A Bench-Scale Test Series for Seabed Soils

by

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SUMMARY AND ACKNOWLEDGEMENTS

This report describes a series of bench-scale test methods developed to characterise the properties of fine-grained soil. The test series, aimed specifically at the needs of offshore pipeline contractors, includes methods to characterise primary consolidation rate, undrained shear strength, drained shear strength, sensitivity, and unit weight.

The test series was performed on slurries of E-grade Kaolin and on two natural seabed muds. This report describes the test methods and presents the results of the tests in all three soil types tested.

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A BENCH-SCALE TEST SERIES FOR SEABED SOILS

Introduction

Subsea oil and gas pipelines are often buried in trenches on the seabed to protect them from damage from fishing gear, anchors, and mooring lines; to reduce the impact of hydrodynamic forces; and for thermal insulation. Trenching methods include high-pressure water jetting, which disperses the soil into the water above the trench; mechanical cutting, which uses moving blades to destroy the soil fabric; and ploughing, a less destructive method which uses a fixed blade to cut the trench and pushes the spoil into piles along the sides of the trench. Trenching by any method in fine-grained soils is assumed to form lumps and chunks of soil and a muddy suspension as water becomes mixed with the soil being removed from, and then replaced into, the trench.

Bolton and Barefoot (1996) developed simple bench-scale test methods to characterise the properties of soil in a simulated state of disturbance by a mechanical trenching operation. Model tests in a sedimentation tank were performed to estimate the rate of consolidation of such a heterogeneous soil-seawater mixture, and a plate penetrometer device was developed to probe for undrained shear strength values of the soil layer at various states of consolidation. Their work showed that the resulting liquefied slurry, while unconsolidated, has greatly reduced uplift resistance, and that the time required for reconsolidation of the soil, and therefore for regain of strength and uplift resistance, was less than that predicted by oedometer tests.

The test series discussed in the following sections builds upon this previous work, refining the methods previously used and developing additional methods for characterising soil slurries using simple devices. A principal aim of this work was to develop a simple set of standard bench-scale tests and to establish the foundation of a simple classification system for fine-grained soils directed specifically at the needs of offshore pipeline constructors. Another objective was to describe the properties of two types of clayey seabed soils, one from off the Atlantic coast of Spain, another from the British sector of the North Sea.

A series of tests was performed on high water-content slurries of E-grade Kaolin, Atlantic Mud, and North Sea Soil, which determined the rate of self-weight consolidation, undrained shear strength, drained shear strength, sensitivity and thixotropic regain, and unit weight – all parameters important in deter-mining the uplift resistance of a backfilled soil. This test series was performed on soils at various initial water contents to assess the effect of the initial degree of mixing of excess water with soil on the final profiles after sedimentation and consolidation.

Description of Test Series

The test series was performed first on E-grade kaolin, then on Atlantic Mud, each at three different water contents, and on North Sea Soil at two different water contents. The test series for the former two soil types consisted of three sets of four tanks, each set of four tanks containing the soil at the same water content. North Sea Soil tests were completed on only 2 tanks, each at a different water content.

Slurry Preparation

Kaolin

E-grade kaolin in granular form was mixed with a 3% sodium chloride solution (simulating seawater, which typically has a salt concentration near 3%) into fully-saturated, homogeneous slurries at three different water contents. The slurries were mixed in an electric blade mixer under vacuum in batches of about 4 litres, each mixed for about 30 minutes. Four batches were prepared at each of three water contents, for a total of 12 batches. Samples of each slurry were taken to measure the initial water content of each; water contents of the three different mixtures were 83% (tanks 1-4), 98% (tanks 5-8), and 112% (tanks 9-12).

Atlantic Mud

Homogeneous Atlantic mud slurries were mixed from the clayey portions of vibrocore samples and 3% sodium chloride solution, first manually to break up large chunks of soil, and then in an 80-litre capacity low-shear electric blade mixer. The initial slurry was mixed at a relatively low water content and deposited into four tanks; more salt water was added, the slurry was mixed again at a higher water content and was deposited into four more tanks; again, more salt water was added, the slurry was mixed at an even higher water content and was deposited into four more tanks. Each slurry was mixed under vacuum for approximately 8 hours before being deposited into the tanks. The water contents of the three different mixtures were: 90% (tanks 1-4), 99% (tanks 5-8), and 107% (tanks 9 - 12).

North Sea Soil

Two 4-litre batches of this soil were mixed from the clayey portions of field samples and 3% sodium chloride solution manually to break up large chunks of clay. Then each batch of soil was mixed in an electric blade mixer for about 1 hour under vacuum to form a homogeneous slurry. As each batch was placed into tanks, samples were taken to measure the initial water content of each slurry. The initial water contents were 87% (tank 1) and 76% (tank 2).

Tanks

The tanks into which the slurries were deposited were 5000-mL polypropylene Griffin squat form beakers (BS 5404). These tanks are translucent, for visual observation of settlement of the soil surface; approximately vertical-sided; and durable. They are 248 mm tall and have an average diameter of 176 mm; they are large enough to take the contents of a 3.5 - 4 litre core sample mixed with excess salt water.

Approximately 150 mm (about 3.5 litres) of soil slurry was poured into each tank. About 500 mL of salt water was poured over the surface of each slurry immediately after the slurry was deposited into the tank, in order to ensure that the slurry layer remained submerged at all times during testing.

Settlement Measurements

Immediately after the soil slurry was deposited in each tank, the level of the surface of the slurry was marked on the side of the tank with a felt-tip marker. A photocopy of a metric ruler was attached firmly to the outside of the tank, with the zero point of the ruler corresponding exactly to the initial surface of the slurry. At various times after deposition of the slurry into the tank, observations of settlement of the slurry surface due to self-weight consolidation were made. Measurable changes in the surface level were marked on the ruler and recorded along with the date and time they were made. Resolution of settlement measurements using this method was 0.5 mm, an improvement over the method of marking on the side of the tank with a felt-tip pen employed by Bolton and Barefoot (1996), which gives 1-2 mm resolution.

Measurable changes in the soil surface level were observed daily for the first several days following deposition of the slurry into the tanks. In the E-grade kaolin and the North Sea Soil, observations continued until no change in the soil level was observed in a period at least twice as long as the last period of time in which a measurable change was recorded (i.e., if the last change in soil level measured was a 1 mm change recorded 5 days after the previous change, settlement was considered "complete" in that tank if no further measurable change was observed 10 days after this 1 mm change was recorded). In the Atlantic Mud test series, the soil had not completely settled according to this criterion after 40 days, but the remainder of the test series was performed on the soil after about 40 days of settlement due to time constraints which prohibited waiting any longer for the soil to be considered "fully consolidated" by this criterion.

Penetrometer Tests

Several plate penetrometer devices were fabricated from aluminium, as described by Bolton and Barefoot (1996), to measure shear strength in the reconstituted soil layers, which were too soft to be measured by more conventional methods. The "plate" of the penetrometers is a thin circular disc, 30 mm in diameter, attached to the end of a hollow hypodermic aluminium tube, 400 mm in length. Attached to the other end of the tube is a thin 2-inch square aluminimn loading plate. Both ends of the tube are threaded; in the centre of both the disc and the loading plate is a small, threaded hole, by which the disc and plate are attached to the tube. Once screwed into place, the disc and plate are held in place by small collars. The tube is placed through two holes in the centre of a support frame consisting of two thin rectangular aluminium strips separated by a cylindrical column in each of the four comers. A diagram of the device is included in Figure 1 of Appendix A.

Small washers, ranging in weight from about 7 grams to 18 grams, were added incrementally to the loading plate. Vernier calipers mounted vertically in a fixed position on a ring stand were used to measure the depth of sink of the penetrometer resulting from the application of each loading increment.

Figure 2 of Appendix A pictures the setup of the penetrometer tests, including tanks, a penetrometer with weights on the loading plate, and mounted vernier calipers.

It was assumed that each penetration influenced a circular area about 3 times the diameter of the plate, or about 90 mm in diameter; therefore, it was hypothesised that in each 176-mm diameter tank, about 4 penetrations could be made in different parts of the tank without the zones of influence of the various penetrations intersecting enough to affect the results of subsequent penetrations. Four penetrometer tests were carried out in one tank to test this hypothesis; the results of this experiment, pictured in Figure 3 of Appendix A, show four virtually identical curves of bearing stress versus penetration depth, indicating that indeed, four penetrations can be made in different parts of one tank without influencing each other.

Reported results of penetrometer tests exclude the bottom 30 mm of the soil in each tank, since results within one plate diameter of the bottom of the tank were assumed to be influenced by the bottom.

Undrained Penetrometer Tests

Undrained penetrometer tests were performed to measure the undrained shear strength of the soil in the tanks. Undrained penetrometer tests were those in which loading increments were added such that the penetrometer displaced rapidly enough not to allow excess pore pressures to drain. In these tests, each load was applied for 15 seconds; after 15 seconds, the penetration depth was measured with the vernier calipers, and the next load increment was immediately applied. Loading increments were chosen so that each increment would produce penetrometer sink of approximately 10 mm.

Analysis of Undrained Penetrometer Results

Following the analysis method used by Bolton (1996), the undrained shear strength was determined using bearing capacity analysis applied to a circular plate of diameter D at depth z. The shear strength (c_u) was related to bearing stress (q_p) by a bearing capacity (N_p):

$$c_u = \frac{q_p}{N_p}$$

The bearing capacity factor, N_p, was taken to increase from $N_o = 6$ at the surface to $N_\infty = 12$ at large depth, according to the expression:

$$N_p = N_o + \frac{(N_\infty - N_o)\left(\frac{z}{2D}\right)}{\left(1 + \frac{z}{2D}\right)} \qquad \text{(Bolton, 1996)}$$

Partially-Consolidated Undrained Penetrometer Tests

Undrained penetrometer tests were performed in some tanks at different times during consolidation, for comparison of shear strengths at various degrees of consolidation. In the E-grade Kaolin and Atlantic Mud tanks, such a test was performed in each of two tanks at each water content; an undrained penetrometer test was performed in both of the North Sea Soil tanks.

Fully-Consolidated Undrained Penetrometer Tests

An undrained penetrometer test was performed in every tank at the end of the self-weight consolidation period.

Drained Penetrometer Tests

Drained penetrometer tests were those in which loading increments were added slowly enough for all excess pore pressures in front of the advancing penetrometer to drain completely, so that the penetrometer came into drained equilibrium and stopped moving. Drained penetrometer tests were carried out at the end of the self-weight consolidation period in 2 tanks at each water content in the E-grade kaolin and Atlantic Mud series, and in both of the tanks containing North Sea Soil. Loading increments were chosen so that each increment would cause the penetrometer to sink a predicted 20 mm. The penetrometer sink was measured several times within the first ½ hour after the application of each new loading increment and approximately hourly for the next several hours; drained equilibrium was assumed to have been reached when three consecutive hourly measurements showed no significant measurable (to the nearest 0.2 mm) change in penetration depth. Generally, each loading period was about 24 hours long.

Drained penetrometer test results are presented in terms of penetrometer bearing stress (q_p) versus penetration depth.

Sensitivity Tests

Immediately after the fully-consolidated undrained penetrometer tests, sensitivity tests were performed on the tanks. First, the supernatant water was removed from the soil surface using a pipet. Then a tank was placed into an apparatus designed to tilt from side to side, administering blows to the tank as it tilted and the edge of the tank hit the surface of the apparatus foundation. This apparatus is pictured in Figure 4 of Appendix A. It consists of a "cradle" made from a round piece of metal, underneath which is a l-inch flange along the diameter of the cradle which acts as a pivot. The tank sits on a l-inch thick piece of wood in the bottom of the cradle; the distance, therefore, between the bottom of the tank in its fully upright position and the apparatus foundation (and therefore, the drop height), is 2 inches. The apparatus is mounted on a wooden foundation in which are two screws; the pivot fits into the grooves in the screws.

Ten blows were administered in each of 4 directions. The directions were chosen such that the axes along which the blows were induced were perpendicular to each other and at 45-degree angles to the axes along which penetrometer tests were made, as shown in Figure 5 of Appendix A. A tank was placed in the sensitivity apparatus, held upright, and allowed to drop to one side under its own weight; brought to the upright position, and allowed to drop to the opposite side. This process was repeated 10 times so that 10 blows to alternating sides along an axis were achieved. Then the tank was removed from the apparatus, rotated 90 degrees, placed back in the apparatus, and the process was repeated along the perpendicular axis for 10 blows to alternating sides. Twenty blows were administered in 35 seconds, although in some of the Atlantic Mud tanks, some experiments were performed with 20 blows per 20 seconds to investigate the dependence of sensitivity on the frequency of blows.

Immediately after the blows were administered to the tank, another undrained penetrometer test was performed in the tank. The sensitivity index was calculated as the ratio of undrained penetrometer bearing stress before the blows (fully-consolidated undisturbed) to that immediately after the blows (post-disturbance).

The supematant water was replaced after the sensitivity tests. The tanks were allowed to sit undisturbed for 7 days. After 7 days, a final undrained penetrometer test was performed in each tank to determine whether there was any regain in shear strength after the sensitivity tests. A thixotropy index was defined as the ratio of undrained penetrometer bearing stress before the sensitivity test (firlly-consolidated undisturbed) to that 7 days after the sensitivity test.

Average Unit Weight Measurements

Measurements of the average unit weight of the soil in the tank were made at several times during the testing series. Supernatant water was pipetted off the soil surface, and the tank and its contents were weighed. The level of the soil surface was marked on the outside of the tank with a felt-tip pen all around the tank and measured from the inside tank bottom. The height of the soil surface was correlated to the volume of soil in the tank using the volume-height relationship depicted in Figure 6 of Appendix A, which was developed by adding known volumes of water to the tank and measuring the height of the water surface with a tape measure.

Average tank unit weight measurements were made in all test series at the end of the self-weight consolidation period, immediately after the sensitivity tests, and 7 days after the sensitivity tests. In the Atlantic Mud test series, average tank unit weight measurements were also made at the beginning of the self-weight consolidation period, immediately after the slurry was deposited in the tanks.

Spot Unit Weight Measurements

A miniature piston sampler, depicted in Figures 7a and b of Appendix A, was used to obtain samples of mud from different locations in the tanks. The outer rod of the sampler was a hollow Perspex tube, 14 mm in inner diameter. The "piston" was a nylon rod, 12.8 mm in diameter. Attached near the bottom of the piston were 2 rubber washers, each 2 mm wide and 14 mm in diameter, spaced about 1 cm apart. Pulling the piston up through the outer rod of the sampler created a suction pressure inside the sampler, causing soil to be sucked into the sampler. By measuring the height to which the soil rose within the tube, and knowing the cross-sectional area, one could determine the volume of the sample. The soil was then extruded from the sampler and weighed.

The samples were placed into an oven and dried so that water contents could be determined. All data for the unit weight and water content of soil samples determined by this method was correlated and an average specific gravity, G_s, was obtained for each soil, by the following relationship:

$$\gamma' = \gamma_w \frac{G_s - G_f}{1 + wG_s},$$

where G_f is the specific gravity of the supernatant fluid, in this case, salt water;
w is the water content of the soil;
γ_w is the unit weight of water; and
γ' is the submerged unit weight of the soil.

Samples from the bottom of the tank and from the top 30 - 50 mm of the tank were obtained and used for unit weight and water content determinations at the end of the self-weight consolidation period, immediately after the sensitivity tests, and 7 days after the sensitivity tests. Sample locations were chosen such that the removal of soil would have minimal impact on future penetrometer tests, yet provide representative samples of undisturbed soil; in general, they were taken from areas between the existing penetrometer pathways and the walls of the tank.

Surcharging

In the test series performed on kaolin six of the tanks were surcharged after the undrained penetrometer tests, instead of being sensitivity tested. The intent was to surcharge the tanks to stress levels representative of the stresses which would be encountered at the bottom of a 1-metre trench, and to perform penetrometer tests after surcharging, to compare the shear strength under field-scale test conditions to the shear strength at reduced stress levels.

A varnished wooden disc, approximately 170 mm in diameter, 23 mm thick, with twelve 5-mm diameter drainage holes around the circumference, was placed on top of the soil surface in each of the six tanks. The tube and plate portions of the penetrometer were inserted through two of the holes along opposite sides of a diameter, each approximately 45 mm from the centre of the disc. Various radially-symmetric objects were placed in the centre of the wooden discs to serve as surcharge weights.

The surcharging method was not as effective as intended for several reasons:

- surcharge weight sufficient to raise the stress in the soil to levels equivalent to stresses 1 metre deep could not be placed on the surface of the soil without tipping over because the soil surface in some cases was not entirely level. The largest surcharge weights which could be placed on the surface yielded stress levels in the soil equivalent to about 0.5-metre depth.
- penetrometer profiles of the soil (after consolidation due to surcharging was thought to be complete) indicated that the surcharge caused a large gain in strength in the top 10-20 mm of soil, immediately beneath the surcharging discs, but that the soil beneath that was not influenced nearly as much by the surcharging. In addition, the soil in the top 10 - 20 mm was so strong after surcharging that the existing penetrometer devices were not sturdy enough or large enough to be loaded enough to properly measure shear strength, but the soil was still too soft to be measured accurately by more conventional means such as shear vane testing.

Because of the problems encountered in trying to properly surcharge the E-grade kaolin, surcharging and post-surcharging penetrometer tests were not performed in Atlantic Mud or North Sea Soil.

Results

Settlement Measurements

Because each tank contained a **different** initial amount of soil, the settlement measurements are presented as normalised (or percentage) **settlement,** i.e., settlement of the soil surface divided by the original height of the soil layer.

Figure la below presents the average **normalised** settlement vs. time plots for E-grade kaolin at each water content; Figure lb presents the same for Atlantic Mud, and Figure lc presents the normalised settlement vs. time plots for both North Sea Soil tanks. Plots of normalised settlement vs. time for each tank can be found in Figures lad (E-grade kaolin) and 2ad (Atlantic Mud) of Appendix B. Figure 3 of Appendix B presents the relationship between initial **slurry** water content and fmal normalised settlement for all 3 soils.

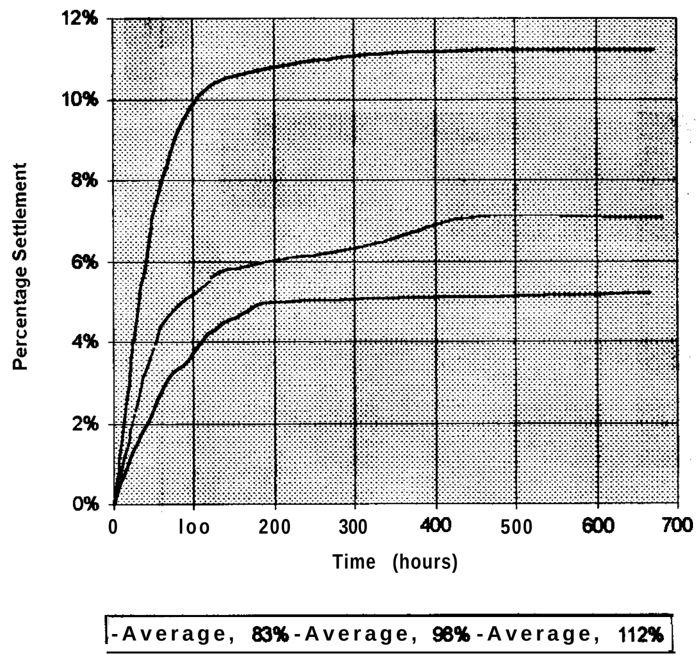

Figure la. Average Normalised Settlement vs. Time, E-grade Kaolin

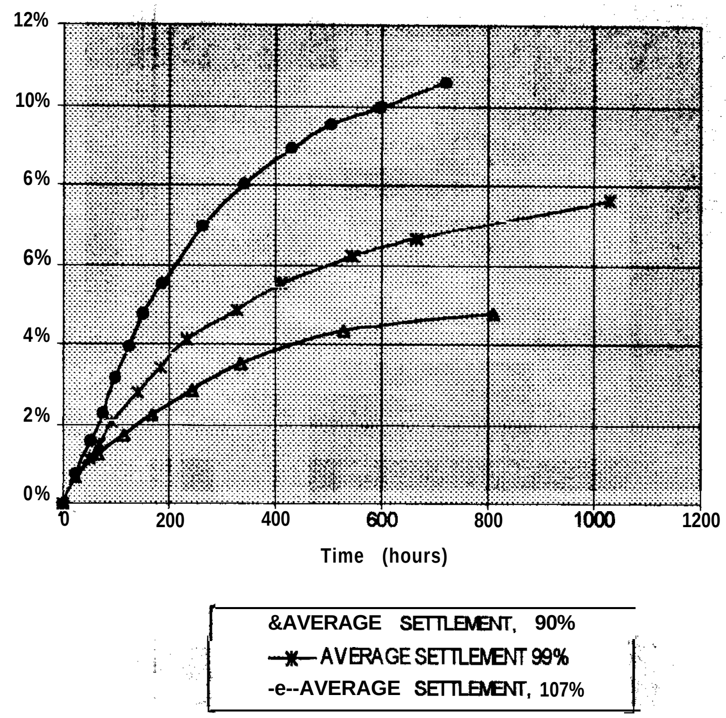

Figure 1 b. Average Normalised Settlement, Atlantic Mud

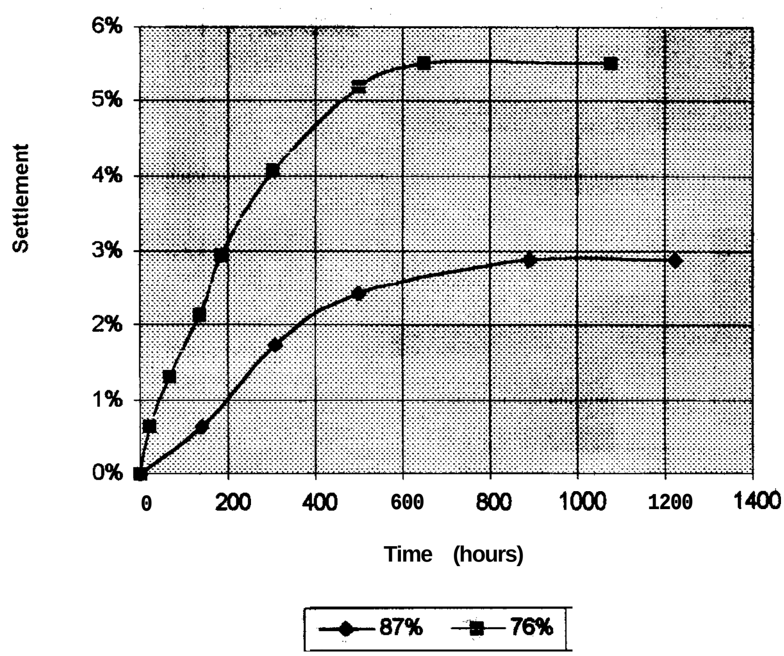

Figure Ic. Normaliseci Settlement vs. Time, North Sea Soil

Coefficients of consolidation (c_v) were determined from the average settlement vs. time plots using the graphical square-root-of-time method (Das, 1994); these values are presented in Table 1 below.

Table 1. Coefficients of Consolidation

E-grade Kaolin		Atlantic Mud		North Sea Soil	
w	c_v (m^2/yr)	w	c_v (m^2/yr)	w	c_v (m^2/yr)
83%	0.78	90%	0.22	76%	0.18
98%	1.4	99%	0.21	87%	0.19
112%	1.2	107%	0.24	---------	----------

For Atlantic Mud, the c_v values obtained in these experiments were in the range of those determined in oedometer tests performed earlier on the soil, as reported by Bolton and Barefoot (1997), but were almost an order of magnitude smaller than those determined in tank sedimentation tests by Bolton and Barefoot (1996).

This apparent discrepancy between the results for coefficient of consolidation in a homogeneous layer and in a layer of soil prepared to approximately simulate the assumed heterogeneous structure of a backfill indicates that the effects of non-homogeneity, large lumps, cracks, and drainage channels present in the simulated (and probably the actual) backfill significantly increase the rate of consolidation. Therefore, values of c_v determined from tank settlement tests in homogeneous layers of soil quite probably provide very conservative estimates for heterogeneous trench backfills. Table 2 below presents the difference in times required for 90% consolidation of a l-metre cover assuming a coefficient of consolidation representative of a heterogeneous layer and a coefficient of consolidation representative of a homogeneous layer.

Table 2. Time Required for 90% Consolidation of a l-metre layer of Atlantic Mud for Different Assumed c_v Values

	c_v = 0.22 m^2/yr	c_v = 1.8 m^2/yr
Time required for 90% consolidation	46 months	5.6 months

Knowledge about the structure of actual clay backfill could provide guidance for applying a sort of "acceleration factor" to c_v or t_{90} values obtained from settlement experiments of homogeneous layers of soil in order to estimate the consolidation time expected for heterogeneous backfill. Using the results in Table 2 above based on Bolton's and Barefoot's (1996) simulation of heterogeneous backfill, such a factor appears to be between about 7 and 9 for Atlantic Mud; that is, 90% consolidation in a 1-metre deep layer of backfill with the same heterogeneous processes occurring as in the experiments performed by Bolton and Barefoot, would consolidate about 7 to 9 times more rapidly than a homogeneous layer of the same soil.

The difficulty in specifying standard procedures for preparing simulated **backfills,** and uncertainty about the structure of real clay backfills at field-scale, make it **difficult** to recommend a standard method for predicting the actual c_v to be expected in real backfill at field-scale. However, a series of sedimentation tests performed on reconstituted soils, ranging from samples mixed with excess seawater for 5 minutes, mixed with excess seawater for 30 minutes, and mixed with excess seawater until homogeneous, for example, could provide a general range of values in which c_v may be expexted to lie, with the c_v obtained from the homogeneous samples being a conservative lower-bound estimate.

