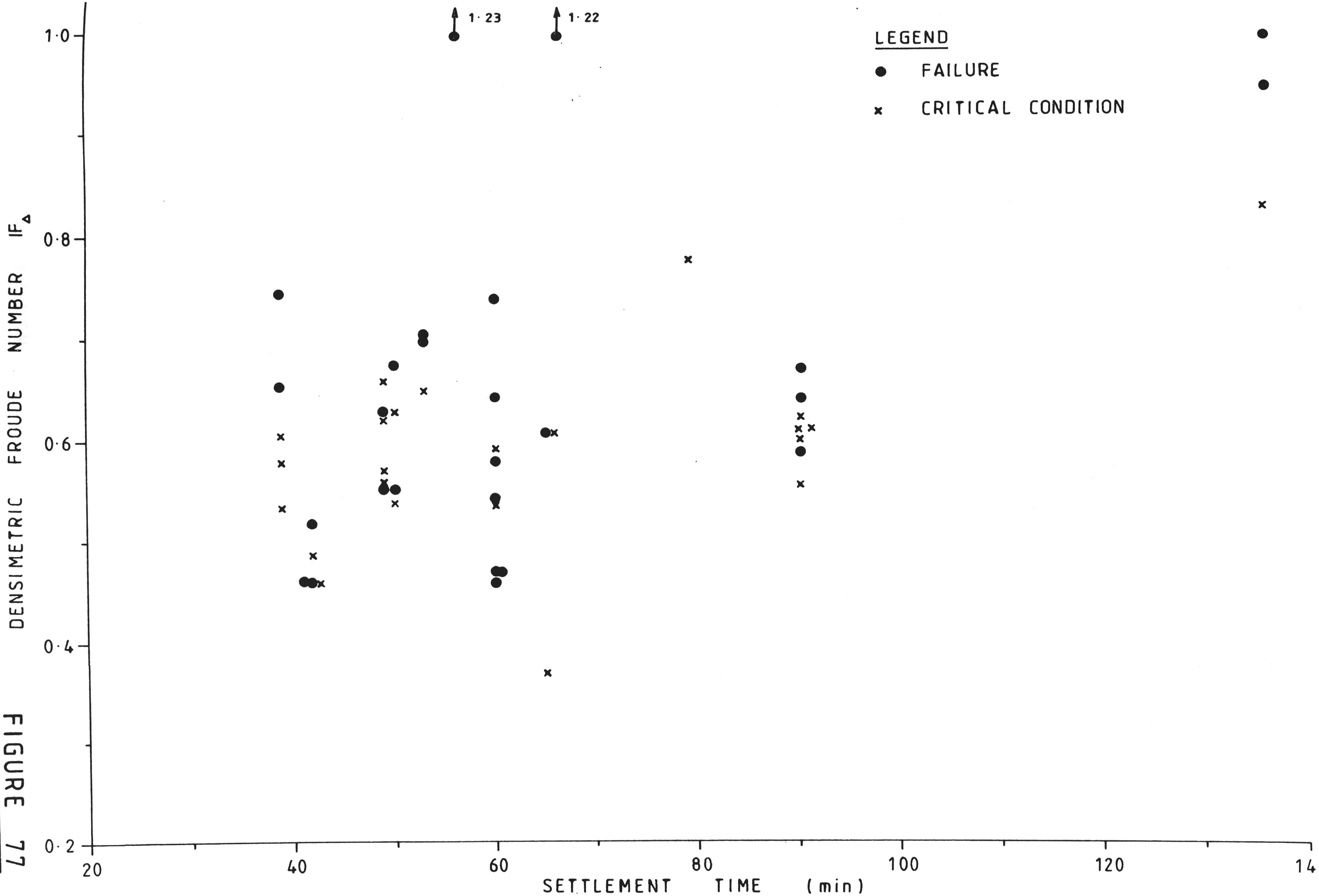


FIGURE 77

