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THE EFFECT OF BENTONITIC SLURRY ON DRILLED SHAFTS

by

Karen L. Tucker
Lymon C. Reese

Research Report Number 351-1F

Research Study 3-5-83-351

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Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH

BUREAU OF ENGINEERING RESEARCH

THE UNIVERSITY OF TEXAS AT AUSTIN

July 1984

PREFACE

This report presents the results of laboratory and field studies of the effect of bentonitic slurry on drilled shafts. Suggestions are made regarding construction procedures and slurry specifications.

The authors wish to thank the State Department of Highways and Public Transportation for their sponsorship of the work and to express their appreciation for the assistance given by many members of their staff. Appreciation is also expressed to Farmer Foundation Company for their assistance and many suggestions throughout the project. Lola Williams and Linda Iverson provided support in the office for both field testing and manuscript preparation.

Karen L. Tucker
Lymon C. Reese

July 1984

ABSTRACT

A series of laboratory and field studies were performed to determine the effect of bentonitic slurry on drilled shafts. Suggestions for construction procedures and slurry specifications are made. When such procedures are followed, no adverse effects have resulted.

SUMMARY

This study concerns the effect of bentonitic slurry on drilled shafts. Studies were performed in the laboratory and in the field. The build up of filter cake in the field was found to be much less than in the laboratory. In addition, construction of drilled shafts using reverse circulation was found to produce a shaft with a uniform diameter.

Suggestions are made regarding proper construction procedures and slurry specifications.

IMPLEMENTATION STATEMENT

This study presents construction procedures and slurry specifications for drilled shafts constructed using bentonitic slurry. Periodic testing of the slurry is an integral part of the specifications.

It is suggested that calipers be used to monitor shaft profiles. In that way, any caving or enlarging of the shaft can be detected.

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CHAPTER 1. INTRODUCTION

Use of Bentonite

In the past few decades, the construction industry has borrowed technology from the petroleum industry, primarily in the usage of bentonitic slurry as a drilling aid. In drilled-shaft construction, the slurry is used to stabilize the shaft during and after drilling and, at times, to circulate cuttings out of the shaft during drilling. Sodium montmorillonite, such as is found in Wyoming, U.S.A., is the base from which bentonitic slurry is formed. The plate-like particles which compose the sodium montmorillonite expand greatly in the presence of water, absorbing a large portion of the water present. Due to the molecular structure of the sodium montmorillonite, bonds are formed between the particles as they swell, and a gel is formed. When the mixture is agitated, the bonds are easily broken, creating a less viscous fluid. The bonds are re-established as the mixture is allowed to stand. A mixture with these characteristics is said to be thixotropic. It is the thixotropic nature of bentonitic slurry which allows it to stabilize an excavation and suspend detritus, making the slurry useful in construction.

The construction industry uses bentonitic slurry in the construction of slurry walls, cut-off walls, and drilled shafts. This report is concerned with drilled-shaft construction. The slurry-displacement method of drilled-shaft construction is used where soil conditions are such that caving or excessive deformation will occur when a hole is excavated. As mentioned previously, the slurry is used to stabilize the excavation. The slurry is then displaced by concrete which is placed through a tremie. The bentonitic slurry is able to stabilize the excavation, preventing caving or excessive deformation, through the formation of a filter cake.

Bentonitic slurry is also used to stabilize the initial stages of an excavation if the casing method is employed. While the research reported herein is principally directed at the slurry-displacement method of construction, the results of the studies are also applicable to the casing method.

Filter-Cake Formation

There are three mechanisms by which a seal is formed at the soil surface, causing filter-cake development. Surface filtration is the most efficient mechanism by which a filter cake is formed. In surface filtration, very little bentonite penetrates the soil. The bentonitic particles remain in the pore spaces as the water from the slurry passes into the soil. As the pore spaces are filled with bentonitic particles, a filter cake is formed on the soil surface (Fig. 1.1). The process continues with time, so that the filter cake thickens and the amount of water passing into the soil decreases.