Undrained Shear Strength of Partially-Consolidated Soil

A soil which is not fully-consolidated w-ill have less shear strength than the fully-consolidated soil, as experiments reported by Bolton and Barefoot (1996) show. Since pipelines are generally put into operation before the backfill is expected to be **fully-consolidated,** it is useful to quantify the degree by which the strength is reduced at various degrees of consolidation. Undrained penetrometer tests were performed at various degrees of consolidation; the results, in terms of shear strength, were compared to the results of tests performed at full consolidation. The correlation between percent consolidation and the ratio of shear strength at partial consolidation to shear strength at full consolidation at various depths is presented in Figure 2 below. Linear fits of the data were developed and are presented below for E-grade kaolin and Atlantic Mud; however, there were not enough data points for the North Sea Soil to develop such a correlation with confidence.

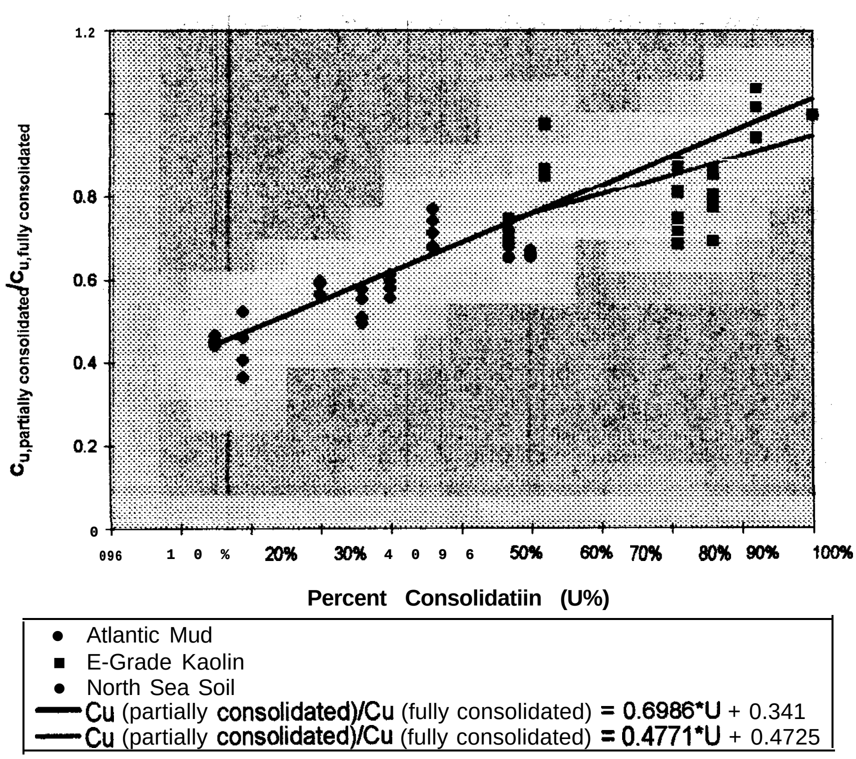

Figure 2. Correlation of Relative Undrained Shear Strength with Degree of Consolidation, All Soil Types

Figures la-f, 2a-f, and 3a-b of Appendix C present the profiles of undrained penetrometer bearing stress with depth for both the partially-consolidated and fully-consolidated cases for each tank of E-grade Kaolin, Atlantic Mud, and North Sea Soil, respectively.

Figure 2 and the figures in Appendix C highlight the importance of allowing adequate time for consolidation of trench backfill at field-scale and provide some guidance for estimating the expected decrease in shear strength (and therefore, presumably, uplift resistance) due to incomplete consolidation.

Undrained Shear Strength of Fully-Consolidated Soil

Figures 3a, 3b, and 3c below present shear strength profiles for all fully-consolidated samples of E-grade Kaolin Atlantic Mud, and North Sea Soil. Figures la-c and 2a-c of Appendix D present undrained shear strengtb profiles for E-grade Kaolin and Atlantic Mud, respectively, for each water content separately.

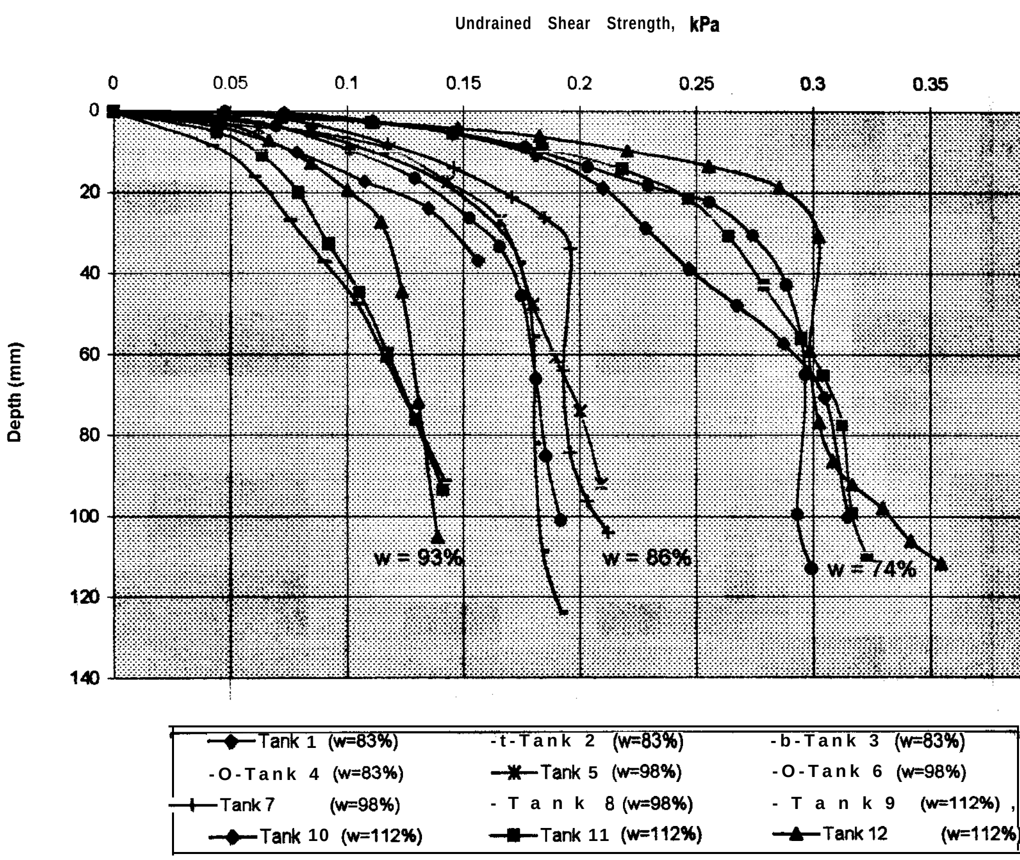

Figure 3a. Undrained Shear Strength Profiles, E-grade Kaolin

The water contents indicated in the legend below the graph are the initial water contents of the slurries; the water contents indicated on the graph under the plots are the water contents of the fully-consolidated soil at the time of testing.

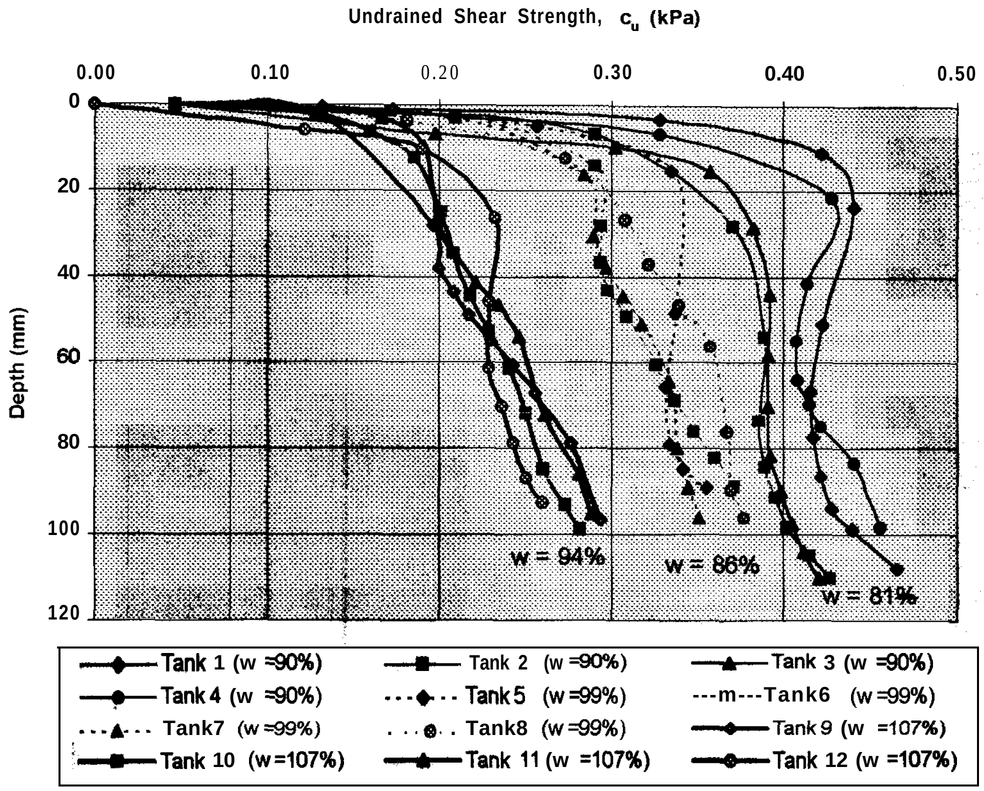

Figure 3b. Undrained Shear Strength Profiles, Atlantic Mud

The water contents indicated in the legend below the graph are the initial water contents of the slurries; the water contents indicated on the graph under the plots are the water contents of the fully-consolidated soil at the time of testing.

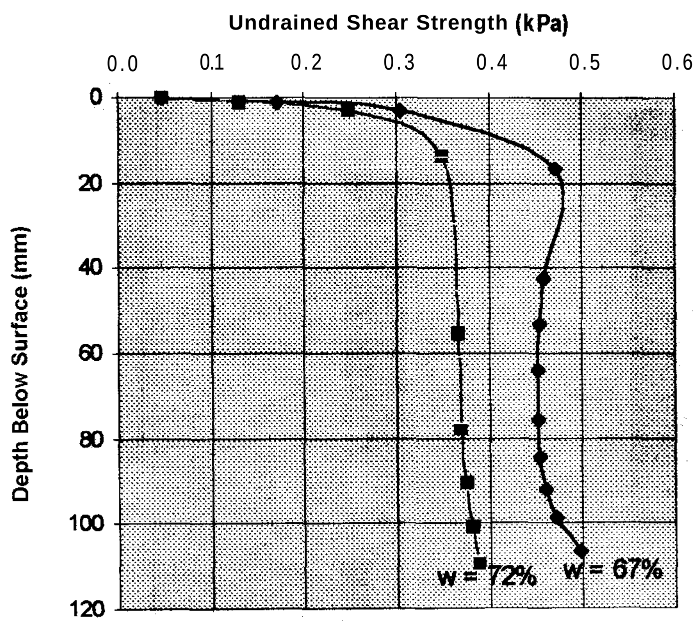

Figure 3c. Undrained Shear Strength Profiles, North Sea Soil

The water contents listed on the chart are those of the fully-consolidated soil layer.

Figures 3a, 3b, and 3c indicate that, particularly in Atlantic Mud and North Sea Soil, there is a large gain in shear strength just below the surface of the soil for about the top 10 mm, and then considerably less gain in shear strength with depth for the remaining part of the profile. This effect seems to be more marked at lower water contents.

Figure 4 below presents the results of undramed shear strength at various depths for all the water contents and soils studied. In some cases, trench backfill may be at lower water contents than the range of water contents studied in these experiments, but Figure 4 indicates an approximately linear relationship between shear strength and water content, so that it should be possible to estimate shear strength at lower water contents by extrapolating from this graph.

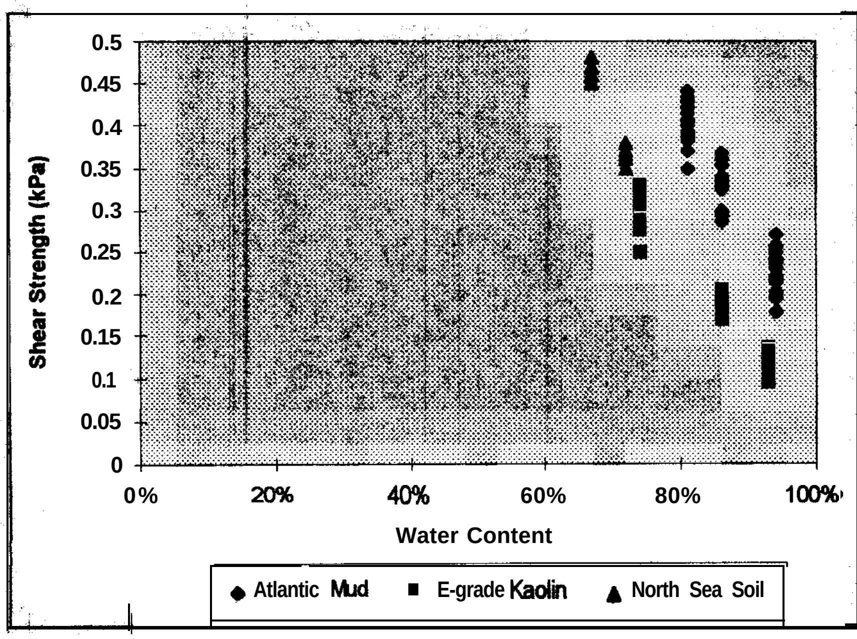

Figure 4. Relationship of Undrained Shear Strength at Various Depths to Water Content, All Three Soil Types

Figures 3a and 3b of Appendix D present the relationship of undrained shear strengths to water contents in E-grade Kaolin and Atlantic Mud respectively, distinguishing between the results at each depth. The shear strength at each water content generally increases *slightly* with depth – a result which coincides with conventional understanding of shear strength generally increasing with depth.

Drained Shear Strengths

Profiles of drained penetrometer bearing stress with depth are presented in Figures la-c of Appendix E. Figures 2a-c, 3a-c, and 4a of the same appendix compare drained and undrained penetrometer bearing stress at various water contents in E-grade Kaolin, Atlantic Mud and North Sea Soil, respectively. These figures show that the profiles of drained penetrometer bearing stress generally are approximately linear throughout the entire profile depth, in contrast to the undrained profiles, which tend to have a much shallower slope near the surface and then a steeper slope below the top 20 - 40 mm.

No generalisations can be made, however, for any of the soil types, regarding comparisons between drained and undrained shear strength from these graphs. In some cases, drained and undrained shear strength for the soil in a given tank appear to be about the same throughout the profile; in some cases, drained strength is slightly larger; in other cases, undrained strength is slightly higher; and in some cases, the drained strength is less than the undrained strength near the surface, but the relationship reverses at greater depths.

There is even quite a bit of discrepancy between some drained penetrometer profiles in the same soil at the same water content in different tanks, implying that the test method has limited precision. Therefore, conclusions which can be drawn from these tests, including correlating drained penetrometer bearing stress values with values of drained uplift coefficient obtained in centrifuge tests, may be limited.

Sensitivity and Thixotropic Regain

Pipelines in operation are subjected to cycles of temperature and pressure which cause the pipeline to buckle upward in the trench. It is thought that the movement of the pipe in response to temperature and pressure cycles disturbs the soil surrounding the pipe, and that this disturbance may reduce the strength of the soil if the soil is sensitive. Some soils regain, either partially or completely, the drop in strength due to sensitivity; this phenomenon is known as thixotropic regain.

Table 3 below presents a summary of the test results for all three soil types. Figures la-f, 2a-1, and 3a-b of Appendix F compare predisturbance, post-disturbance, and thixotropic regain penetrometer profiles for each tank tested.

As seen from Table 3, the sensitivity observed in each soil at a depth of 20 mm was greater than that observed at 80 mm. This result indicates that the method of applying disturbance has a greater effect on the top of the soil layer than on the bottom. Table 3 also suggests that either none of the soils is overly sensitive, or the method of inducing disturbance in the soil was not effective.

In most cases, the shear strength 7 days after sensitivity testing was actually ***greater than the*** original strength of the undisturbed soil. This result, coupled with the observation discussed in the next section that the unit weight of the soil generally increased during this time period, may indicate that some secondary consolidation due to plastic readjustment of the soil fabric, is occurring during this time.

Table 1 of Appendix F summarises the results of experiments performed to investigate the effect of rate of application of blows on the sensitivity index in Atlantic Mud. This table shows that for the Atlantic Mud tanks at the lowest water content, the faster application of disturbance led to a smaller sensitivity index, but the results at the other two water contents do not show a conclusive difference in sensitivity index between the two rates of blow application. However, the difference which was found to exist at the lower water content suggests the importance of standardising the rate of application of blows in order to achieve consistent results.

Table 2 of Appendix F summarises the results of experiments performed to investigate the effect of the number of blows applied to a tank on the sensitivity index, in Atlantic Mud. As expected, there is generally an increase in sensitivity index with an increase in the number of blows to the tank.

Table 3. Summary of Sensitivity and Thixotropic Regain Results

	Sensitivity Index†		Thixotropy Index‡	
Depth Below Surface	*20 mm*	80 *mm*	20 *mm*	80 *mm*
Atlantic Mud				
w* = 81%	1.71	0.98	1.03	0.83
w* = 84%	1.79	0.99	1.07	0.77
w* = 94%	1.71	1.14	0.98	0.83
E-grade Kaolin				
w* = 74%	1.60	1.01	0.93	0.71
w* = 86%	1.53	1.20	0.86	0.70
w* = 93%	1.96	1.25	0.69	0.64
North Sea Soil				
w* = 67%	1.95	0.96	1.30	0.93
w* = 72%	2.17	1.10	1.24	0.97

† Sensitivity Index = $\frac{q_{p(\text{fully consolidated, undisturbed})}}{q_{p(\text{post-disturbance})}}$; values listed are average values for all tanks tested at this water content.

‡ Thixotropy Index = $\frac{q_{p(\text{fully consolidated, undisturbed})}}{q_{p(\text{7 days after sensitivity testing})}}$; values listed are average values for all tanks tested at this water content.

* Water contents listed in table are the water contents after full self-weight consolidation.

Unit Weight

Values of average (tank) unit weight and average spot values of unit weight of samples taken from the bottom and from the top 50 mm of the soil layer are summarised in Tables 4, 5, and 6 below.

The results for tank average unit weights are accurate to +/- 0.4 kN/m^3; spot values of unit weight are considered to be accurate to within +/- 0.35 kN/m^3 (these estimates are based on the estimated level of uncertainty inherent in the methods of measurement of weight and height).

The results presented in these tables indicate some disagreement between the tank average unit weights and the spot values determined from samples taken with the piston sampler; the tank average values are generally about 0.4 to 0.6 kN/m^3 lower than the range between the values of unit weight at the top and bottom of the tank. This discrepancy suggests that one or both methods of determining unit weight contain some systematic error. No obvious source of this systematic error is known; the level of accuracy of both methods was thought to be quite high. The most likely sources, however, are errors in the measurement of height of soil in the tanks or in the measurement of volume inside the piston sampler. Known volumes of water could be placed in the piston sampler and the height of the water could be measured in order to develop a correlation between height and volume to verify the measured inner diameter of the tube used in volume calculations and thereby to verify or refute the hypothesis that measurements using this device contain systematic error.

Table 4. Unit Weight (kN/m³) Values for E-grade Kaolin
Average Values for all tanks tested at each water content

	Tank Average	Top	Bottom
Original Slurry: w = 83%			
Fully-consolidated	14.74	15.02	15.34
Post-Disturbance	14.75	16.09	15.27
7 days after sensitivity testing	14.94	15.28	15.59
Original Slurry: w = 98%			
Fully-consolidated	14.25	14.61	14.73
Post-disturbance	14.15	14.47	1472
7 days after sensitivity testing	14.56	14.97	15.17
Original Slurry: w = 112%			
Fully-consolidated	13.98	-------	--------
Postdisturbance	14.09	-------	--------
7 days after sensitivity testing	14.59	15.00	15.05

Table 5. Unit Weight (kN/m³) Values for Atlantic Mud
Average Values for all tanks tested at each water content

	Tank Average	Top	Bottom
Original Slurry: w = 90%	14.12		
Fully-consolidated	14.43	14.87	15.26
Post-Disturbance	14.57	14.91	15.18
7 days after sensitivity testing	14.60	14.96	15.24
Original Slurry: w = 99%	14.06		
Fully-consolidated	14.31	14.76	14.75
Post-disturbance	14.36	14.67	14.80
7 davs after sensitivitv testing	14.60	14.72	15.06
Original Slurry: w = 107%	13.33		
Fully consolidated	14.19	14.20	14.67
Postdisturbance	14.16	14.40	14.71
7 davs after sensitivitv testing	14.22	14.56	14.85

Table 6. Unit Weight (kN/m^3) Values for North Sea Soil

	Tank Average	Top	Bottom
Original Slurry: w = 76%			
Fully-consolidated	15.43	15.70	14.22
Post-Disturbance	15.30	15.49	15.41
7 days after sensitivity testing	--------	15.43	15.81
Original Slurry: w = 87%			
Fully-consolidated	15.28	15.96	15.78
Post-disturbance	15.27	15.71	15.94
7 days after sensitivity testing	15.37	15.68	15.85

In E-grade kaolin, there is about a 3% increase in average unit weight between the fully-consolidated measurement and the measurement 7 days after sensitivity testing. Also the difference between the unit weights at the top and bottom of the soil layer in E-grade kaolin is about 0.2 to 0.3 kN/m^3.

In Atlantic Mud, the average unit weight of the soil increased by 2% (lower water contents) to 6% (highest water content) between the original slurry state and 7 days after sensitivity testing, when the soil was generally at its most dense. Also, there is a difference of about 0.3 to 0.4 kN/m^3 between the unit weight at the top and bottom of the soil layer.

Since there were only two tanks of North Sea Soil measured (and, therefore, the benefits of averaging are not available), the trends in the data for unit weight are less clear for this soil type.

All values of water content and unit weight measured were correlated to determine values of specific gravity for each soil. The values obtained were:

- E-grade Kaolin G_s = 2.52 +/- 0.01 (obtained from 56 samples)
- Atlantic Mud: G_s = 2.52 +/- 0.02 (obtained from 64 samples)
- North Sea Soil: G_s = 2.66 +/- 0.07 (obtained from 9 samples)

Potter (1996) states that the supplier of E-grade kaolin quotes a specific gravity of 2.6 for the soil. The result of these experiments is somewhat lower than this known value. This discrepancy suggests that there may be some error in the method of measuring unit weight in samples obtained by the piston sampler, since there is little doubt about the accuracy of water content measurements.

Concluding Remarks

The test series presented in this report has good potential in describing many properties of soil in trench backfill. The repetition of experiments on several tanks containing the same soil at the same water contents yielded results which generally indicate good repeatability. The following aspects of the test series require further investigation or refinement:

- the extrapolation of results of coefficient of consolidation in a homogeneous layer to a heterogeneous **backfill**, which may contain lumps, cracks, and drainage channels, and may therefore consolidate much more rapidly than the homogeneous layer;
- the usefulness of results obtained in drained penetrometer tests, which fail to show clear trends compared with undrained penetrometer test results;
- investigation into the source of the systematic error which appears to be present in one or both methods of determining unit weight.

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Bolton, M.D. & Barefoot, A.J. (1997). The variation of critical pipeline trench back-fill properties. *Proceedings, Conference on Risk-Based and Limit State Design and Operation of Pipelines,* IBC Technical Services, Aberdeen.