DECANT TEST RESULTS

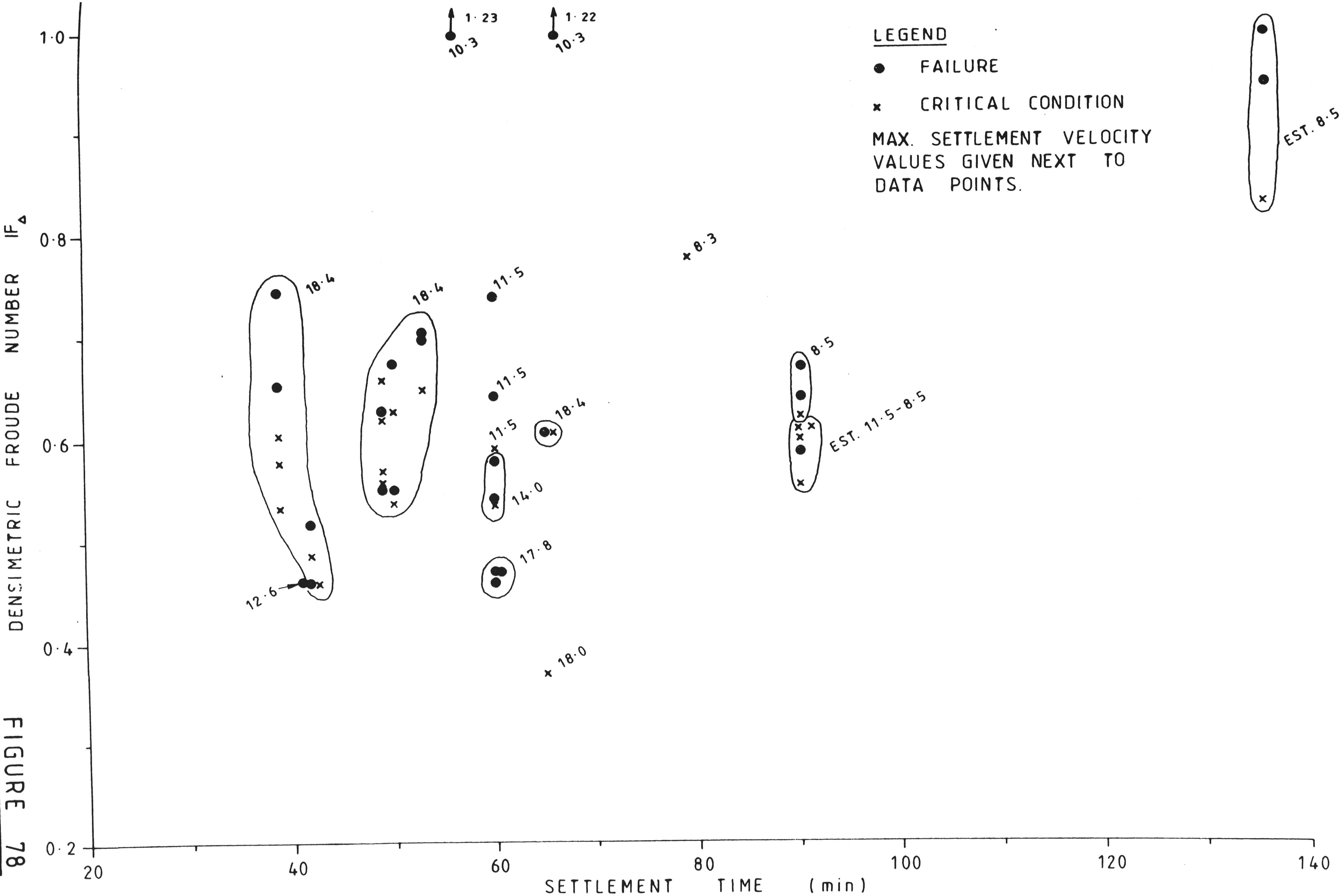


FIGURE 78