Deep filtration is a more complex mechanism of filter-cake development than is surface filtration. During deep filtration, the slurry penetrates the soil several millimeters before a seal is formed (Fig. 1.2). As a result, a seal is not formed as quickly as in surface filtration, and, thus, filter-cake development is slower. The third mechanism of filter-cake development is rheological blocking and is the least efficient of the three mechanisms. In rheological blocking, a seal is formed as a result of the shear stresses between the slurry and the soil particles. The slurry penetrates the soil until the shear stresses are such that the slurry can go no further. In some instances, the slurry will penetrate several meters into the soil. As would be expected,

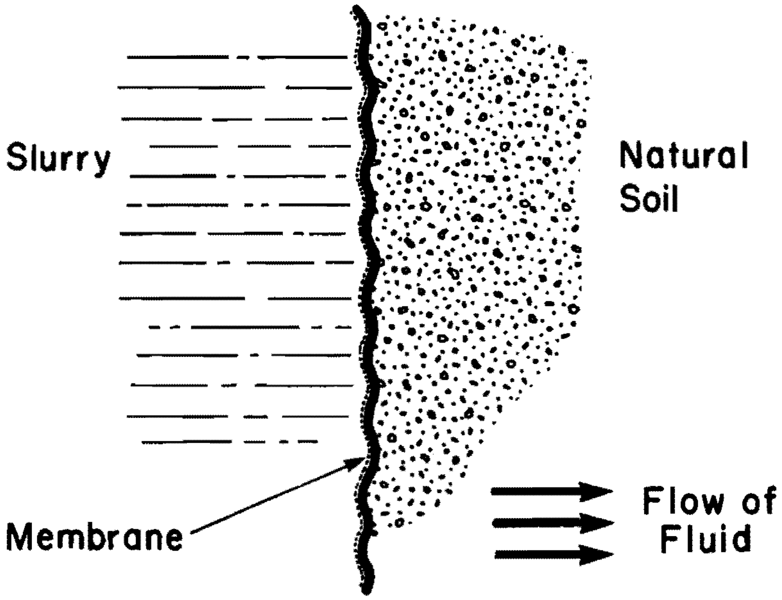


Fig. 1.1. Surface filtration.