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APPENDIX A: APPARATUS AND TEST PROCEDURES
SUPPORTING MATERIAL

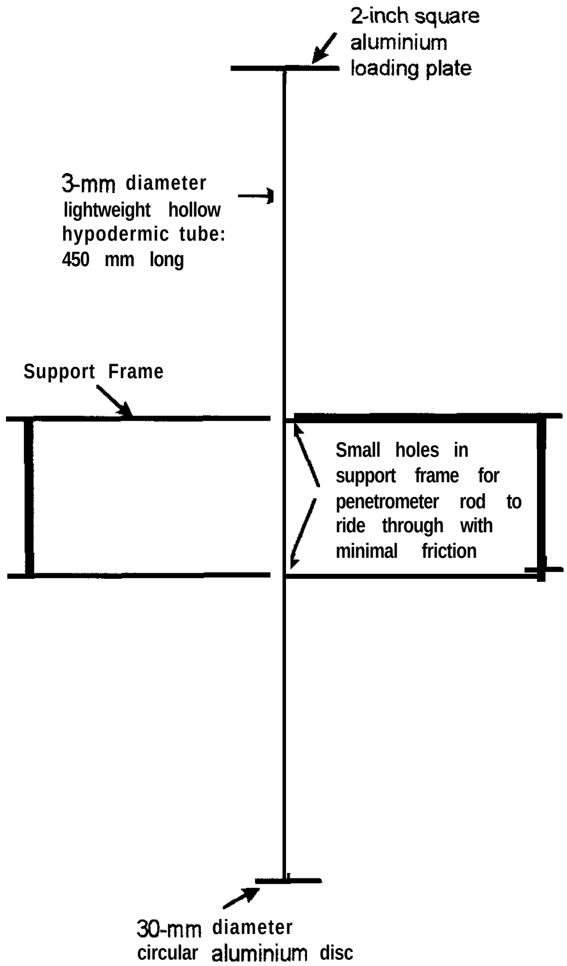

Figure 1. Simplified Diagram of Penetrometer

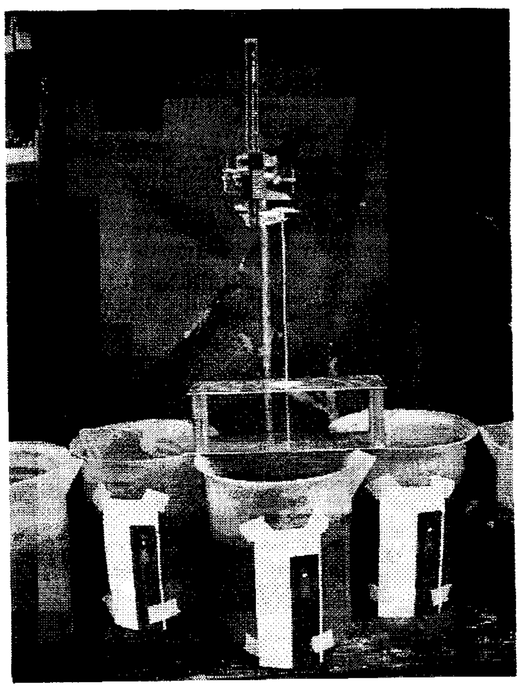

Figure 2. Photograph of Penetrometer in Use, with Tank and Vernier Calipers

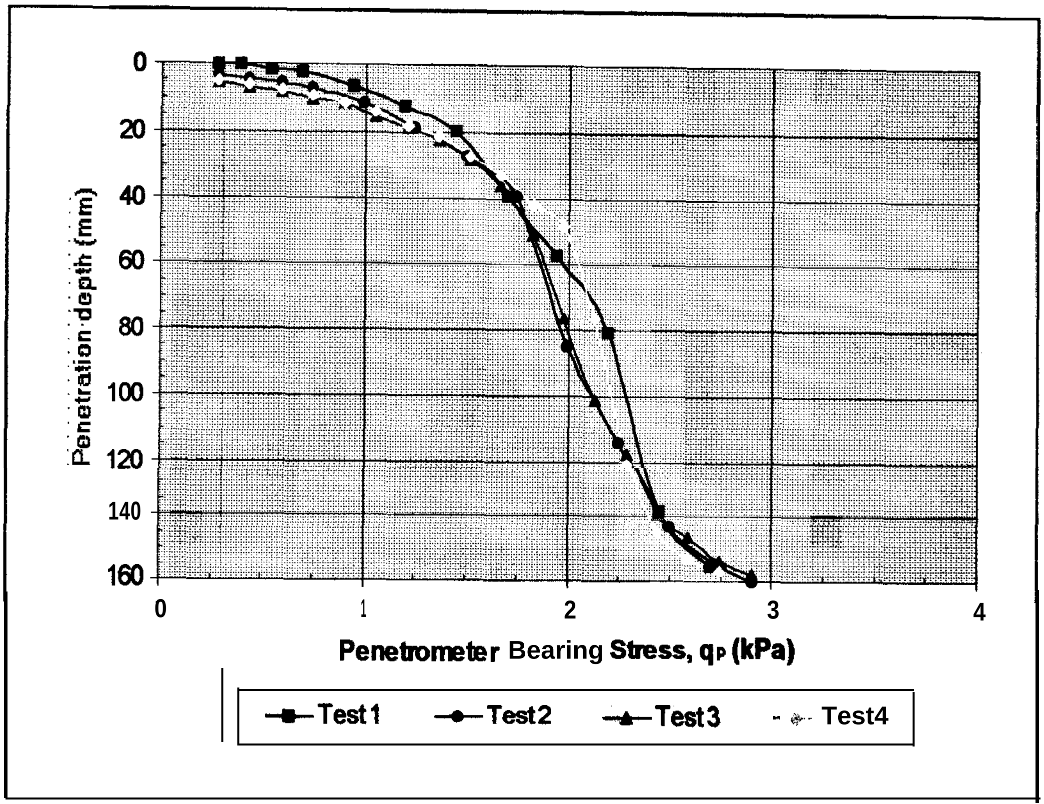

Figure 3. Four Undrained Penetrometer Profiles in the Same Tank of Kaolin at the Same Time, with Similar Results

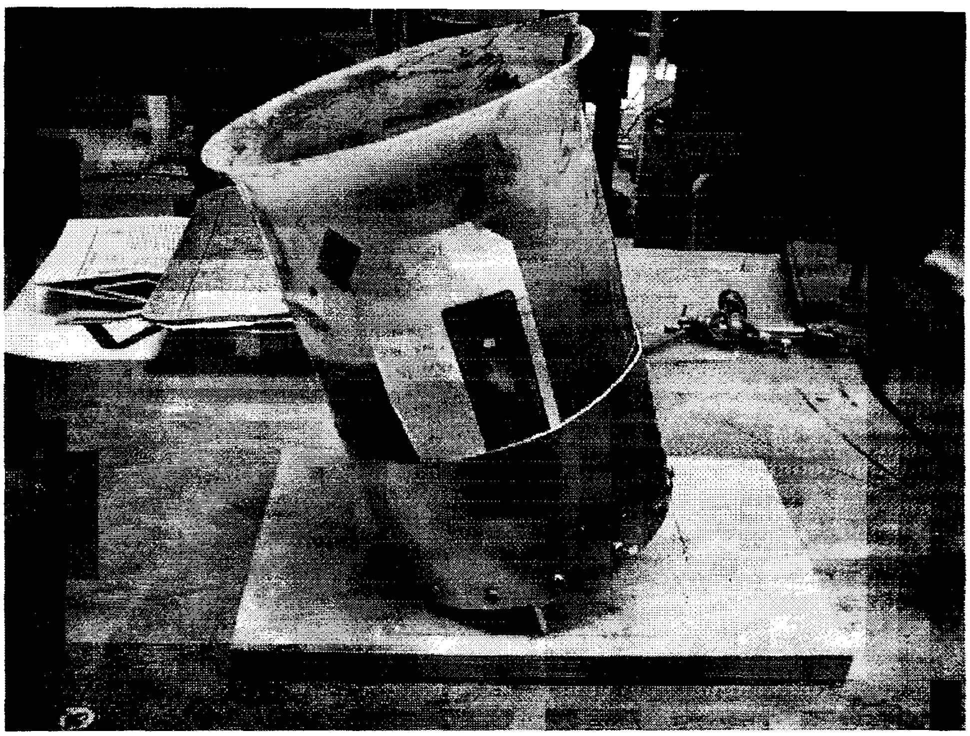

Figure 4. Photograph of Apparatus for Administering Blows to Tanks for Sensitivity Testing

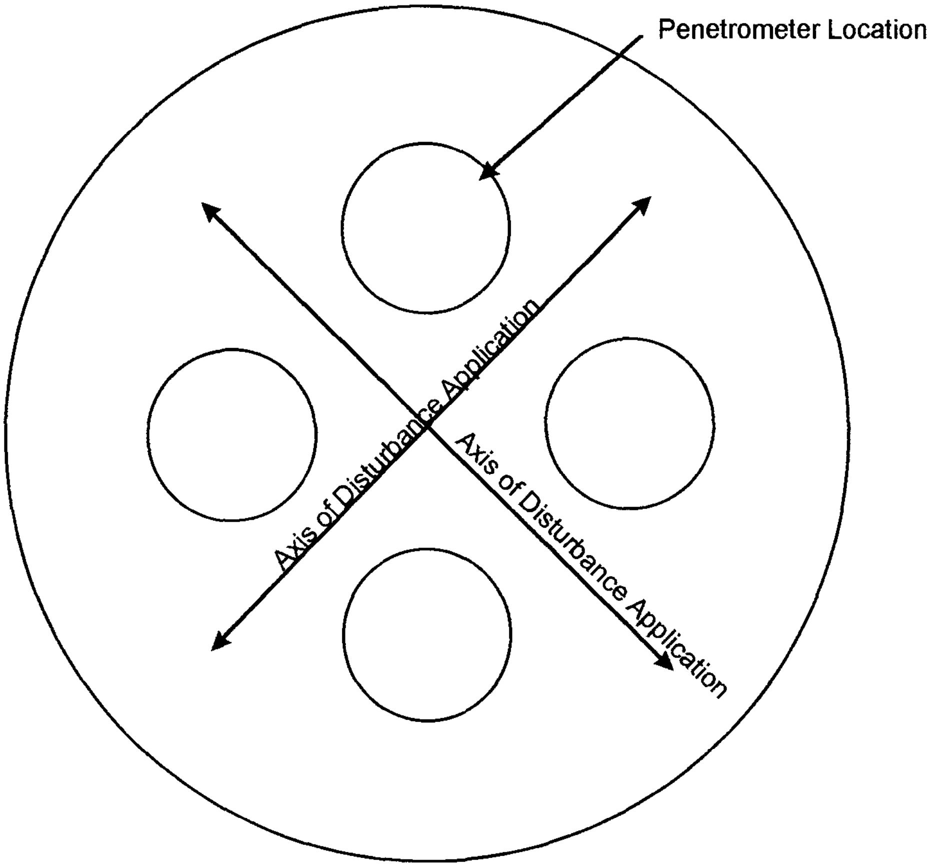

Figure 5. Plan Diagram of Tank, Indicating Penetrometer Locations and Orientation of Axes of Disturbance Application