DECANT TEST RESULTS

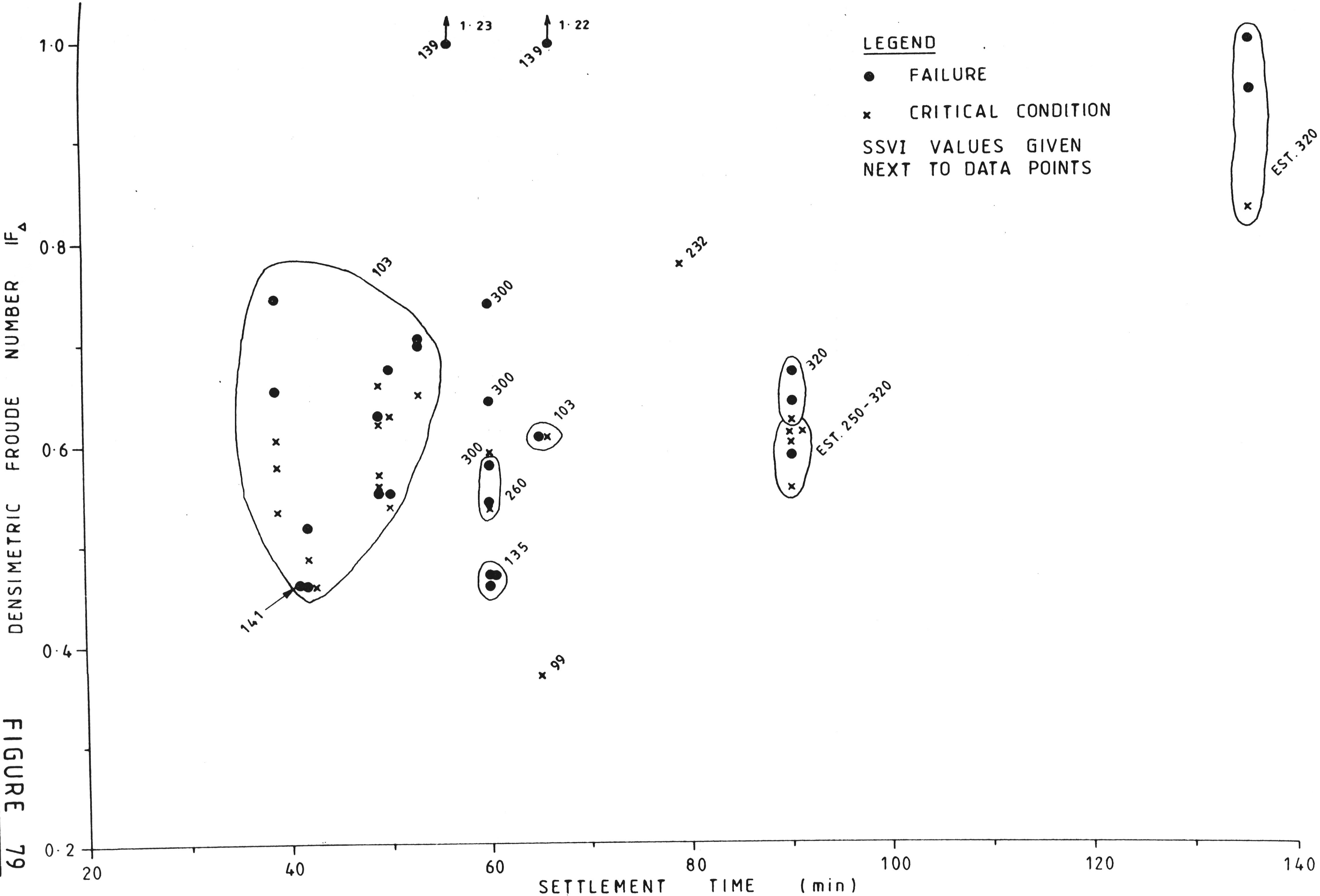