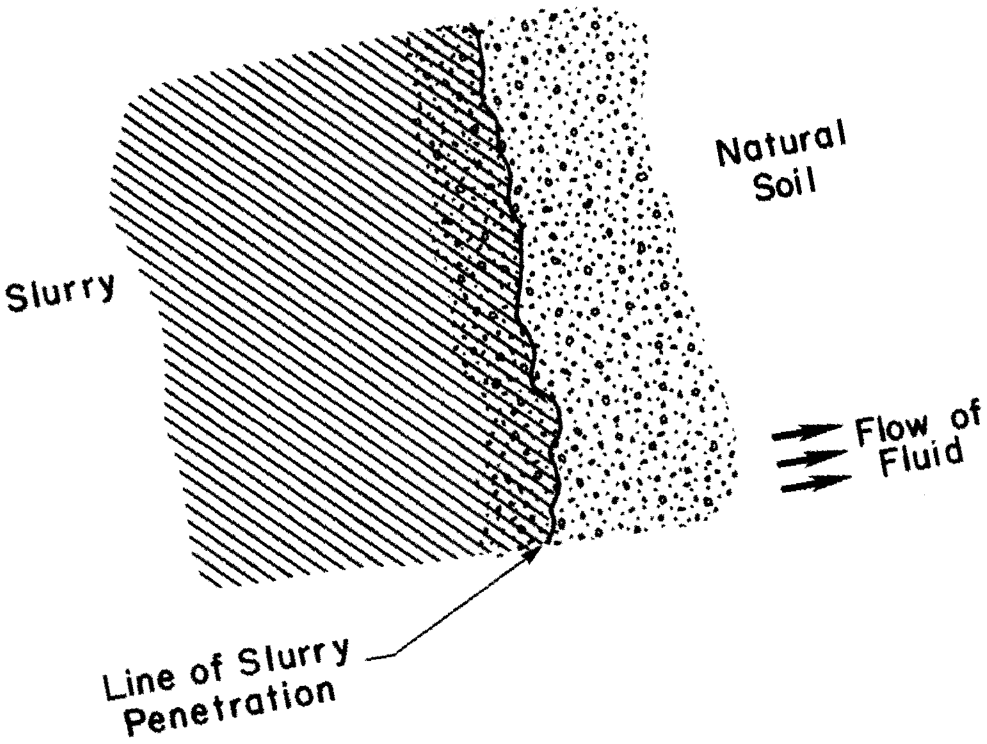


Fig. 1.2. Deep filtration.

the amount of time required for a seal to form is much greater than with the other mechanisms, and the slurry loss is also greater. In addition, the presence of the slurry in the soil could reduce the angle of internal friction, thereby decreasing the stability of the soil.

Rheological blocking, as stated above, is the least efficient mechanism for filter-cake development. Deep filtration is less efficient than is surface filtration, but is still very effective. Surface filtration, and deep filtration to a lesser extent, lead to substantial filter-cake development. Regardless of the mechanism by which the filter cake develops, the longer the slurry remains in an excavation, the thicker the filter cake. Thus, the amount of time between completion of the excavation and the placement of the concrete influences the filter-cake thickness. Little filter-cake development, and, thus, time between completion and concrete placement, is desirable due to concern over whether or not the filter cake is removed when the concrete displaces the slurry.

Concrete Placement

In the construction of drilled shafts concrete placement is usually accomplished through the use of a tremie. In the slurry-displacement method of construction the concrete rises from the base of the shaft to the top, displacing the slurry as it rises (Fig. 1.3). Care must be taken to ensure that the mouth of the tremie remains embedded a short distance into the concrete at all times. Thus, only the top portion of the concrete column will be contaminated by the slurry. In addition, the possibility of slurry inclusions will be greatly reduced because a continuous concrete column will be formed. Due to its high unit weight, highly contaminated slurry is not easily displaced by the concrete and may collect or deposit sediment on the reinforcement. Thus, the slurry should be cleaned of detritus before concrete is placed.