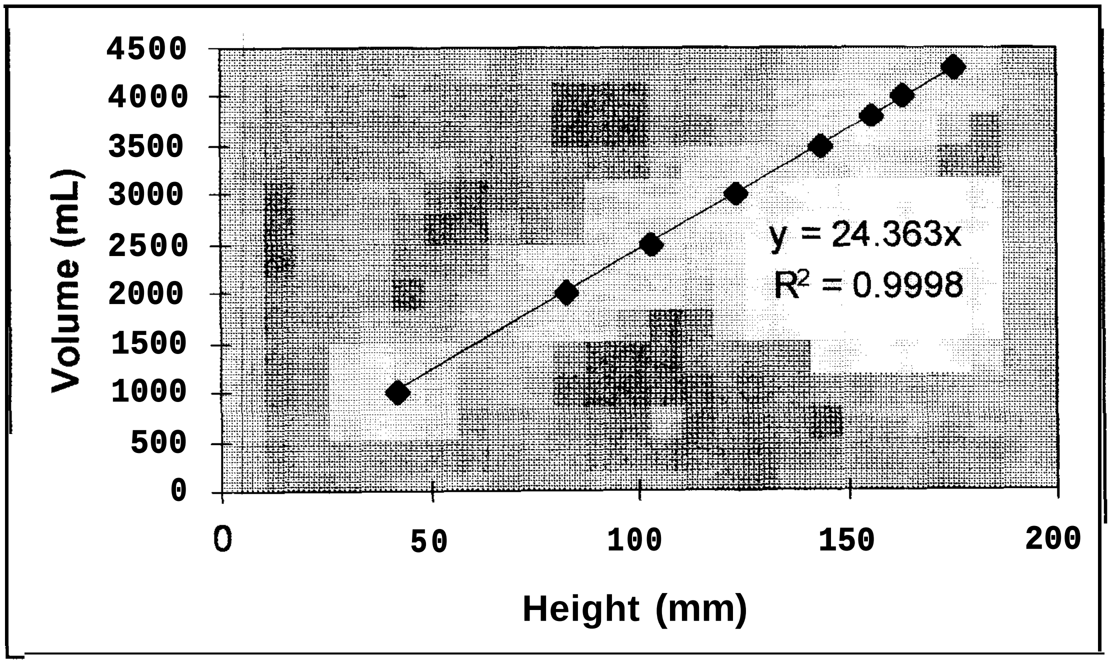

Figure 6. Volume vs. Height Relationship in Tanks

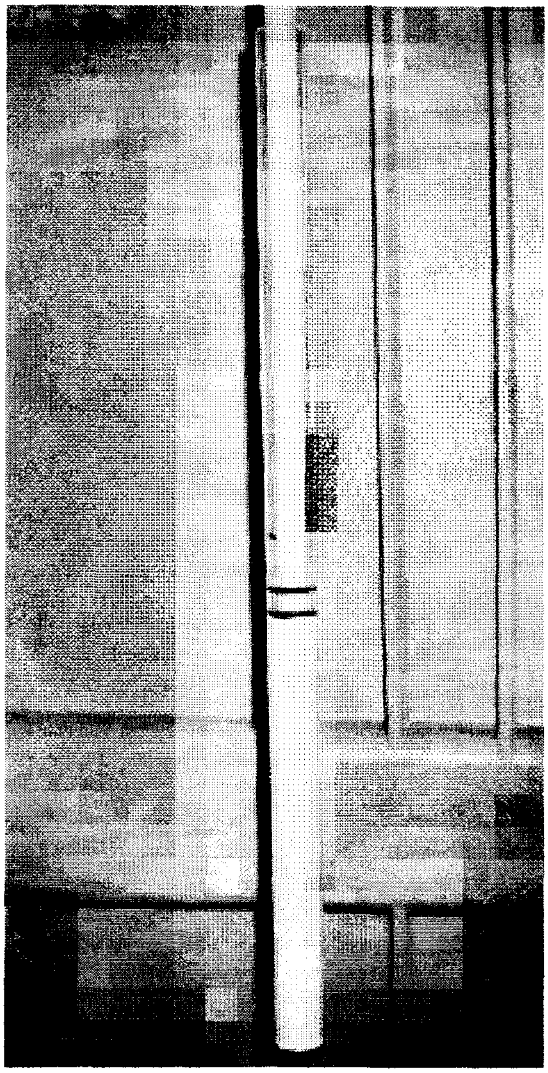

Figure 7a. Photograph of Piston Sampler Containing Sample of E-grade Kaolin

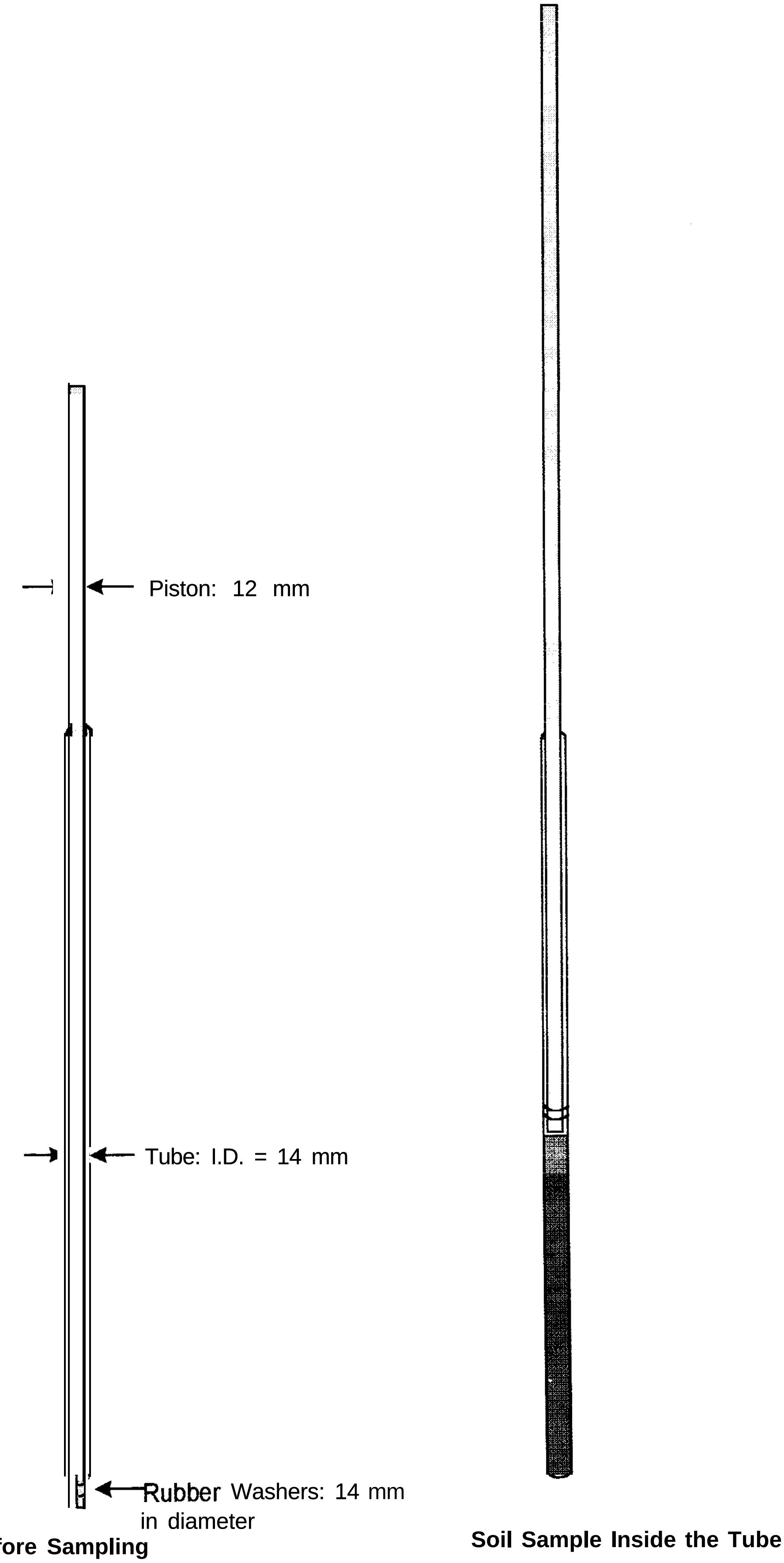

Figure 7b. Diagrams of Piston Sampler Before Sampling and Containing a Sample

APPENDIX B: SETTLEMENT CHARTS

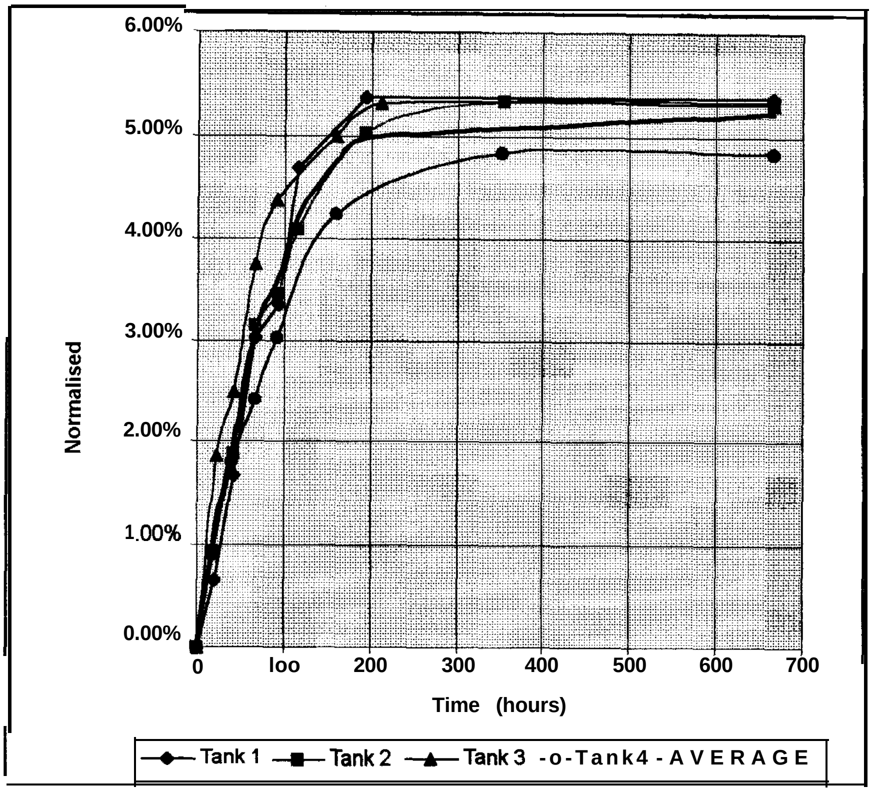

Figure la. Normalised Settlement vs. Time, Kaolin, 83% Water Content

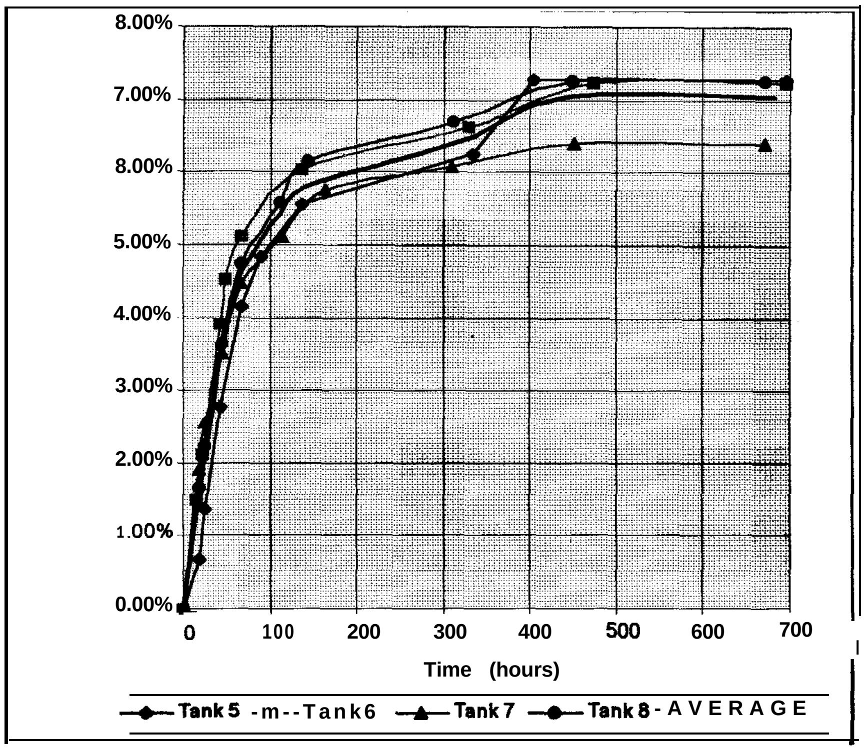

Figure 1 b. Normaiised Settlement vs. Time, Kaolin, 98% Water Content

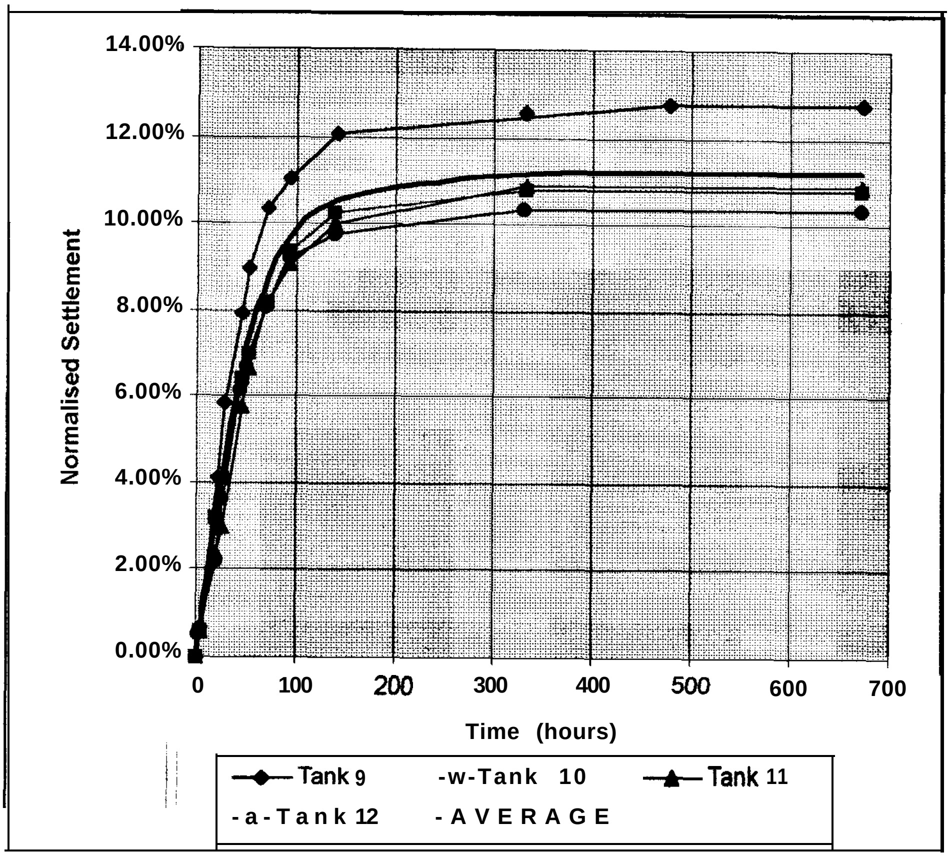

Figure Ic. Normalised Settlement vs. Time, E-grade Kaolin, 112% Water Content

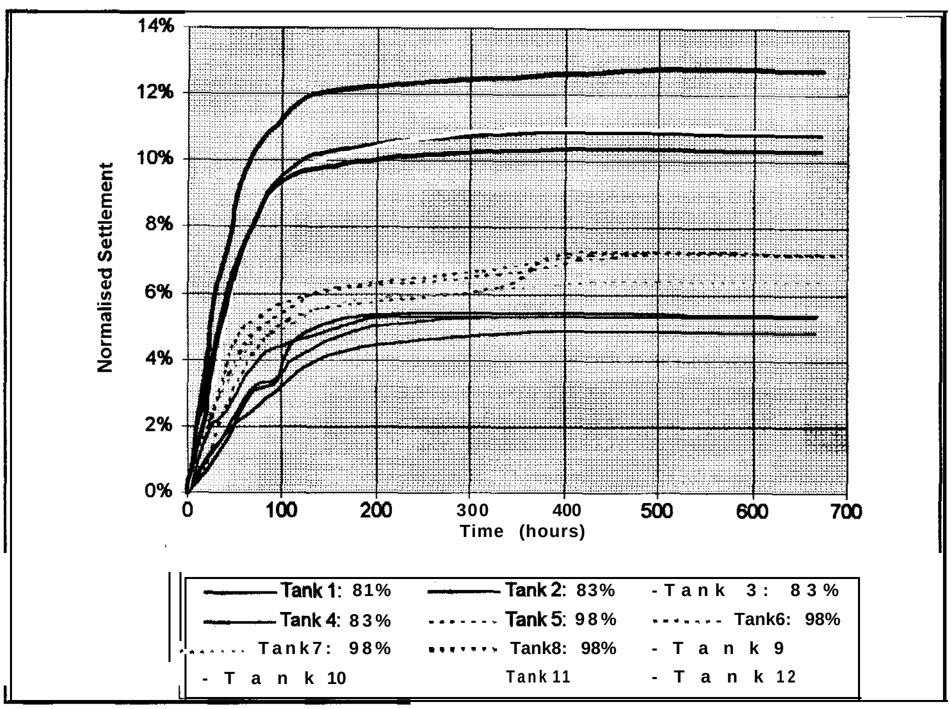

Figure Id. Normalised Settlement vs. Time, E-grade Kaolin, All Data

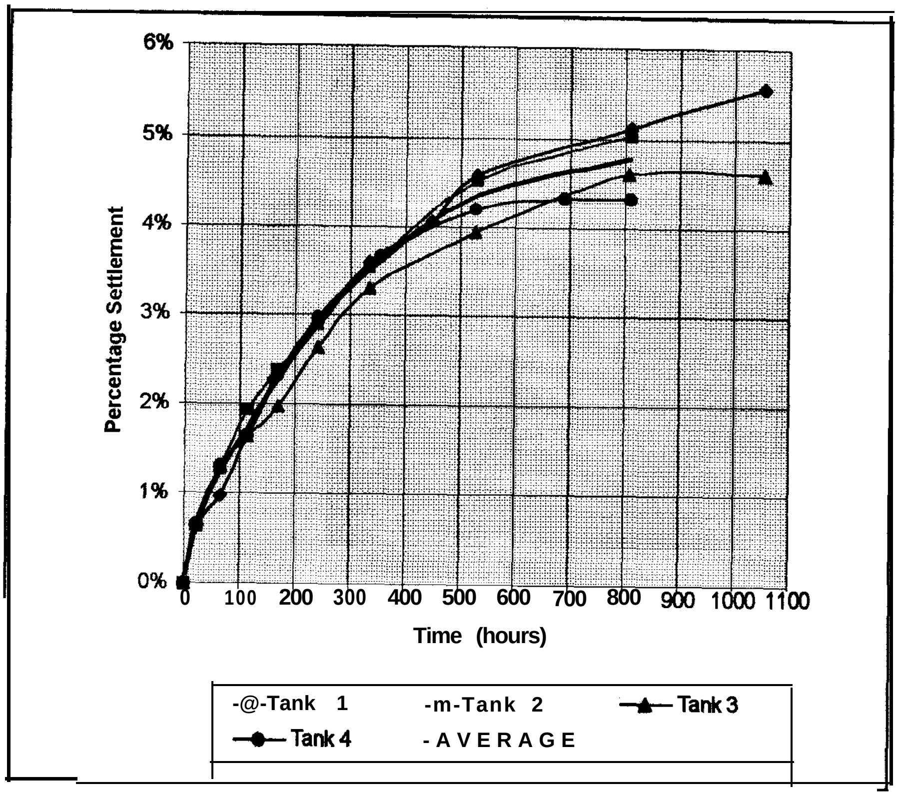

Figure 2a. Normalised Settlement vs. Time, Atlantic Mud, 90% Water Content

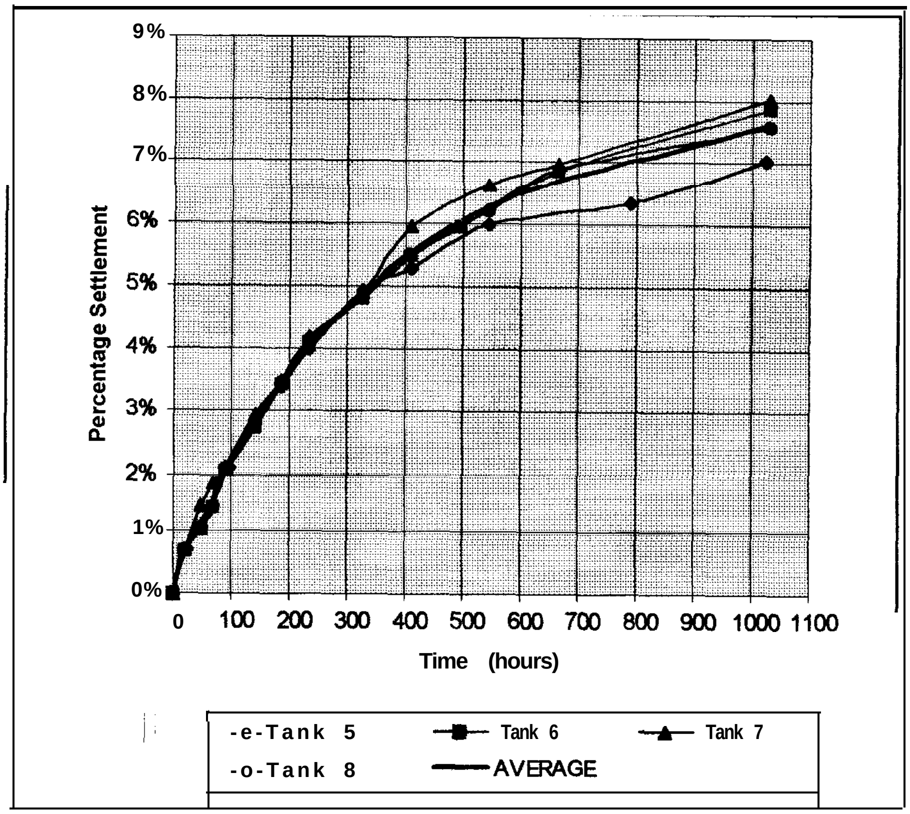

Figure 2b. Normalised Settlement vs. Time, Atlantic Mud, 99% Water Content

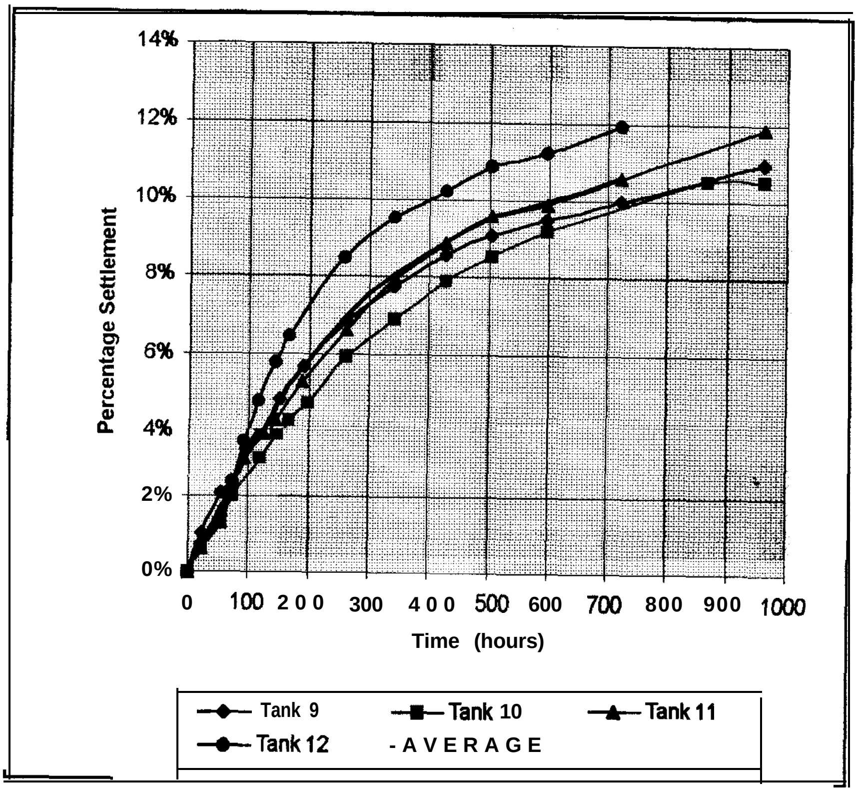

Figure 2c. Normalised Settlement vs. Time, Atlantic Mud, 107% Water Content

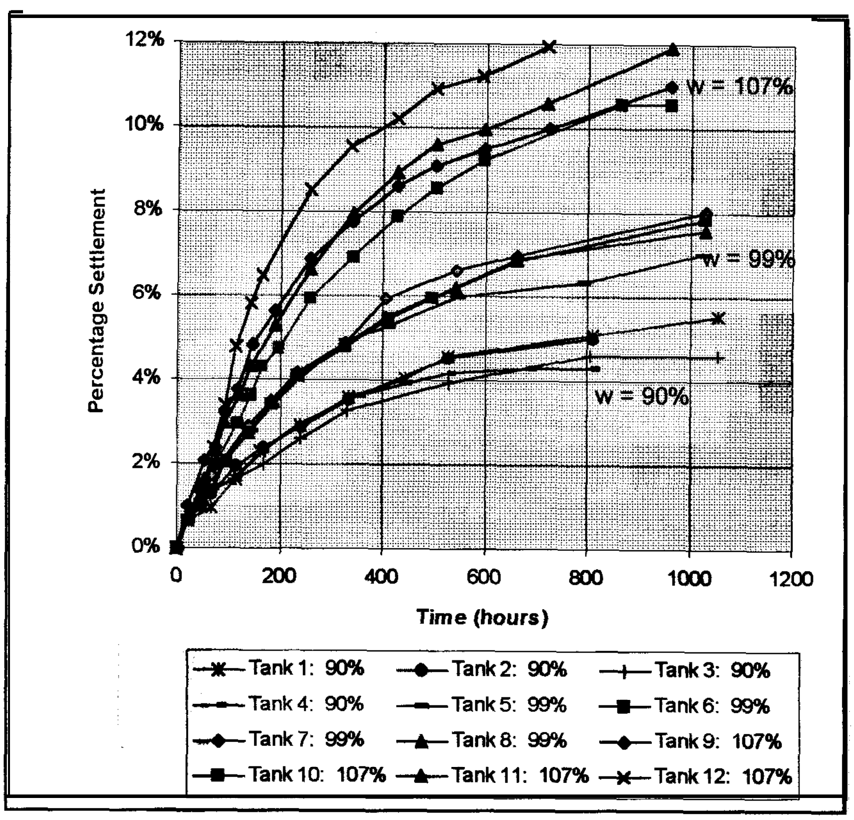

Figure 2d. Normalised Settlement vs. Time, Atlantic Mud, All Data

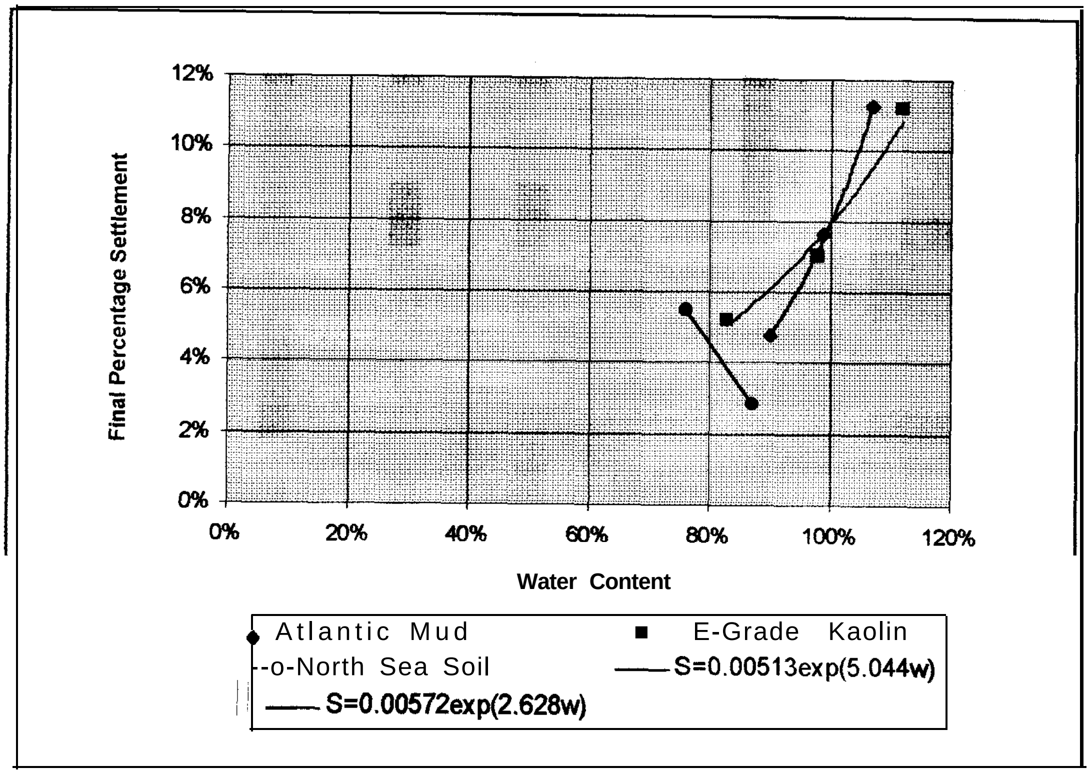

Figure 3. Total Normalised Settlement vs. Initial Water Content, All Soils

Appendix C: Partially-Consolidated Shear Strength Charts

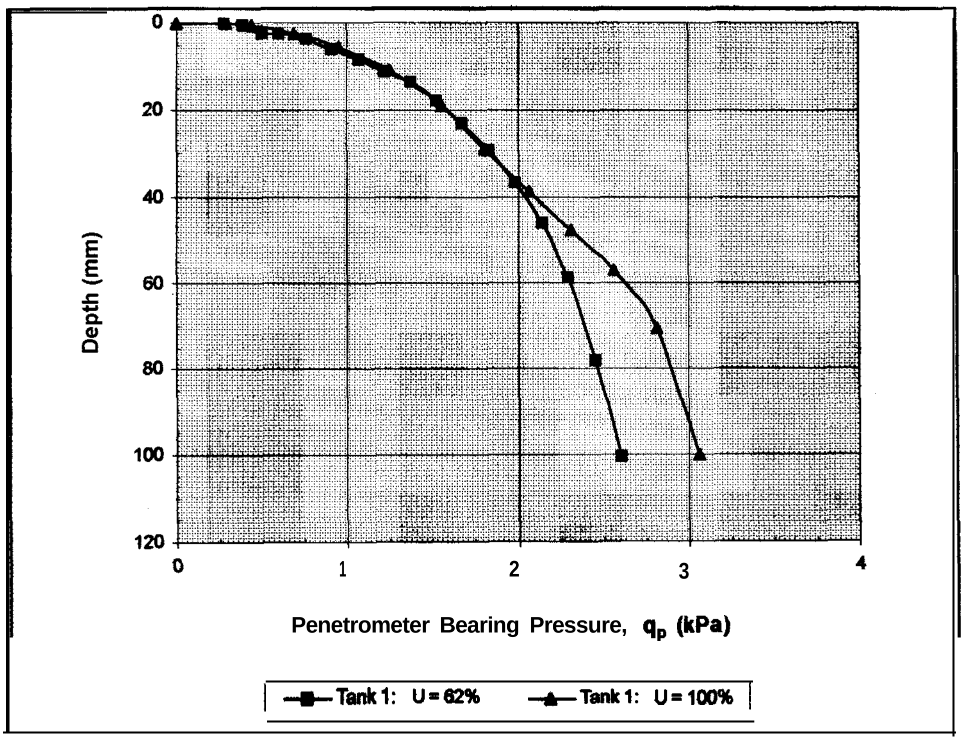

Figure la. E-Grade Kaolin, 83% Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

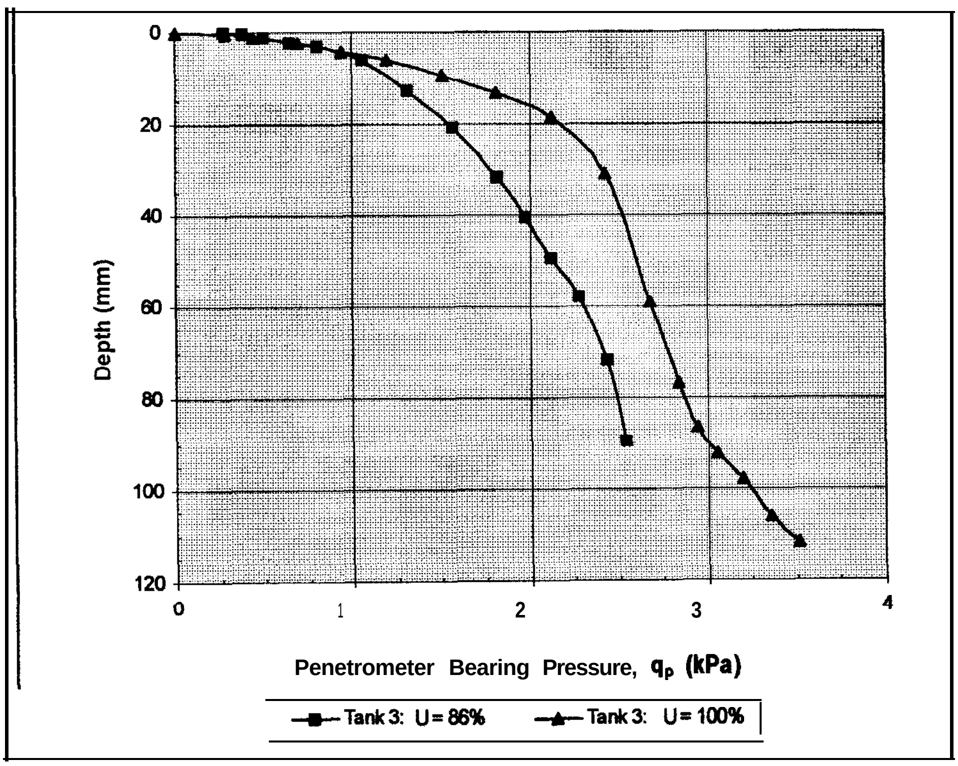

Figure lb. E-Grade Kaolin, 83% Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

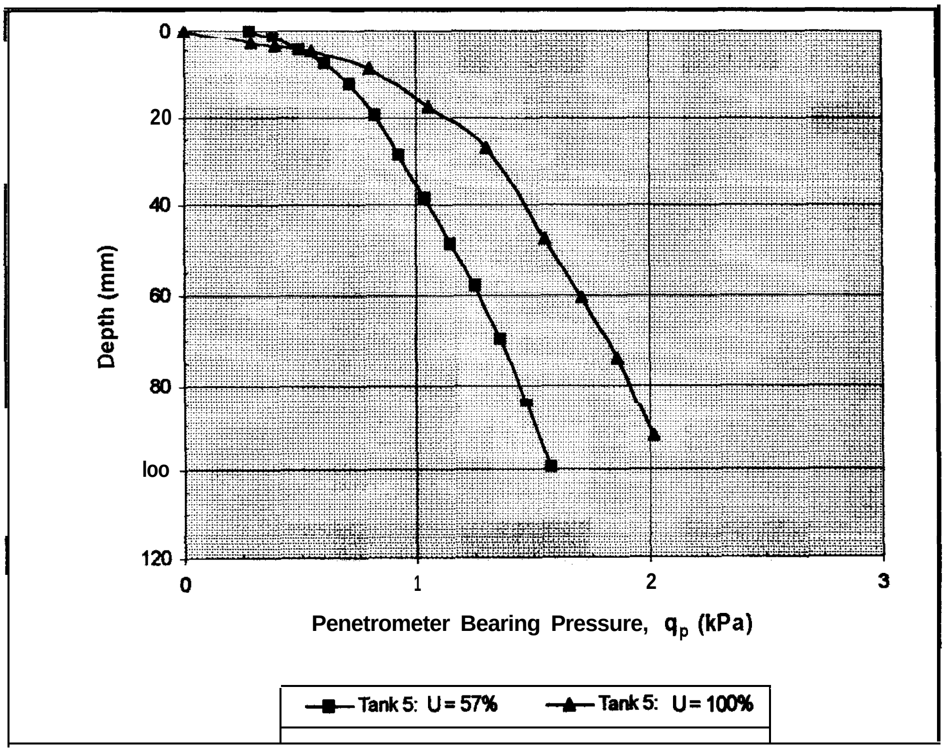

Figure Ic. E-Grade Kaolin, 98% Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

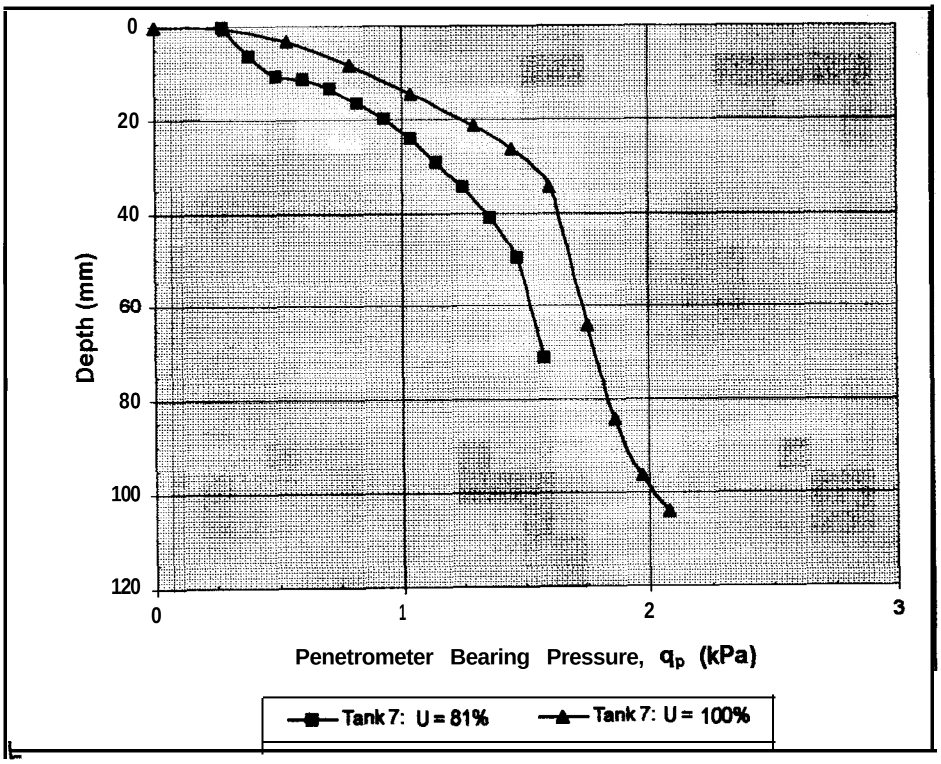

Figure Id. E-Grade Kaolin, 98% Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

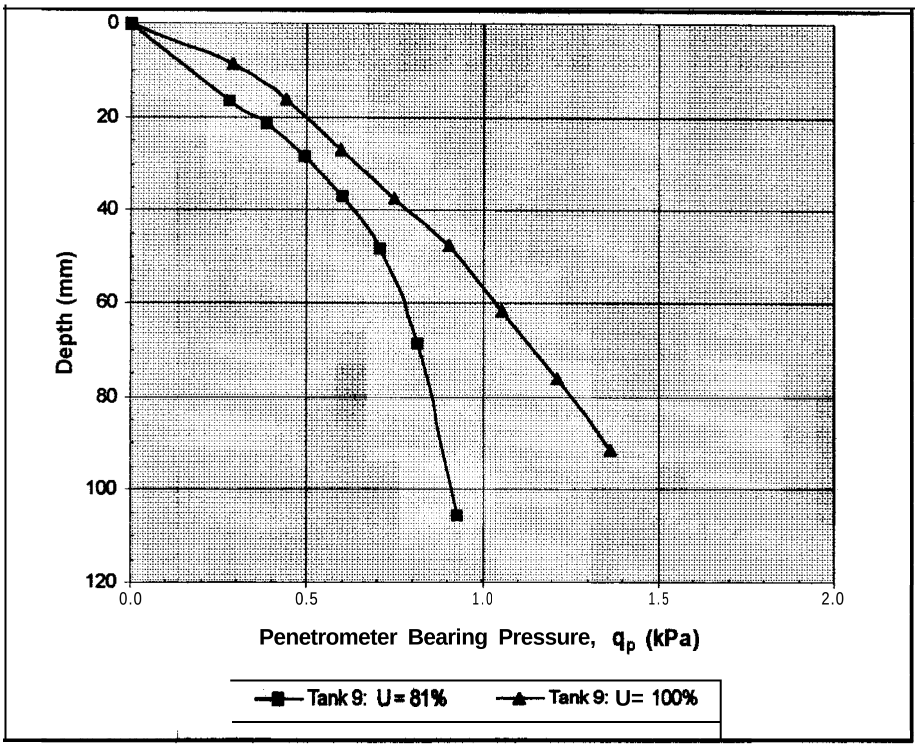

Figure le. E-Grade Kaolin, 107% Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

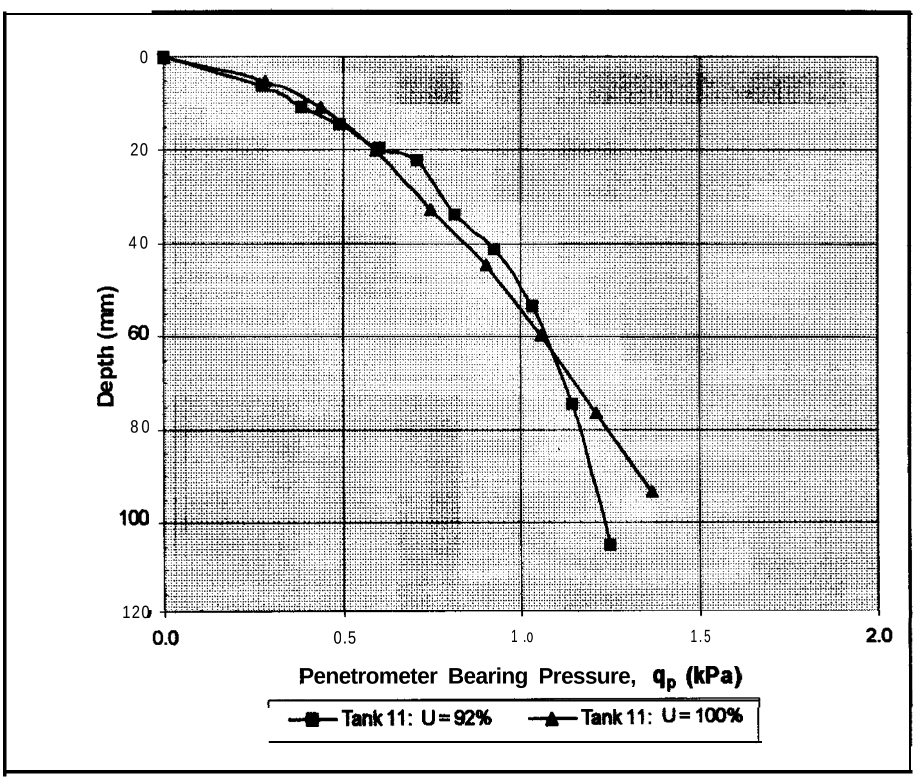

Figure If. E-Grade Kaolin, 107% Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