FIGURE 79

DECANT TEST RESULTS

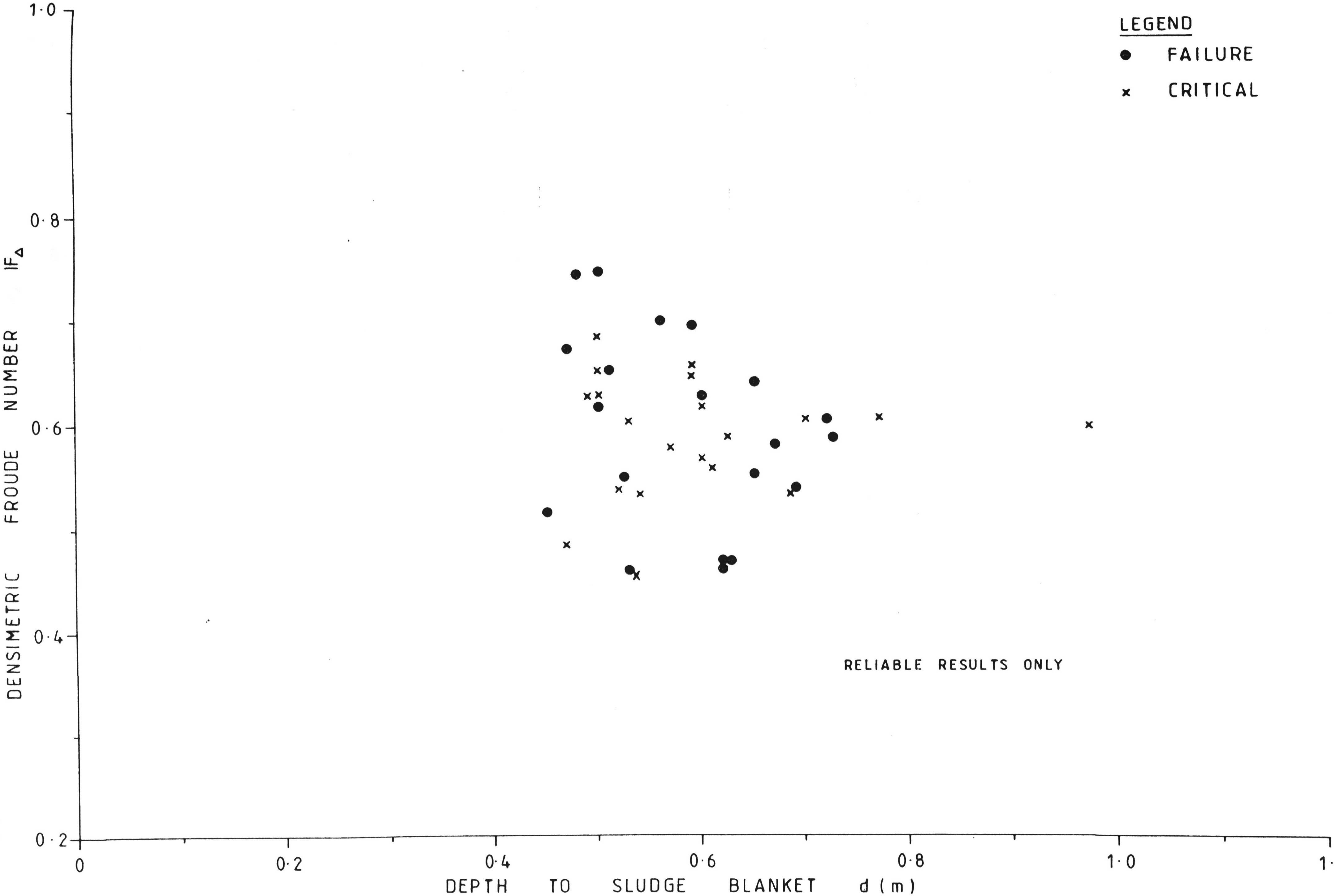