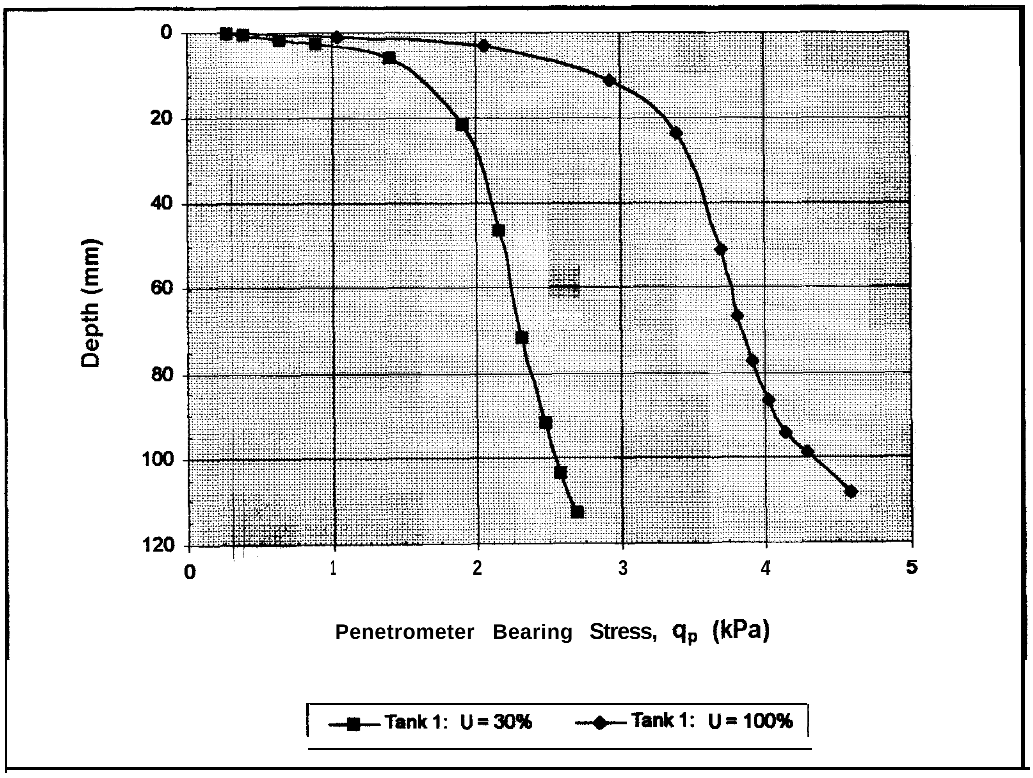

Figure 2a. Atlantic Mud, 90% Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

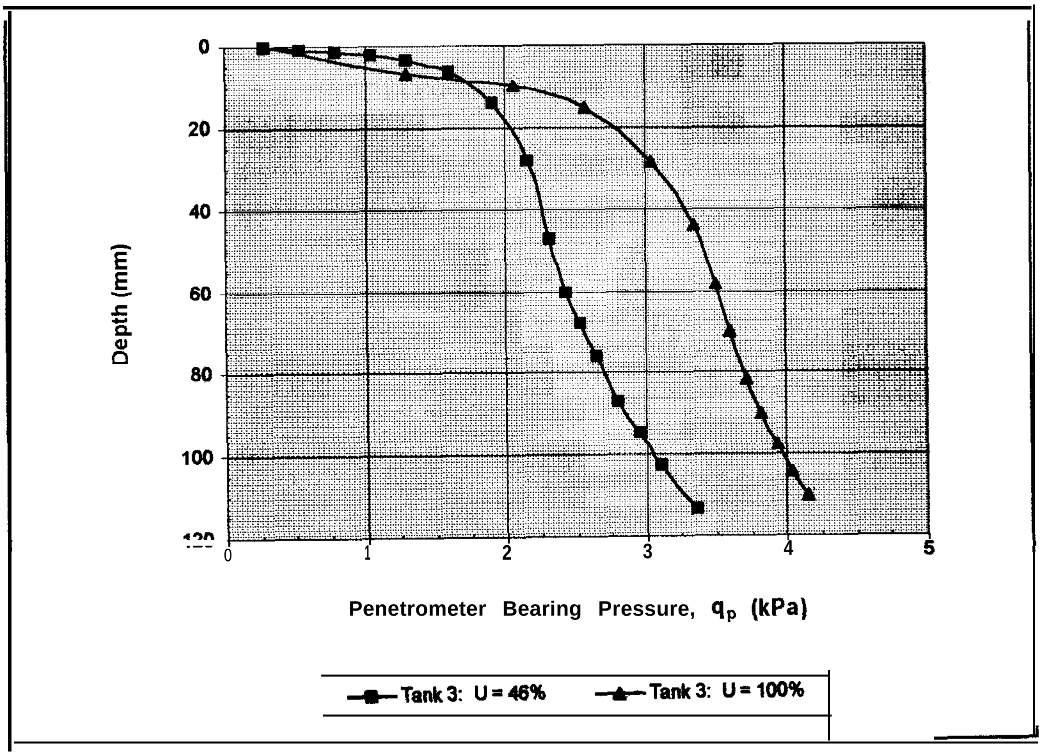

Figure 2b. Atlantic Mud, 90% Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

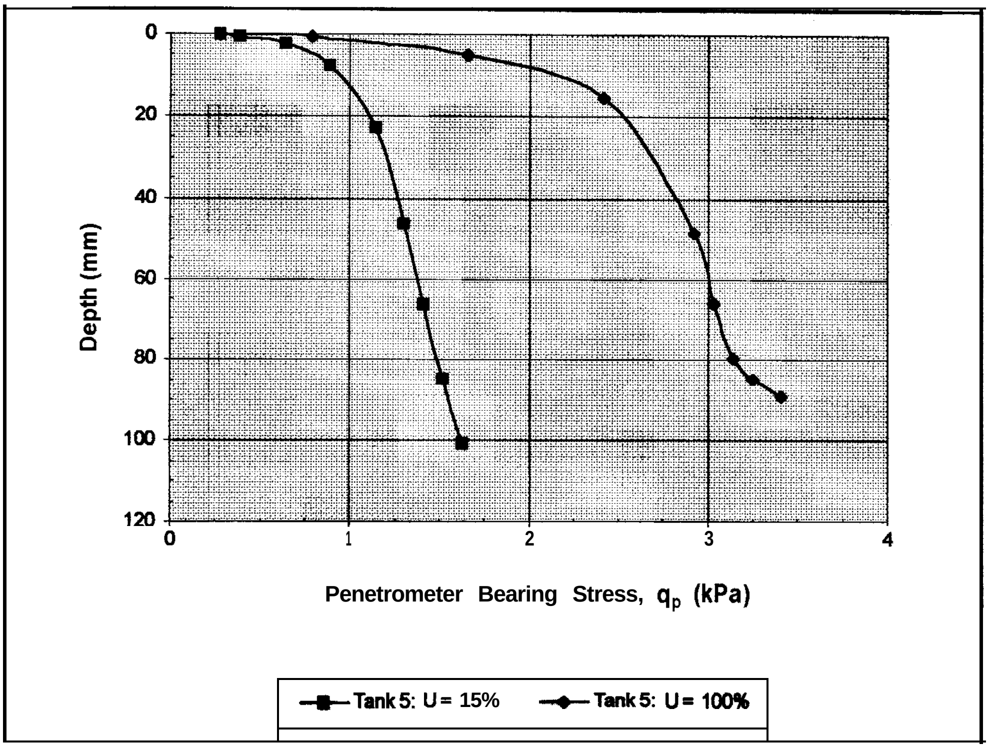

Figure 2c. Atlantic Mud, 99% Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

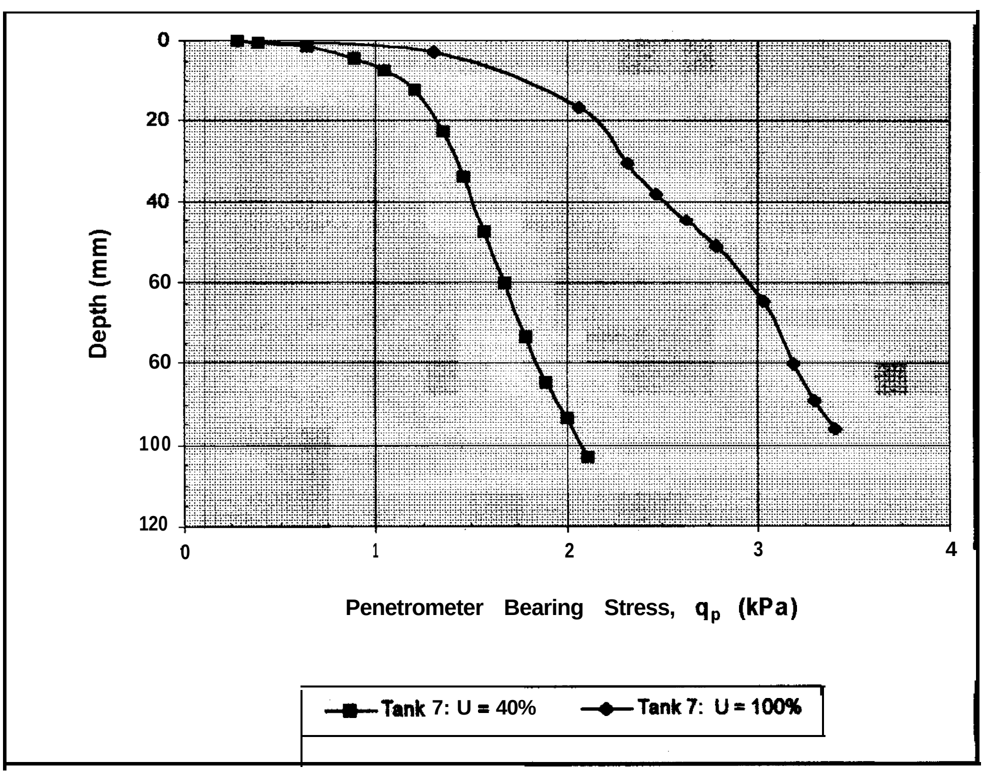

Figure 2d. Atlantic Mud, 99% Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

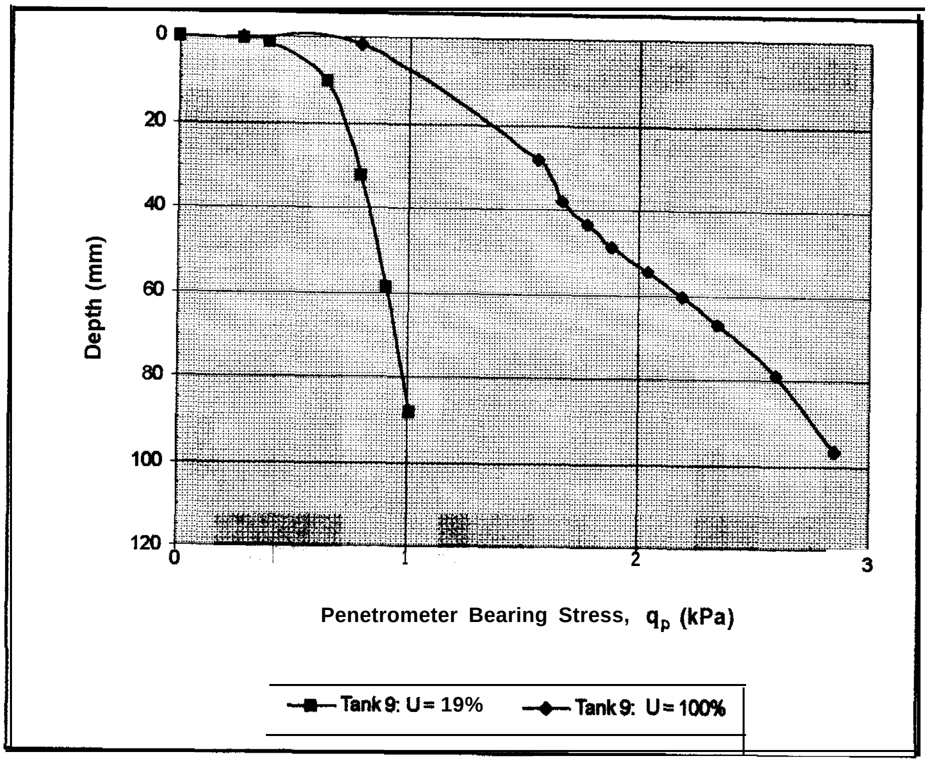

Figure 2e. Atlantic Mud, 107% Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

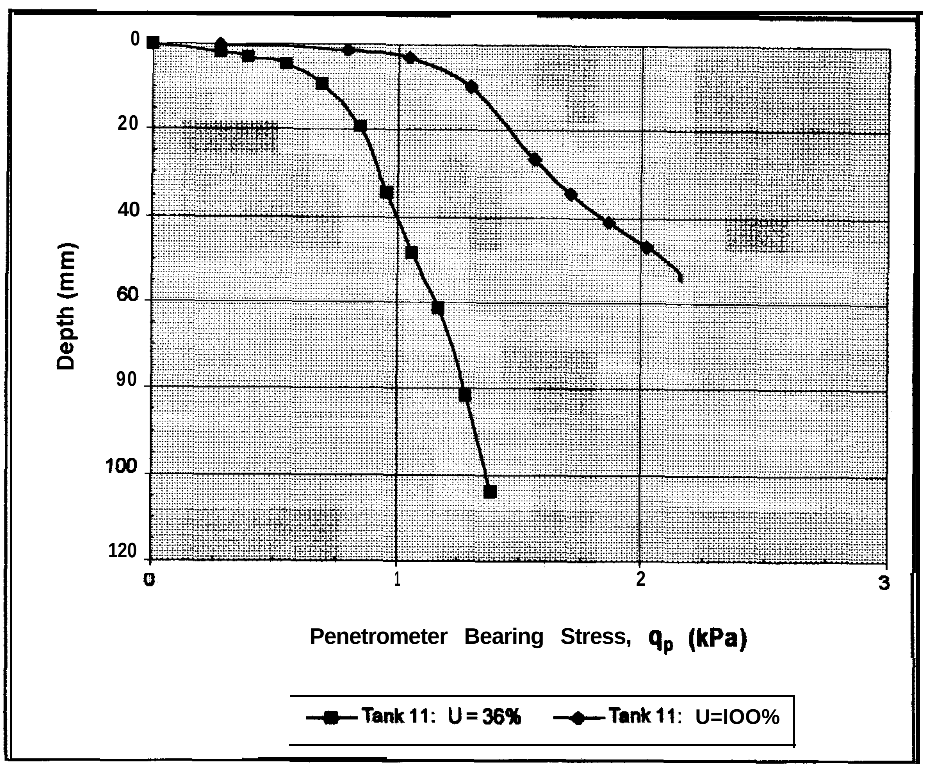

Figure 2f. Atlantic Mud, 107% Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

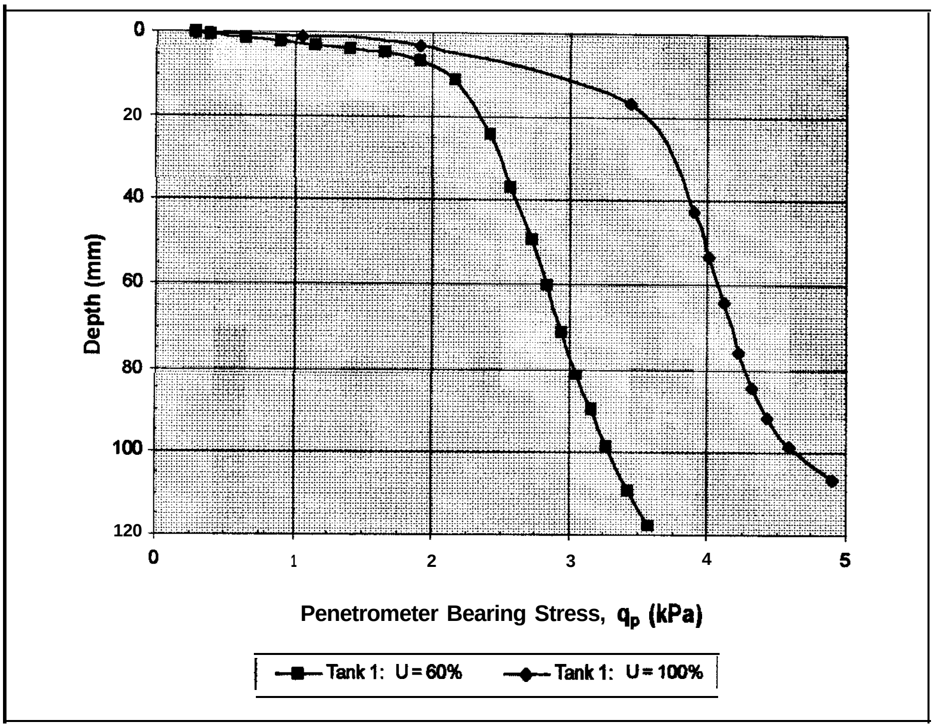

Figure 3a. North Sea Soil, 87% Initial Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

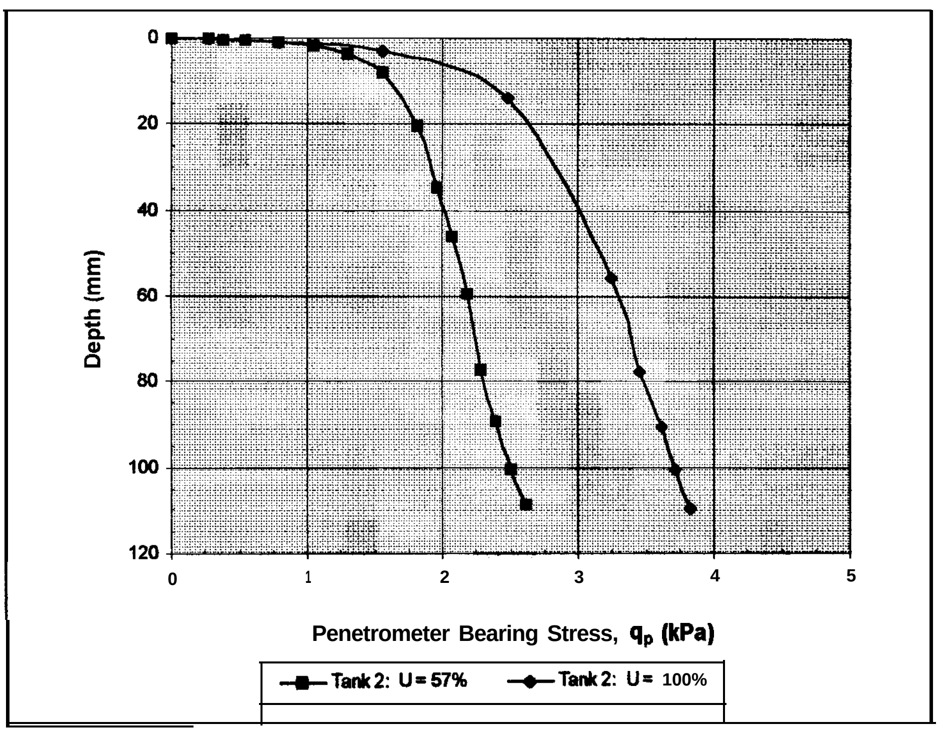

Figure 3b. North Sea Soil, 76% Initial Water Content: Undrained Penetrometer Bearing Stress Profiles Comparing Partially and Fully Consolidated Cases

APPENDIX D: UNDRAINED SHEAR STRENGTH CHARTS

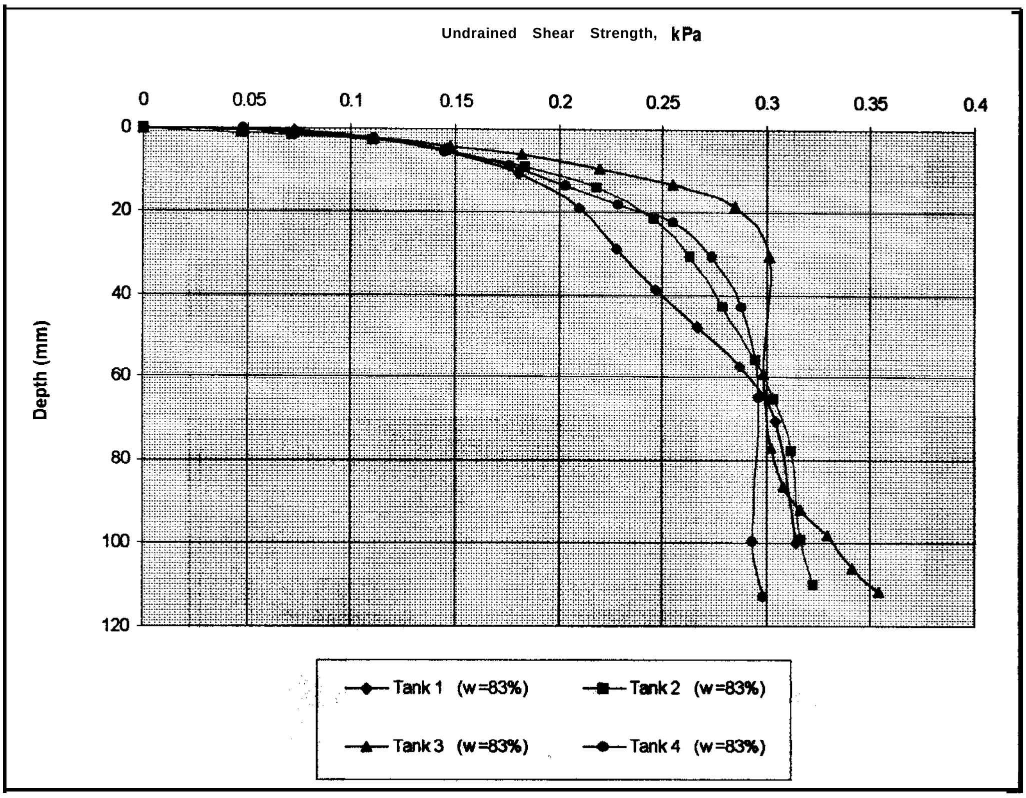

Figure la. Undrained Shear Strength Profiles, E-grade Kaolin, Initial Water Content 83%

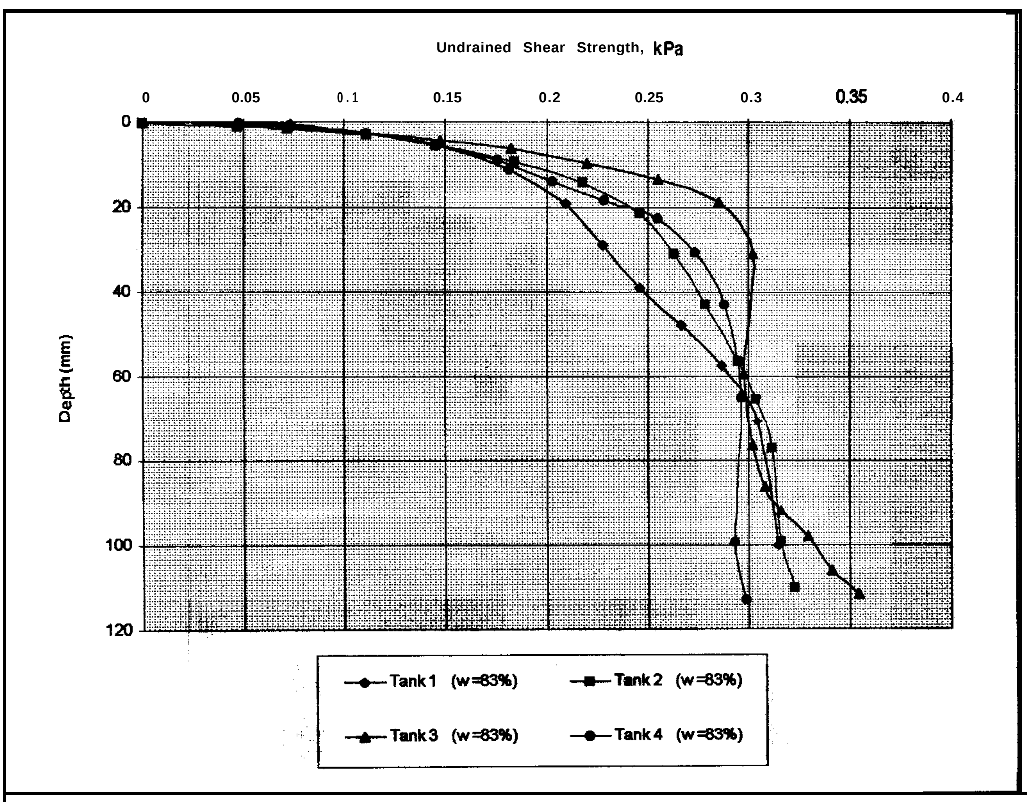

Figure 1 b. Undrained Shear Strength Profiles, E-grade Kaolin, Initial Water Content 98%