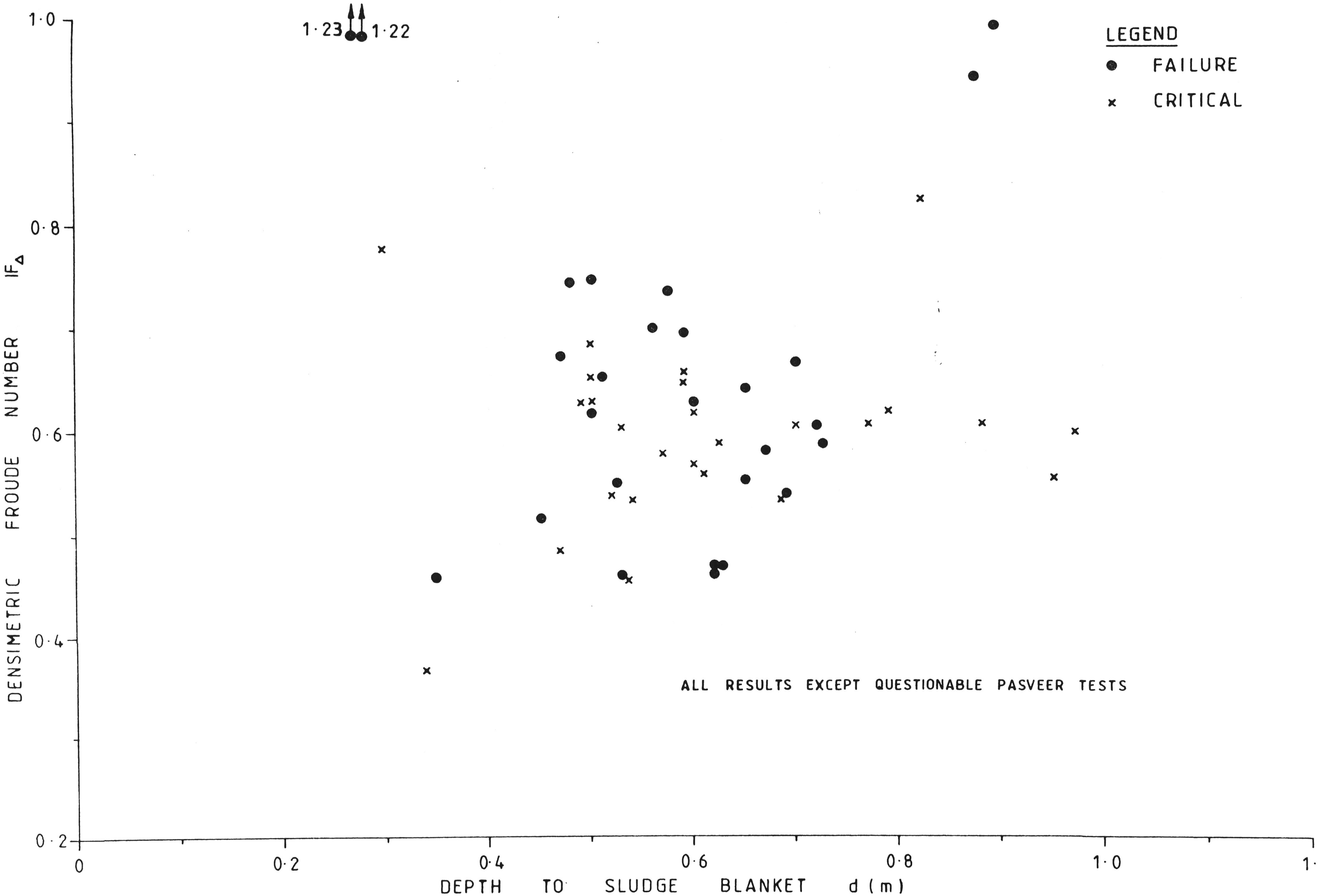