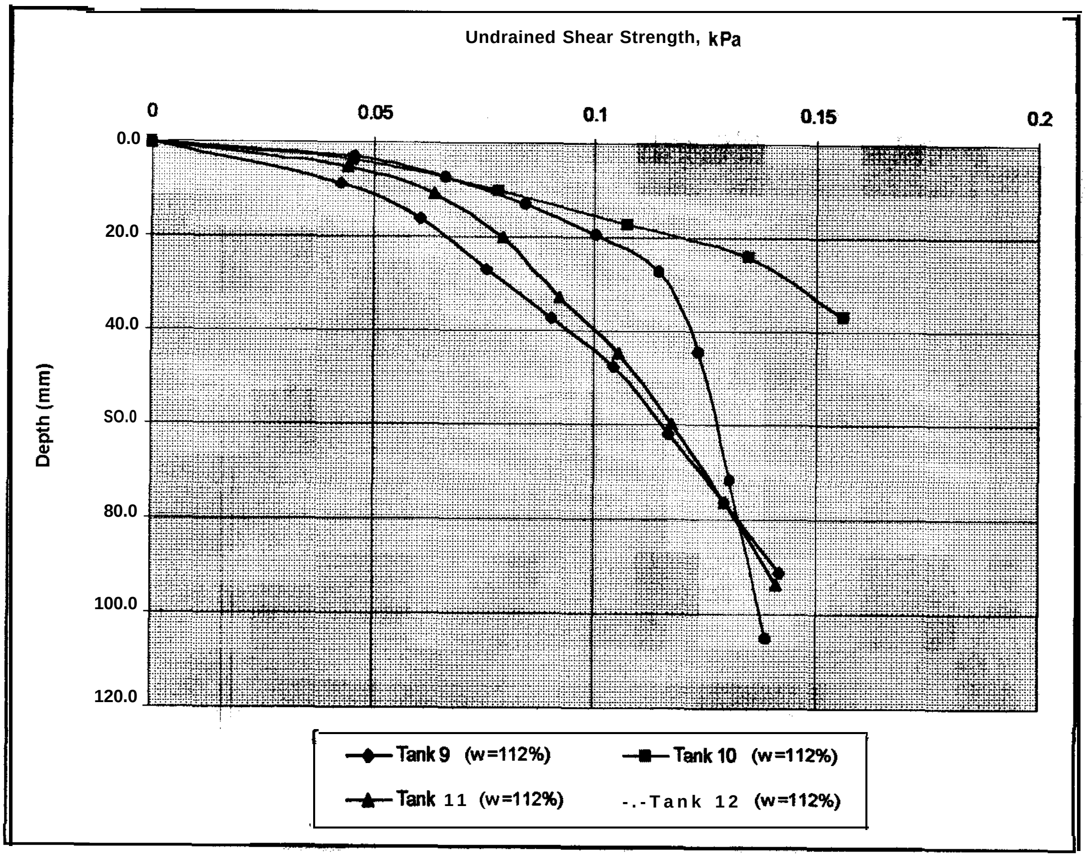

Figure Ic. Undrained Shear Strength, E-grade Kaolin, Initial Water Content = 112%

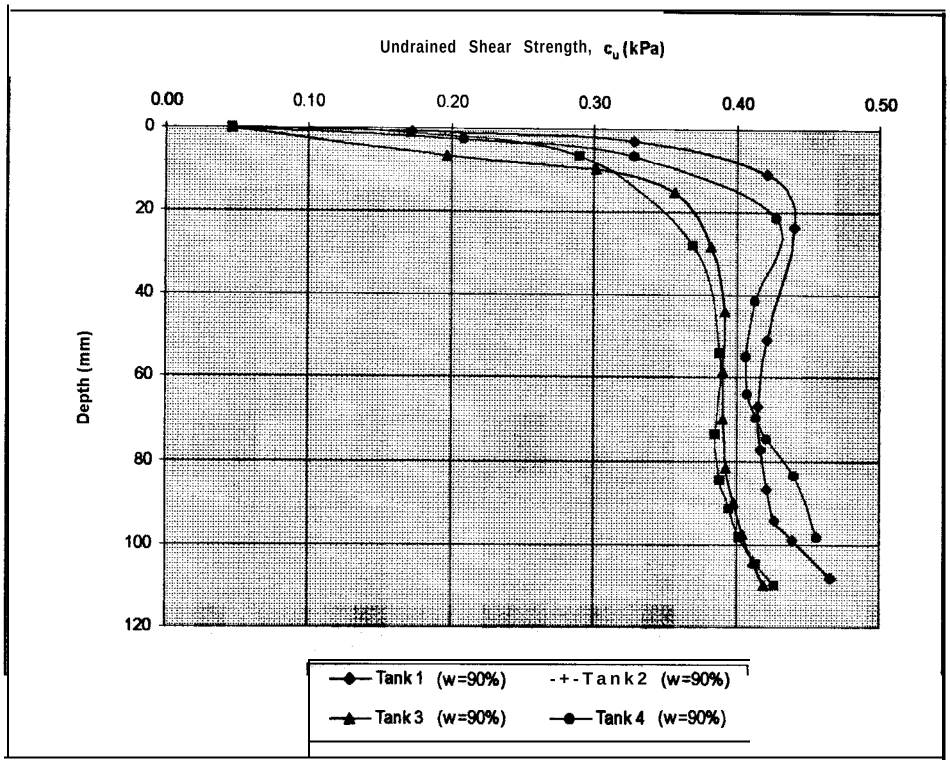

Figure 2a. Undrained Shear Strength Profiles for Atlantic Mud, Final Water Content 81%

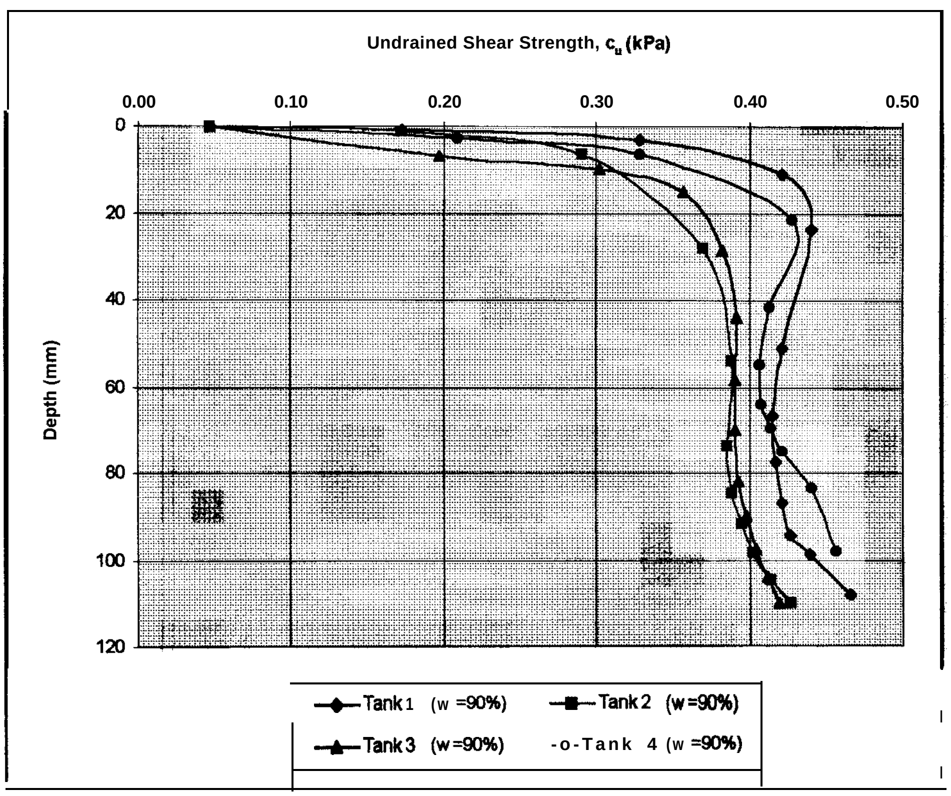

Figure 2b. Undrained Shear Strength Profiles for Atlantic Mud, Final Water Content 86%

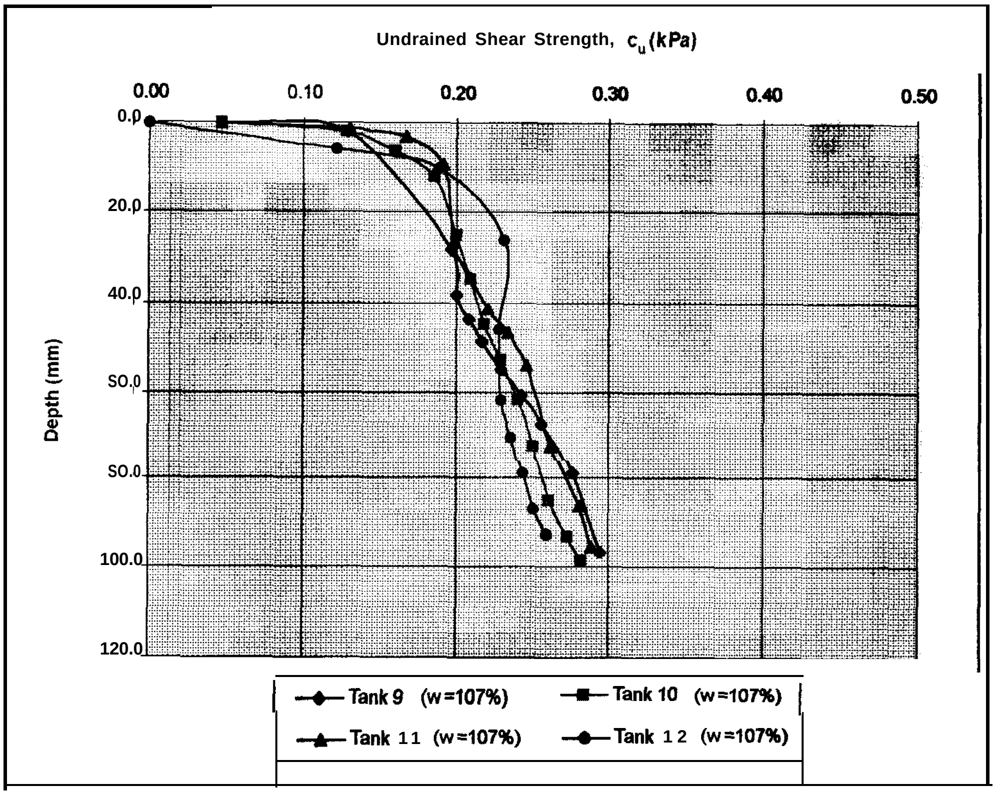

Figure 2c. Undrained Shear Strength Profiles for Atlantic Mud, Final Water Content 94%

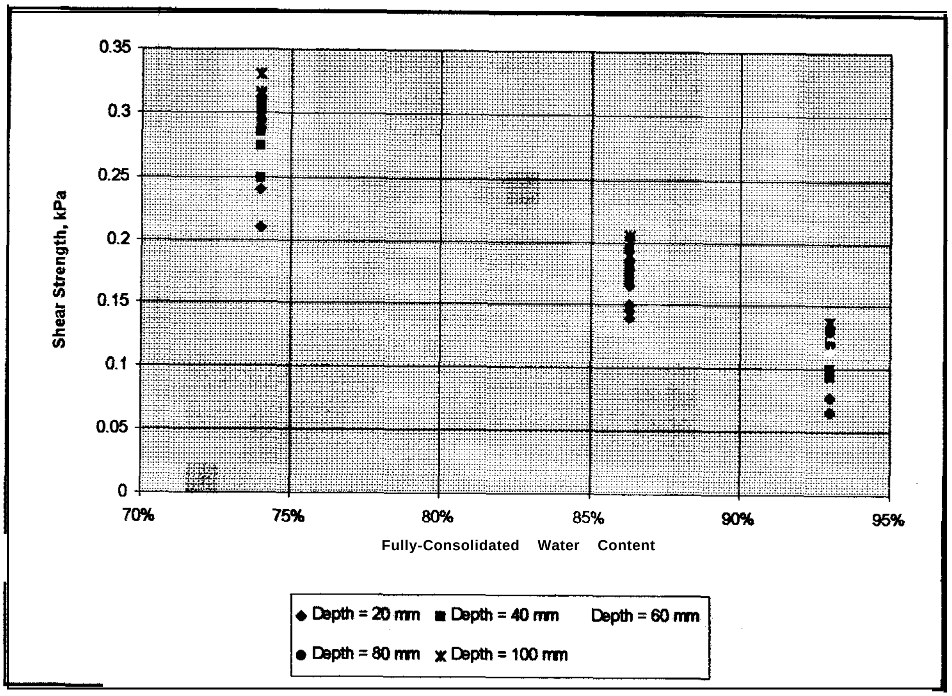

Figure 3a. Shear Strength vs. Fully-Consolidated Water Content at Various Depths, E-grade Kaolin

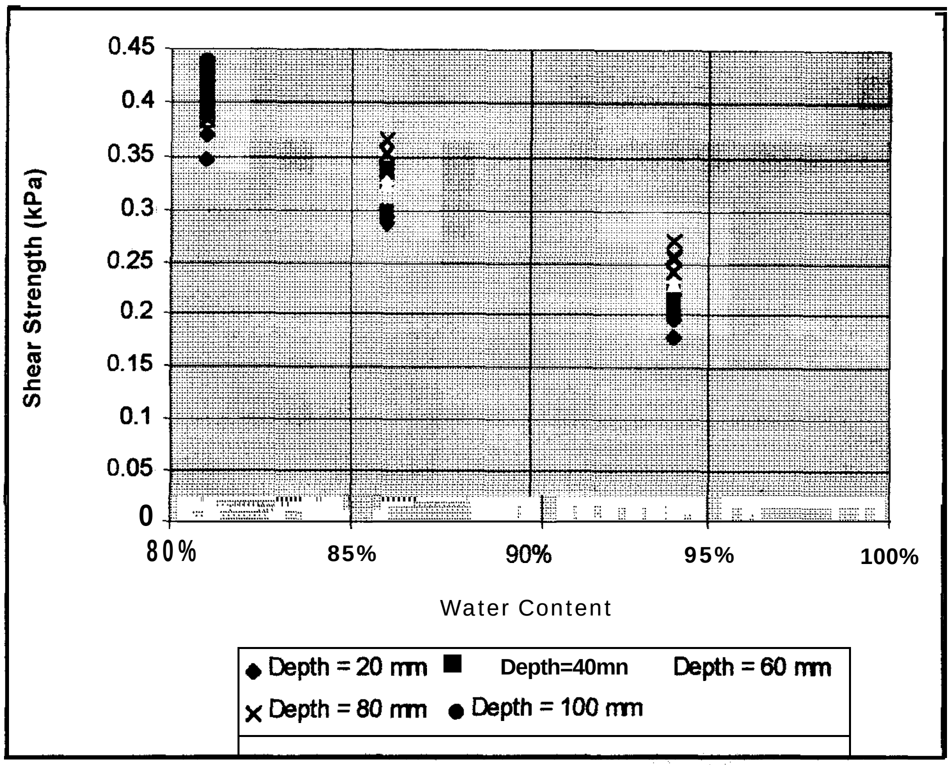

Figure 3b. Shear Strength vs. Fully-Consolidated Water Content at Various Depths, Atlantic Mud

APPENDIX E: DRAINED PENETROMETER PROFILES

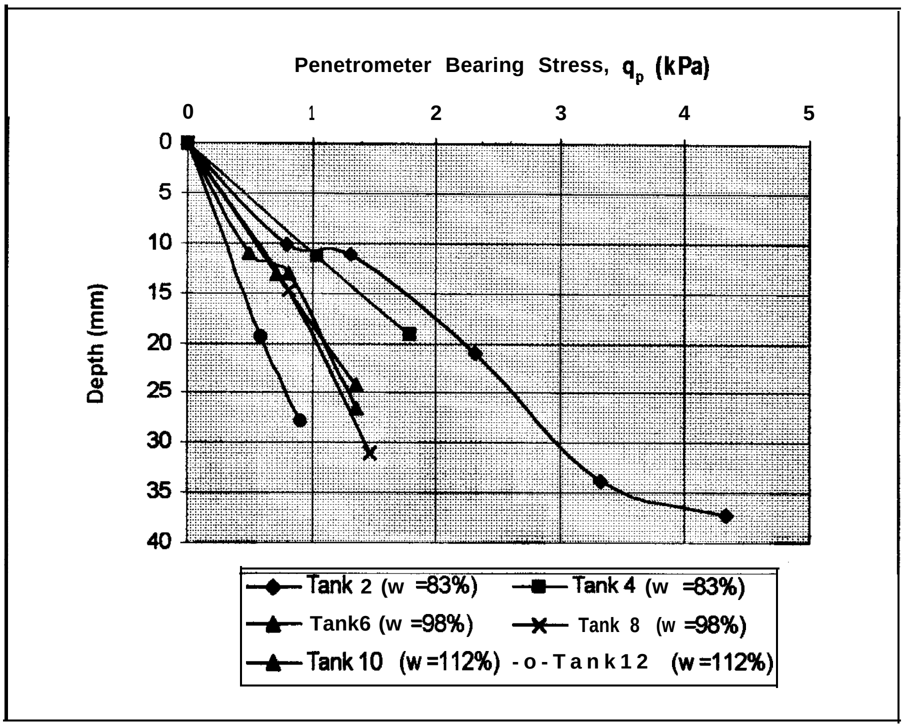

Figure la. Drained Penetrometer Profiles, E-grade Kaolin

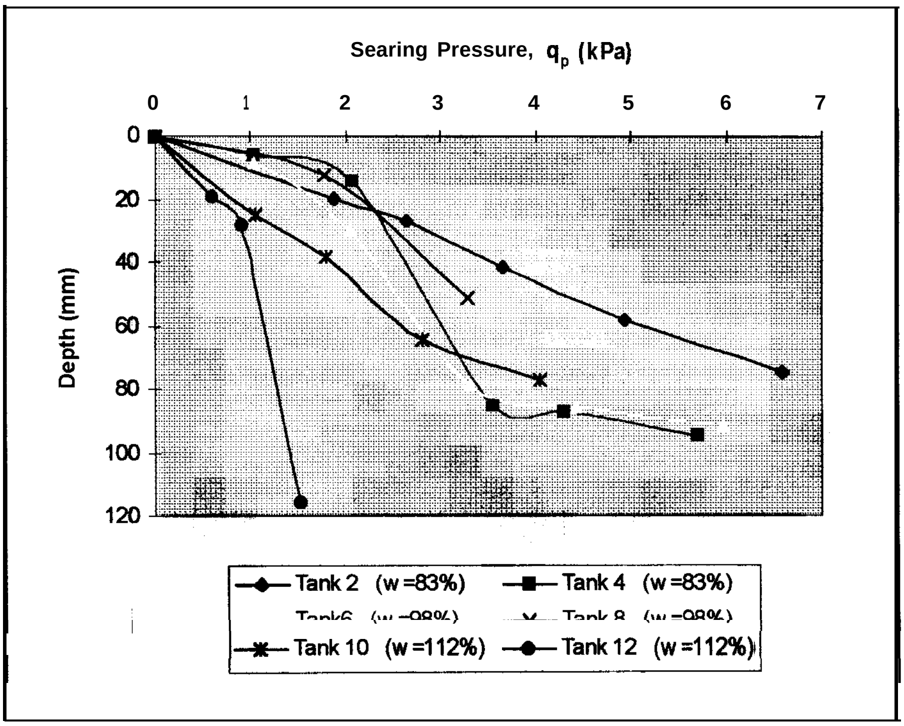

Figure 1 b. Drained Penetrometer Profiles, Atlantic Mud

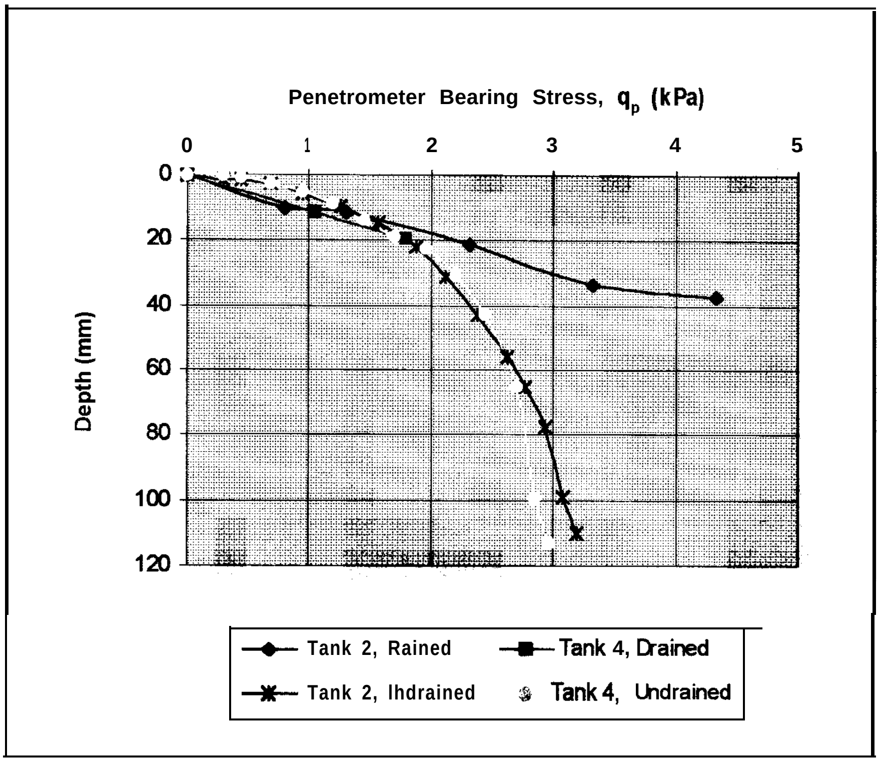

Figure 2a. Drained and Undrained Penetrometer Profiles, E-grade Kaolin, 83%

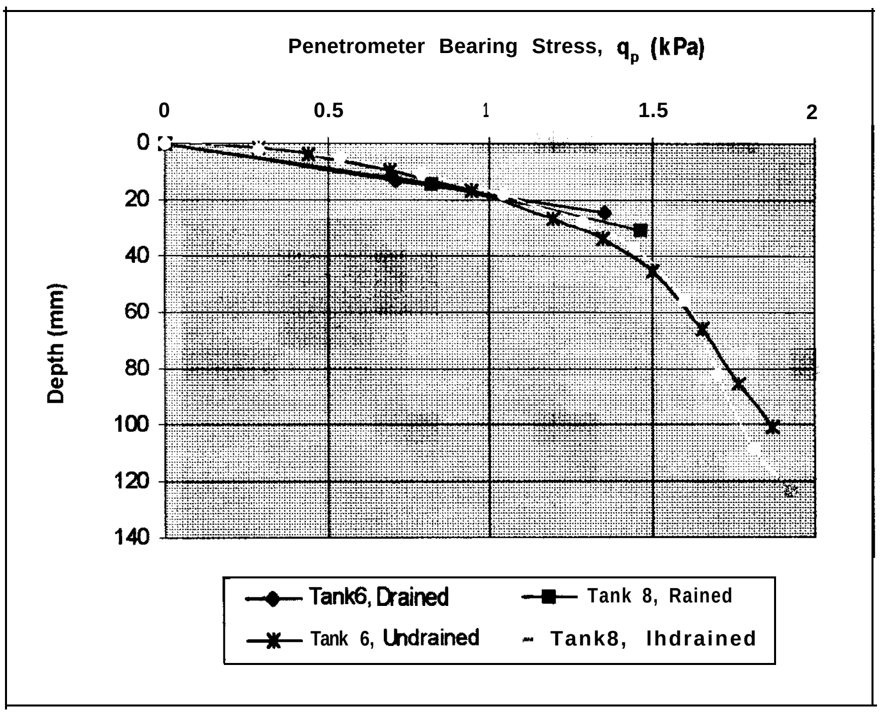

Figure 2b. Drained and Undrained Penetrometer Profiles, E-grade Kaolin, 98%

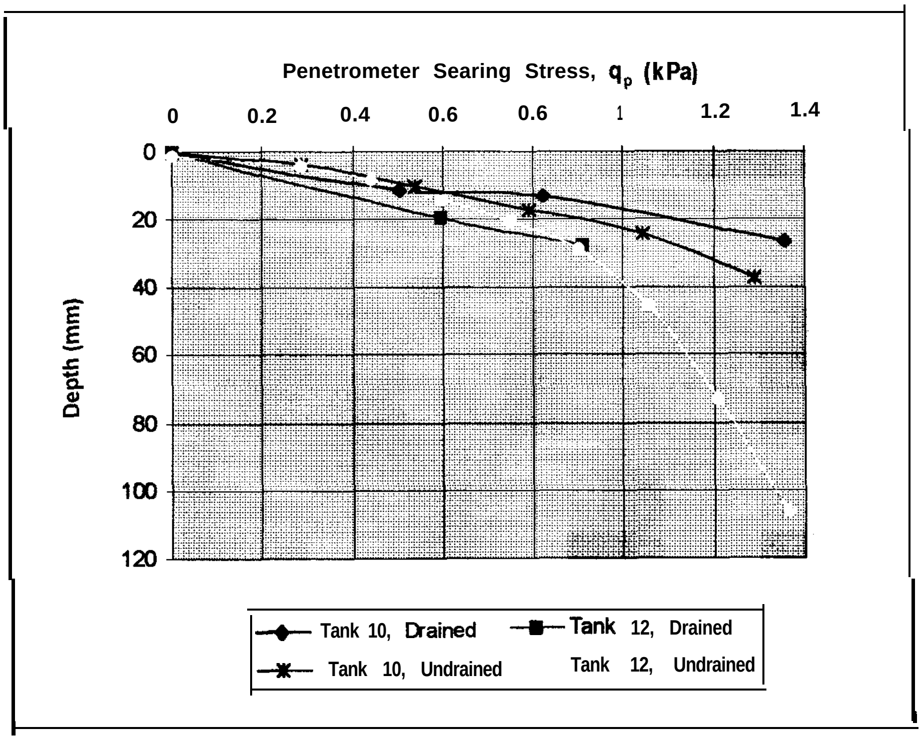

Figure 2c. Drained and Undrained Penetrometer Profiles, E-grade Kaolin, 112%

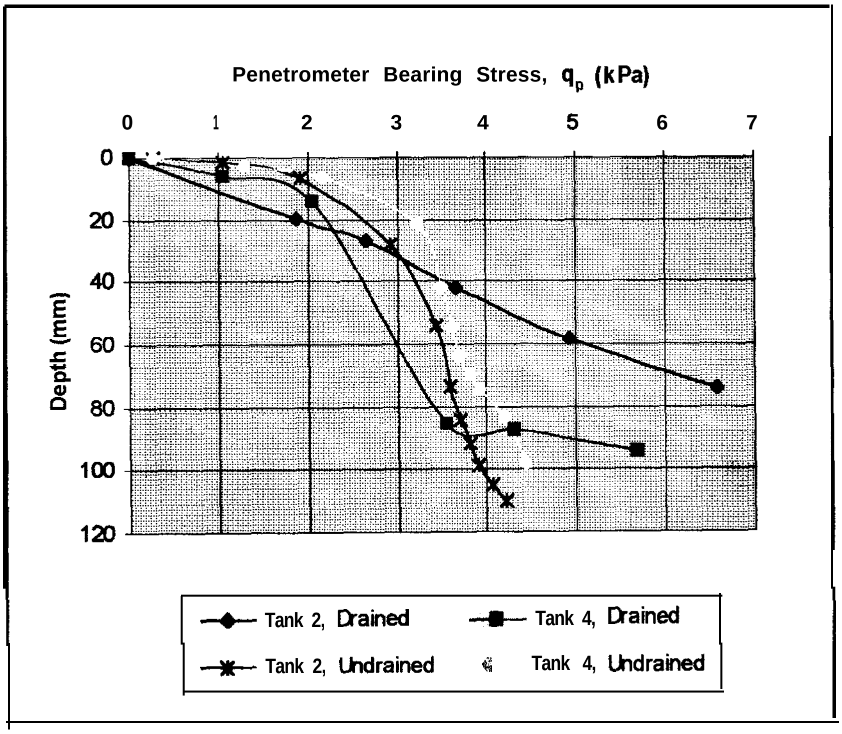

Figure 3a. Undrained and Drained Penetrometer Profiles, Atlantic Mud, 90%

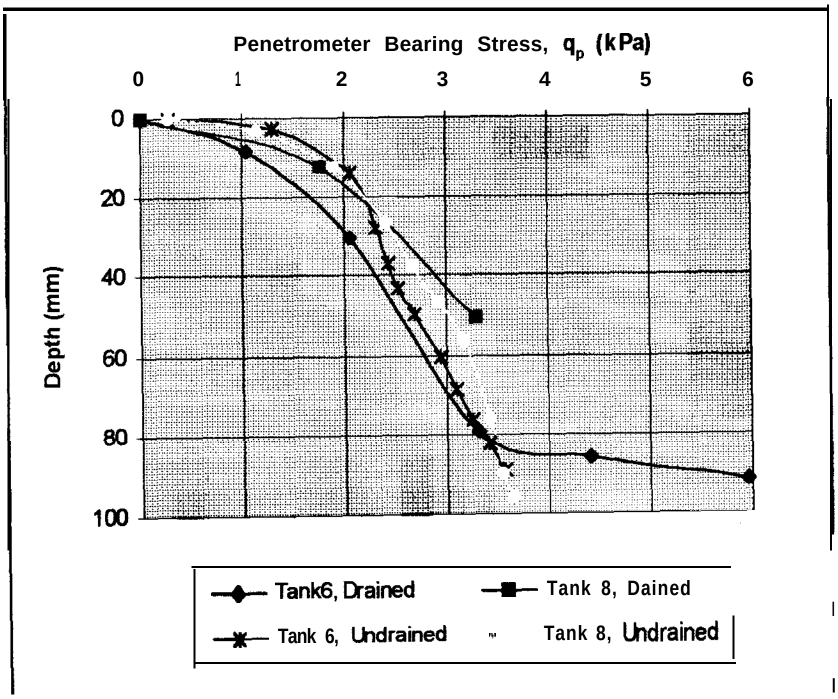

Figure 3b. Drained and Undrained Penetrometer Profiles, Atlantic Mud, 99%

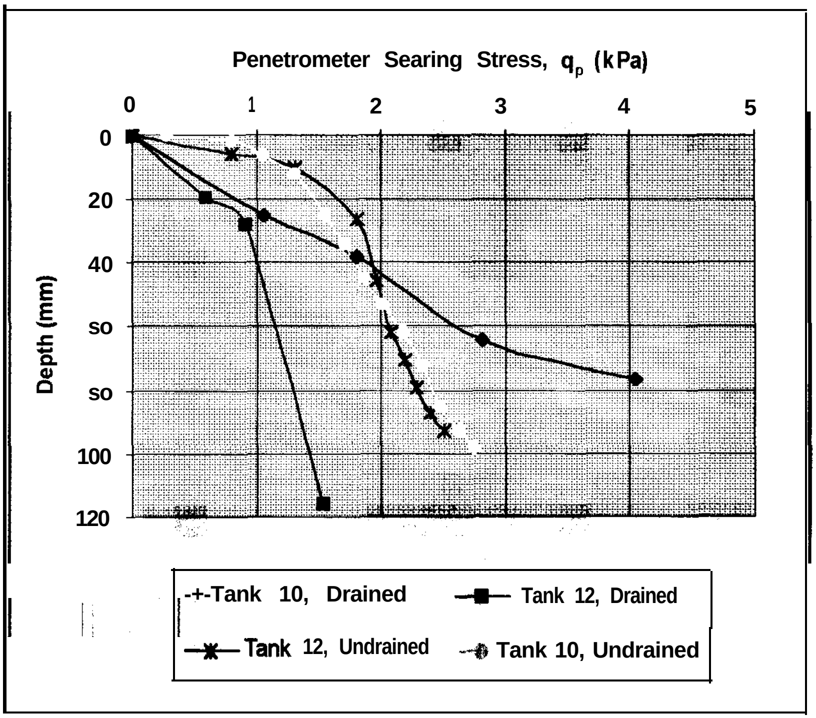

Figure 3c. Drained and Undrained Penetrometer Profiles, Atlantic Mud, 107%

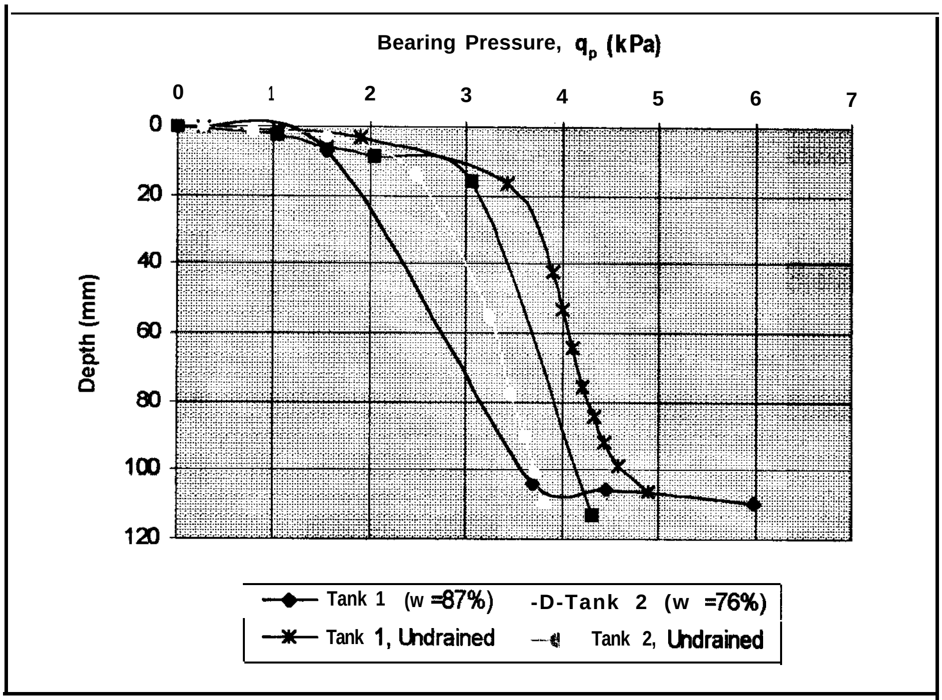

Figure 4a. Drained and Undrained Penetrometer Profiles, North Sea Soil

APPENDIX F: SENSITIVITY AND THIXOTROPIC REGAIN CHARTS

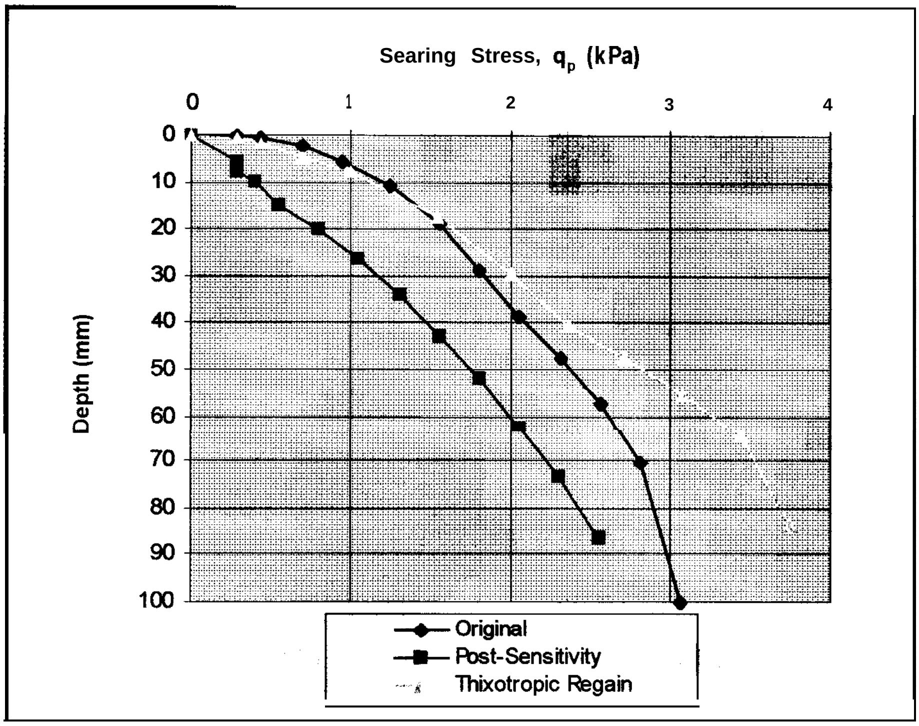

Figure la. Sensitivity and Thixotropic Regain, Tank 1, E-grade Kaolin, w = 74%

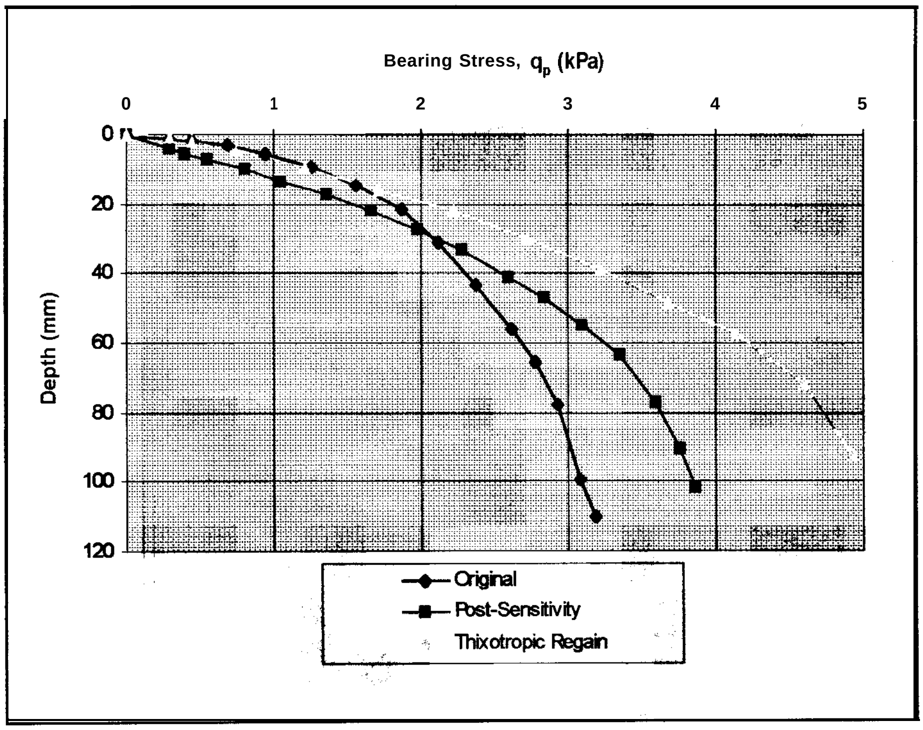

Figure lb. Sensitivity and Thixotropic Regain, Tank 2, E-grade Kaolin, w = 74%

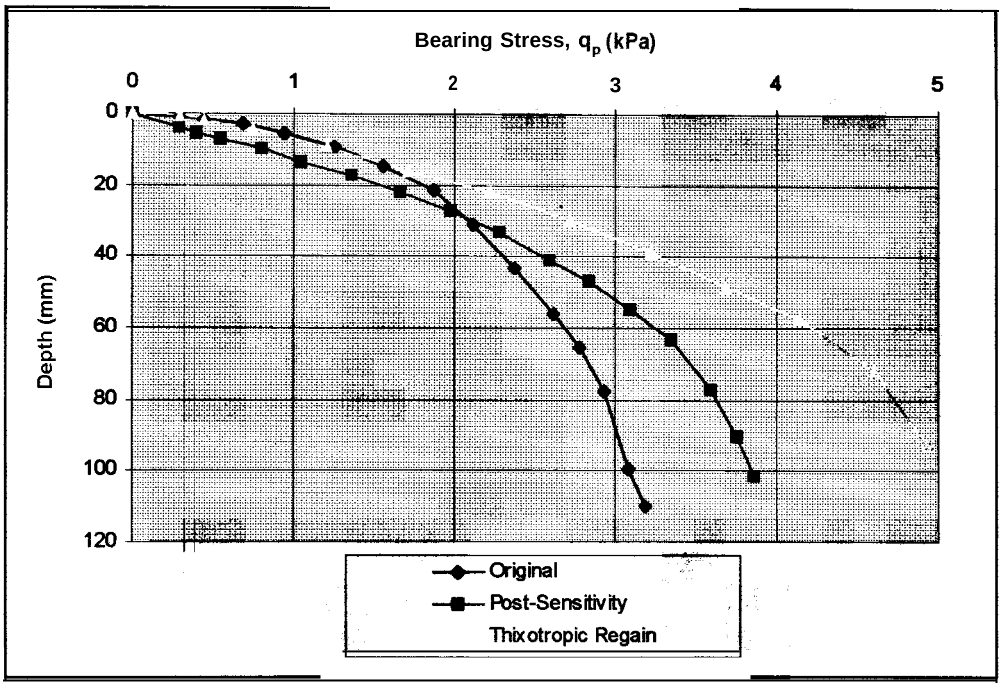

Figure Ic. Sensitivity and Thixotropic Regain, Tank 5, E-grade Kaolin, w = 86%

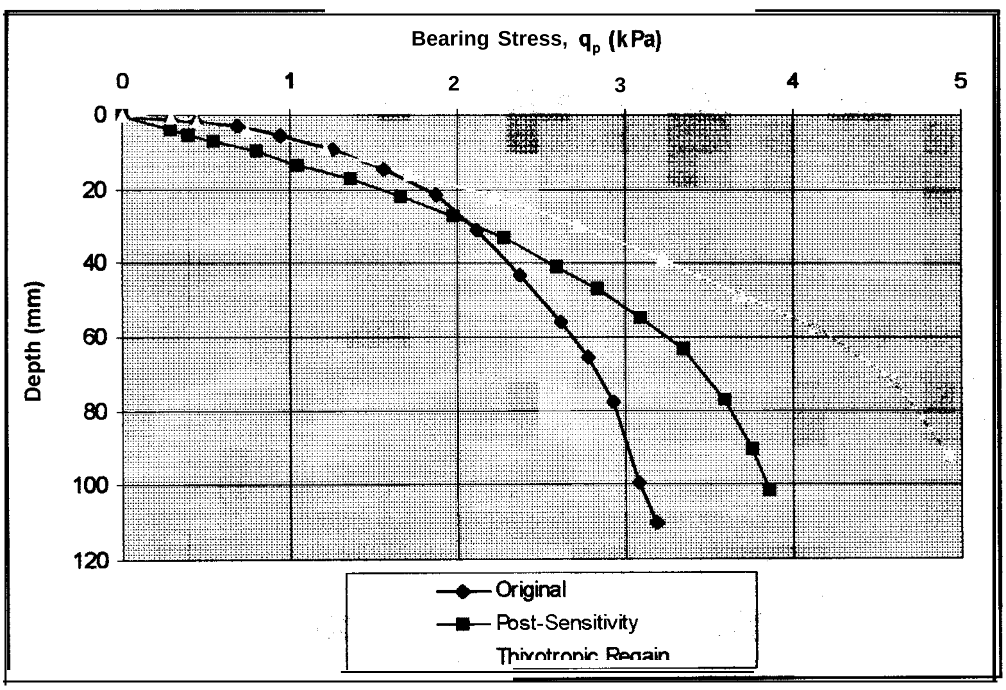

Figure Id. Sensitivity and Thixotropic Regain, Tank 6, E-grade Kaolin, w = 86%

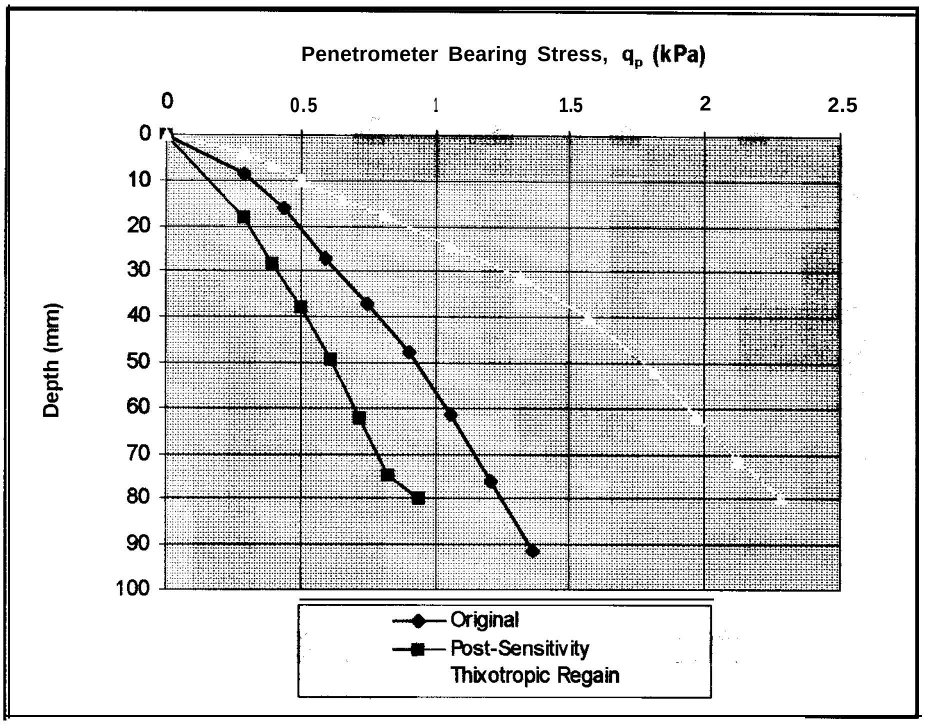

Figure le. Sensitivity and Thixotropic Regain, Tank 9, E-grade Kaolin, w = 93%

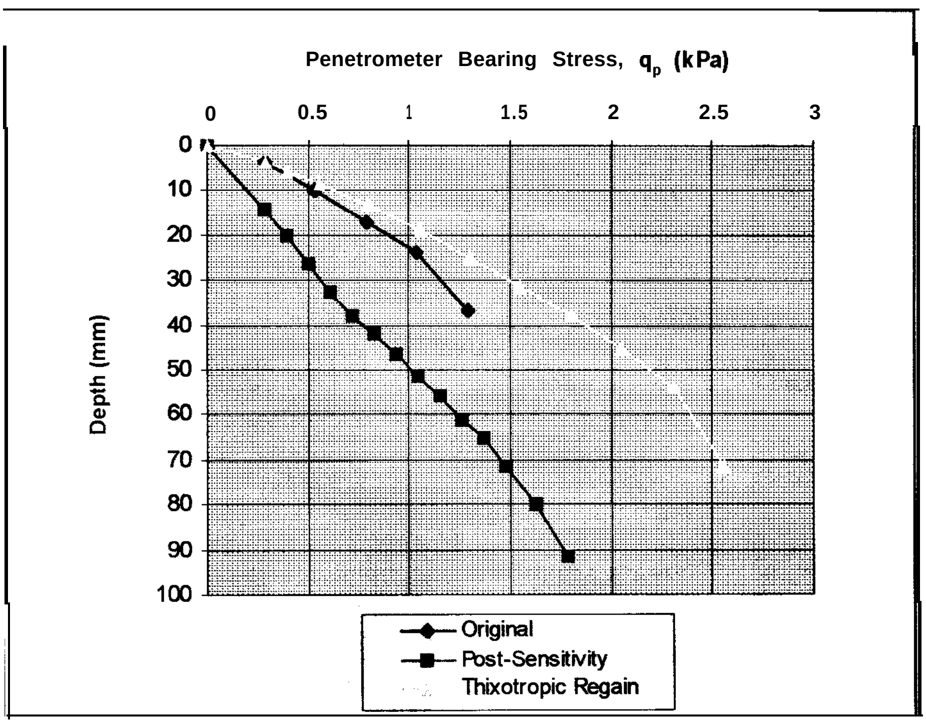

Figure If. Sensitivity and Thixotropic Regain, Tank 11, E-grade Kaolin, w = 93%

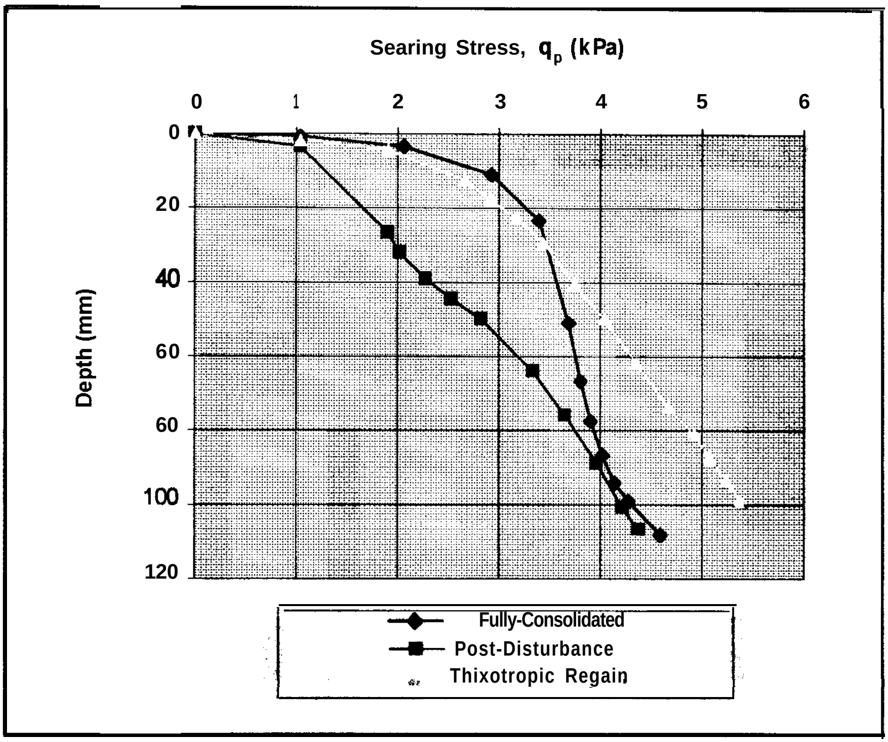

Figure 2a. Sensitivity and Thixotropic Regain, Tank 1, Atlantic Mud, w = 81%

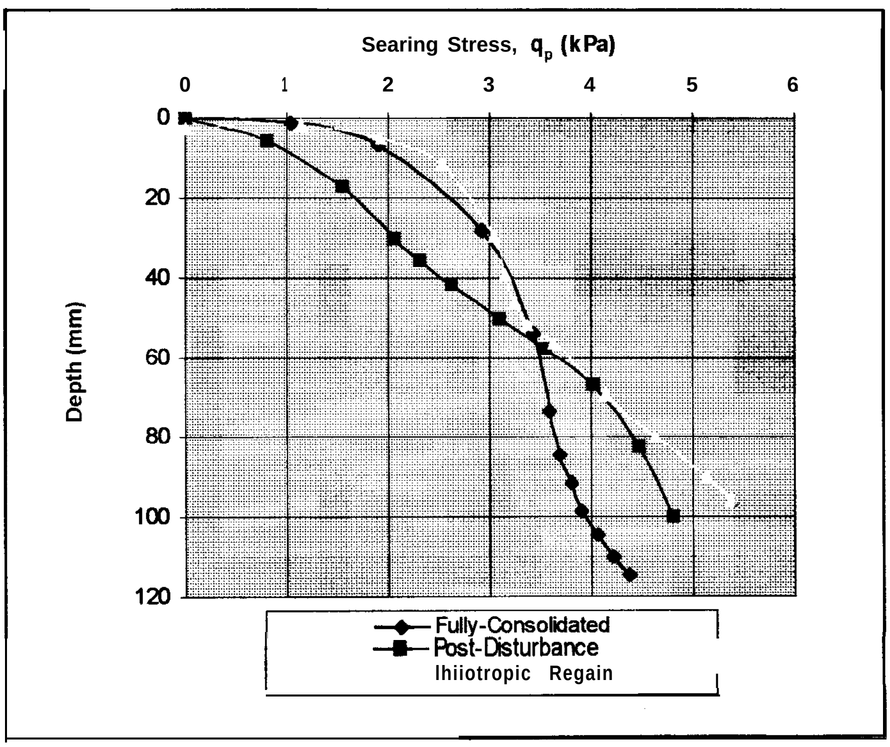

Figure 2b. Sensitivity and Thixotropic Regain, Tank 2, Atlantic Mud, w = 81%

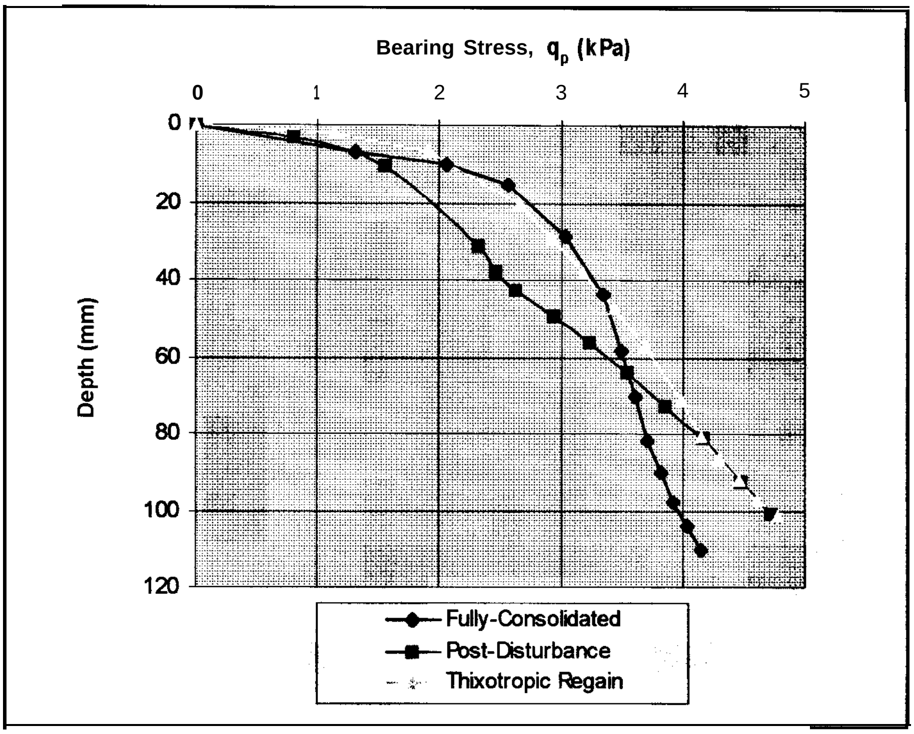