FIGURE 80

DECANT TEST RESULTS



DECANT TEST RESULTS

FIGURE 81

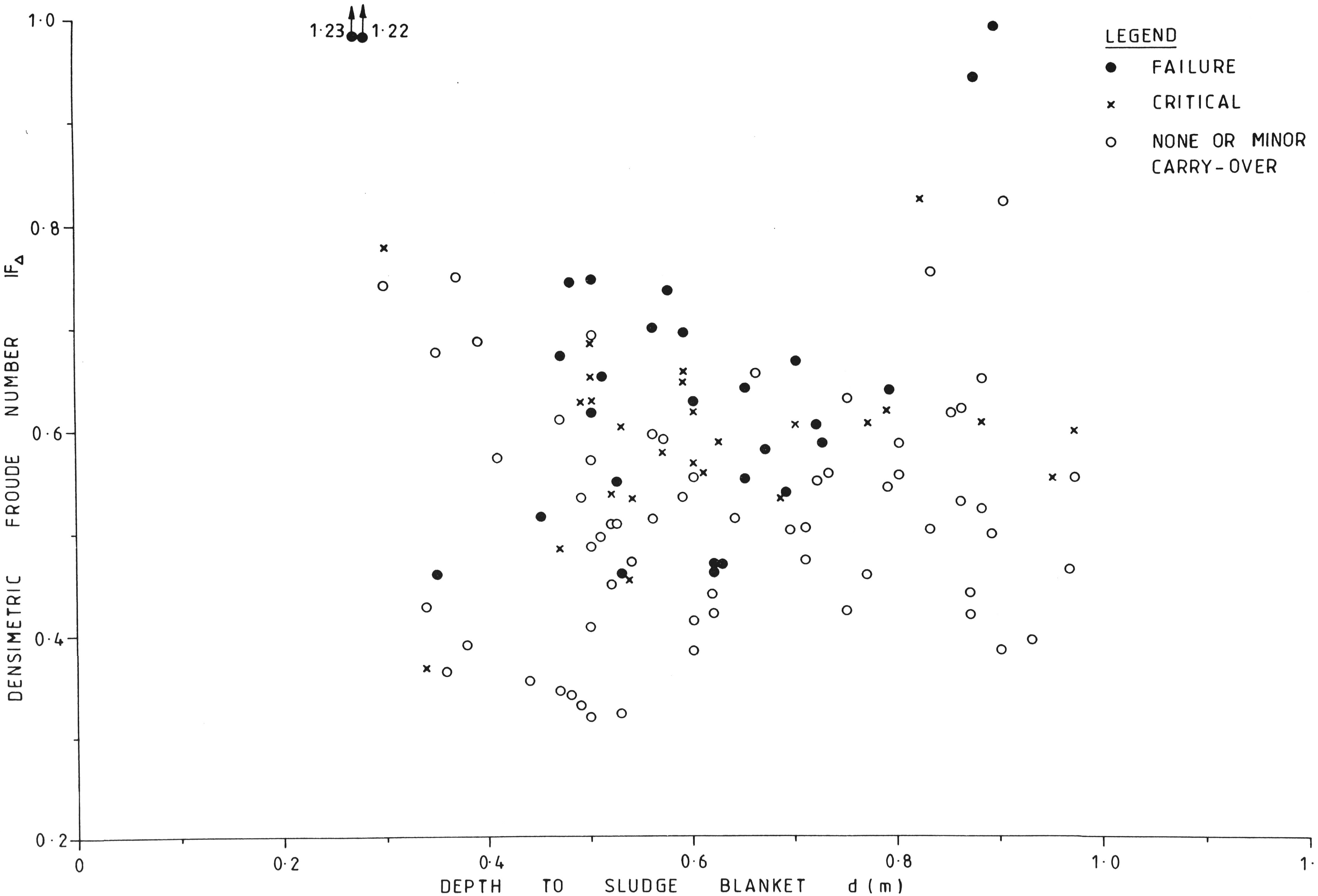


FIGURE 82

DECANT TEST RESULTS