Figure 2c. Sensitivity and Thixotropic Regain, Tank 3, Atlantic Mud, w = 81%

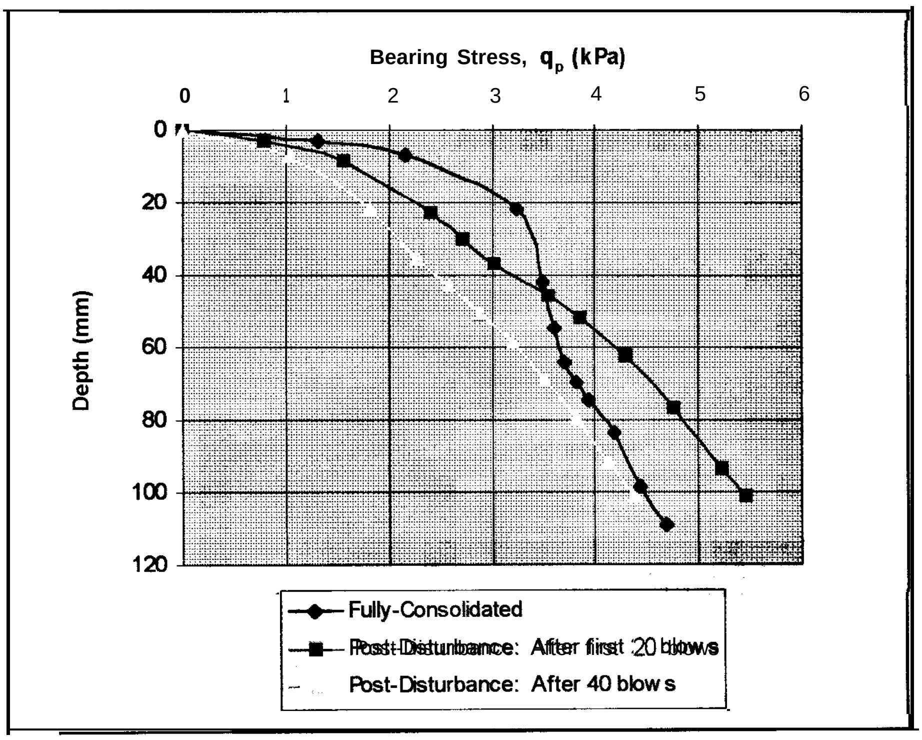

Figure 2d. Sensitivity and Thixotropic Regain, Tank 4, Atlantic Mud, w = 81%

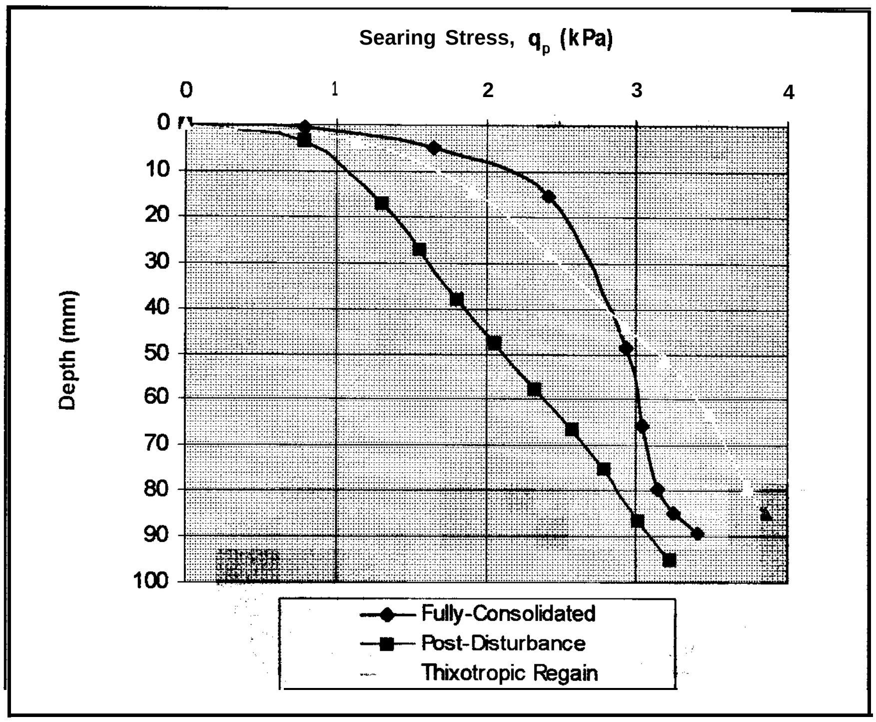

Figure 2e. Sensitivity and Thixotropic Regain, Tank 5, Atlantic Mud, w = 86%

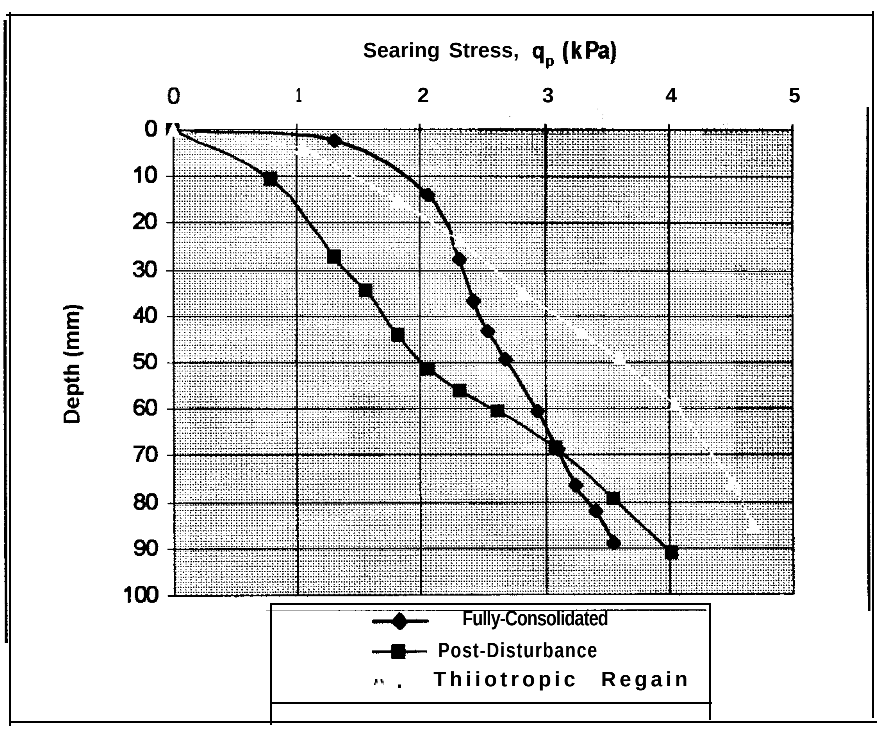

Figure 2f. Sensitivity and Thixotropic Regain, Tank 6, Atlantic Mud, w = 86%

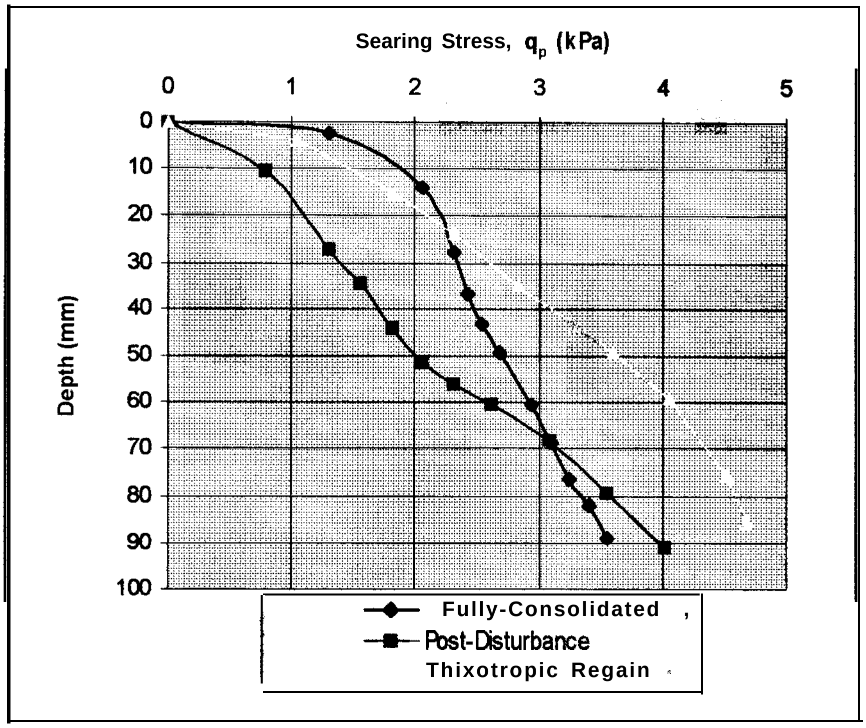

Figure 2g. Sensitivity and Thixotropic Regain, Tank 7, Atlantic Mud, w = 86%

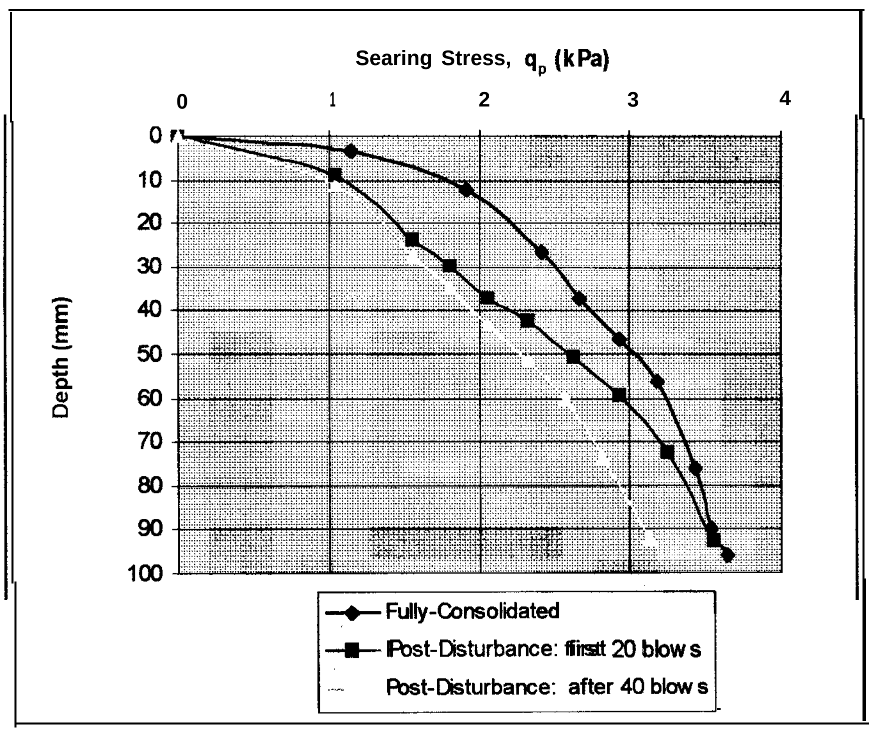

Figure 2h. Sensitivity and Thixotropic Regain, Tank 8, Atlantic Mud, w = 86%

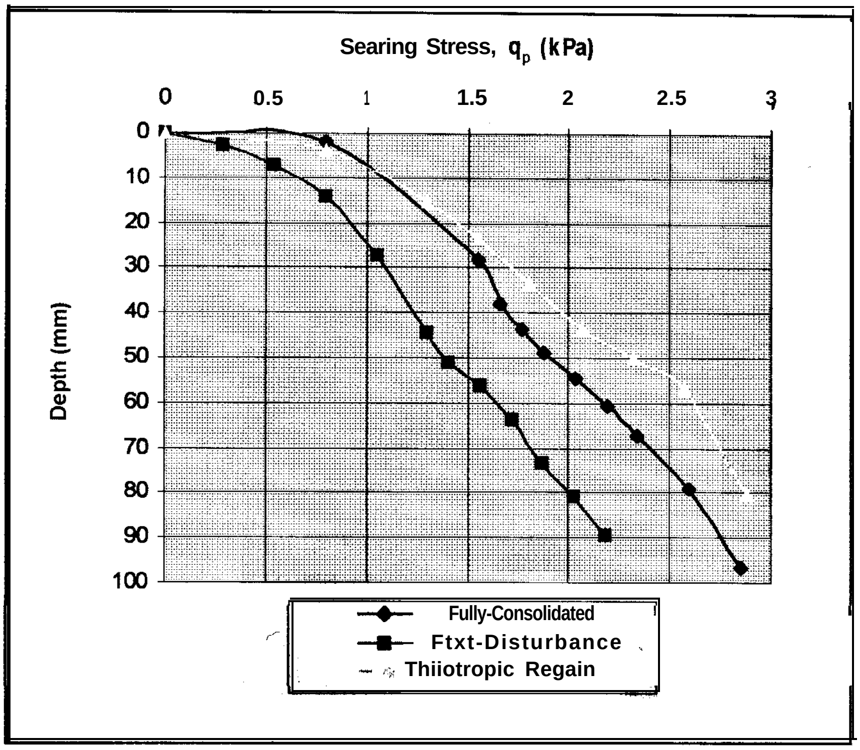

Figure 2i. Sensitivity and Thixotropic Regain, Tank 9, Atlantic Mud, w = 94%

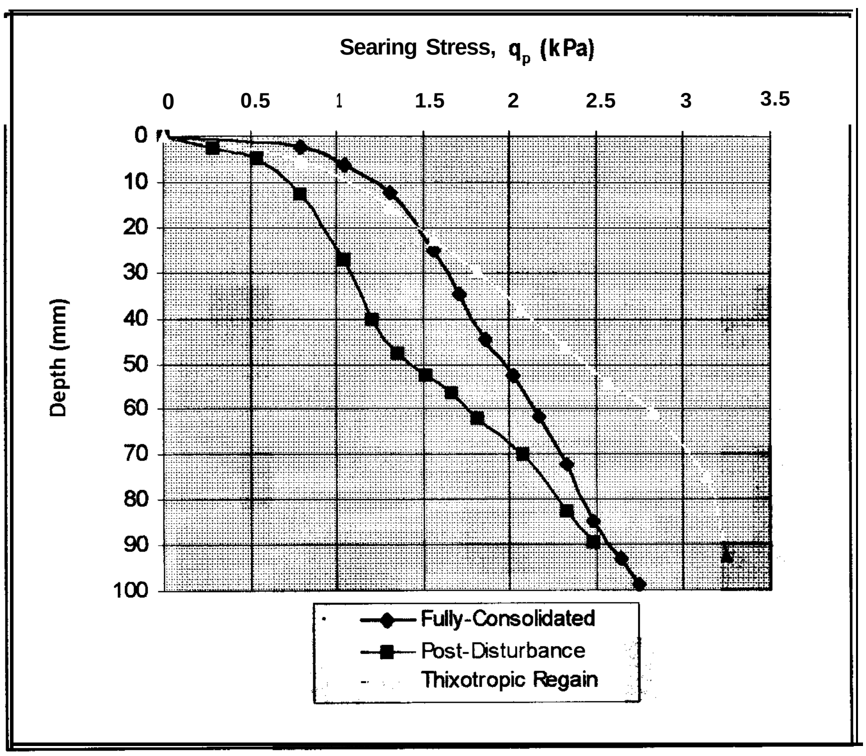

Figure 2j. Sensitivity and Thixotropic Regain, Tank 10, Atlantic Mud, w = 94%

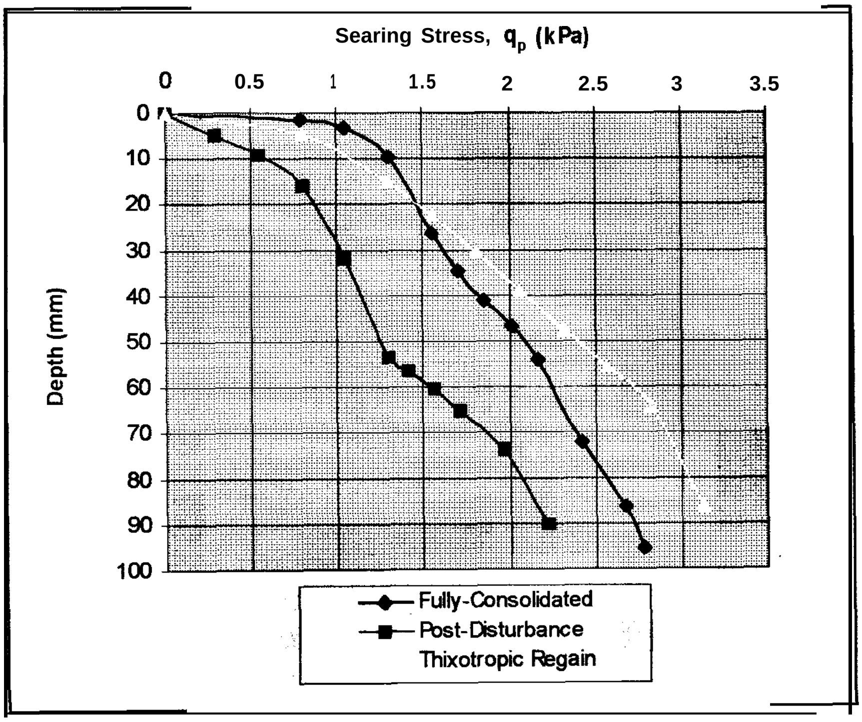

Figure 2k. Sensitivity and Thixotropic Regain, Tank 11, Atlantic Mud, w = 94%

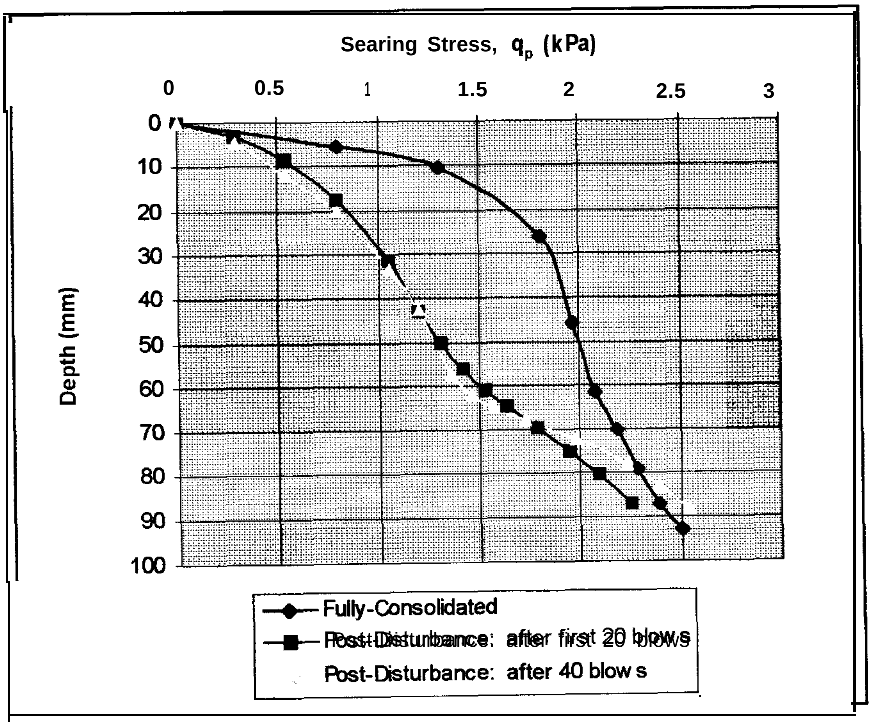

Figure 21. Sensitivity and Thixotropic Regain, Tank 12, Atlantic Mud, w = 94%

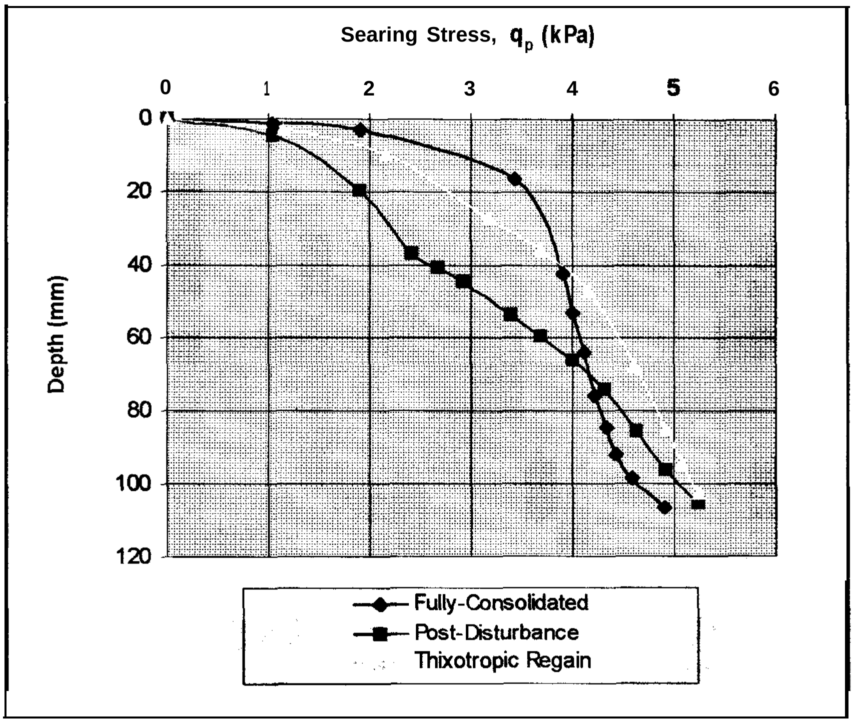

Figure 3a. Sensitivity and Thixotropic Regain, Tank 1, Galley Soil, w = 67%

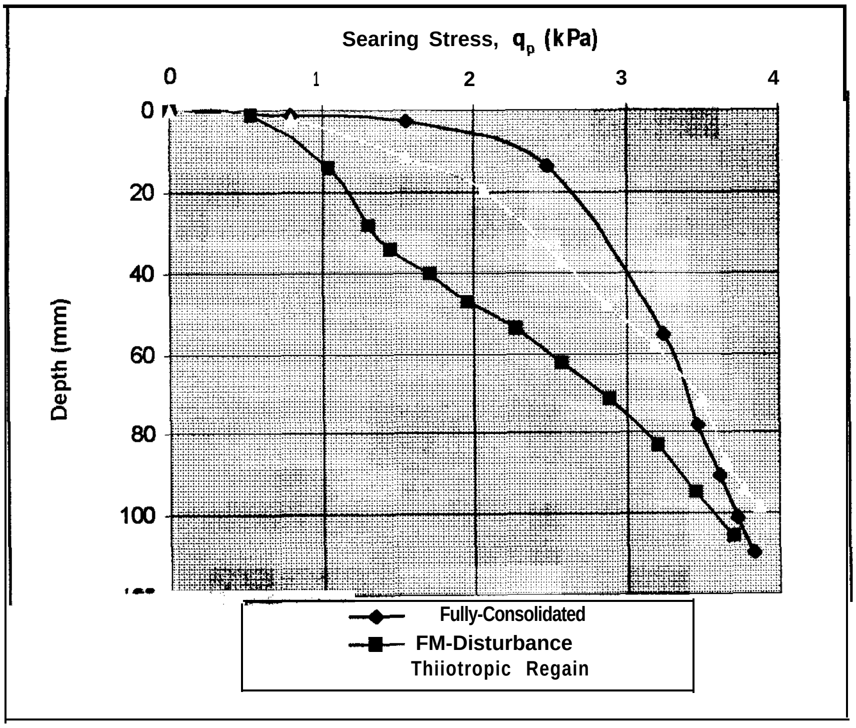

Figure 3b. Sensitivity and Thixotropic Regain, Tank 2, Galley Soil, w = 72%

Table 1. Effects of Rate of Blow Application on Sensitivity Index, Atlantic Mud

	Sensitivity Index, 20 mm	Sensitivity Index, 80 mm
w = 81%		
20 blows/20 sec*	1.53	0.82
20 blows/35 sec†	1.76	1.03
SI(fast)/SI(slow)	0.87	0.80
w = 88%		
20 blows/20 sec**	1.69	1.14
20 blows/35 sec††	1.82	1.08
SI(fast)/SI(slow)	0.93	1.06
w = 94%		
20 blows/20sec***	1.68	1.24
20 blows/35 sec†††	1.72	1.10
SI(fast)/SI(slow)	0.97	1.12

* Tank2
** Tank7
***Tank 11
† Average of Tanks 1, 3, and 4
†† Average of Tanks 5, 6, and 8
††† Average of Tanks 9, 10, and 12

Table 2. Effect of Number of Blows on Sensitivity Index, Atlantic Mud

	w = 81%	w = 86%	w = 94%
$SI_{(20\ blows)}/SI_{(40\ blows)}$, 20 mm depth	0.79	0.93	0.95
$SI_{(20\ blows)}/SI_{(40\ blows)}$, 80 mm depth	0.75	0.86	1.1