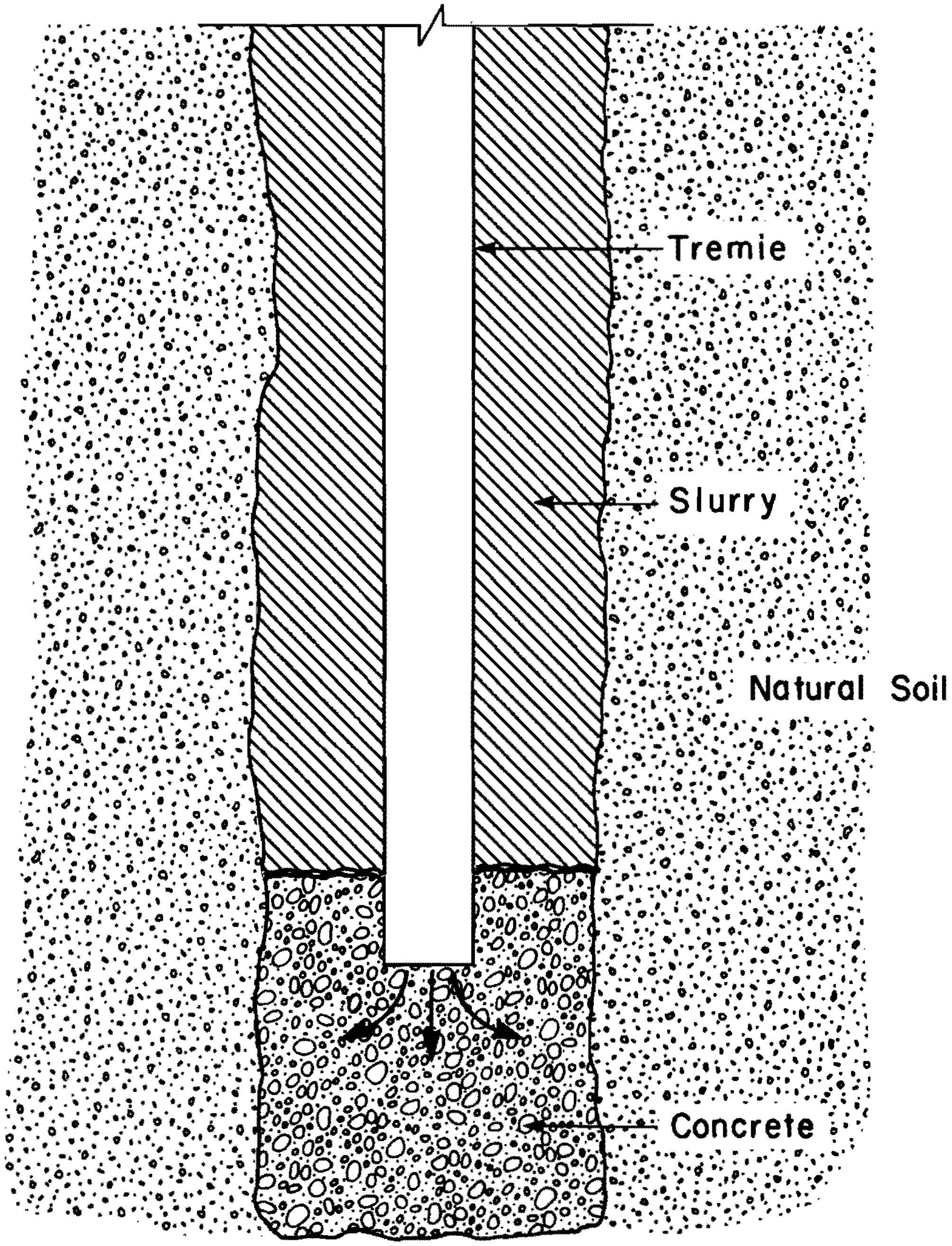


Fig. 1.3. Concrete placement by tremie.

In the casing method of constructing drilled shafts, the casing may be driven through a surface stratum of sand with a vibratory hammer. Construction proceeds by excavating through the casing into non-caving soil below the casing. But, as is frequently the case, excavation can be initiated through the surface sand by use of bentonitic slurry until a relatively impermeable, non-caving soil is reached. Then a casing is set, the slurry is bailed from the casing, and excavation proceeds. The casing is sealed at its bottom in the non-caving soil by use of downward force and torque with the result that slurry is trapped in the annular space between the outside of the casing and the excavation. It is important that the trapped slurry be displaced by concrete when the casing is pulled. Thus, the behavior of slurry and its interaction with concrete is important in this latter casing method.

As the concrete rises, it scrapes the walls of the shaft, presumably removing the filter cake (Fig.1.4). However, evidence exists that the filter cake is not always completely removed by the rising concrete, particularly in pervious soils. Fleming and Sliwinski (1977) report observations of the excavated faces of diaphragm walls in pervious soils on which the bentonitic cake remained partly, or totally, on the surface of the concrete. Wates and Knight (1975) also conclude that the filter cake remains during casting. In view of these observations, questions arise as to what effect, if any, does the remaining filter cake have on shaft capacity, particularly in terms of skin friction. Also, how does the strength of the filter cake compare with the strength of the surrounding soil, and how strong are the bonds between the soil and the filter cake and between the concrete and the filter cake?

Investigations

Various investigations have been undertaken to determine whether or not the slurry-displacement method of drilled-shaft construction has any effect on

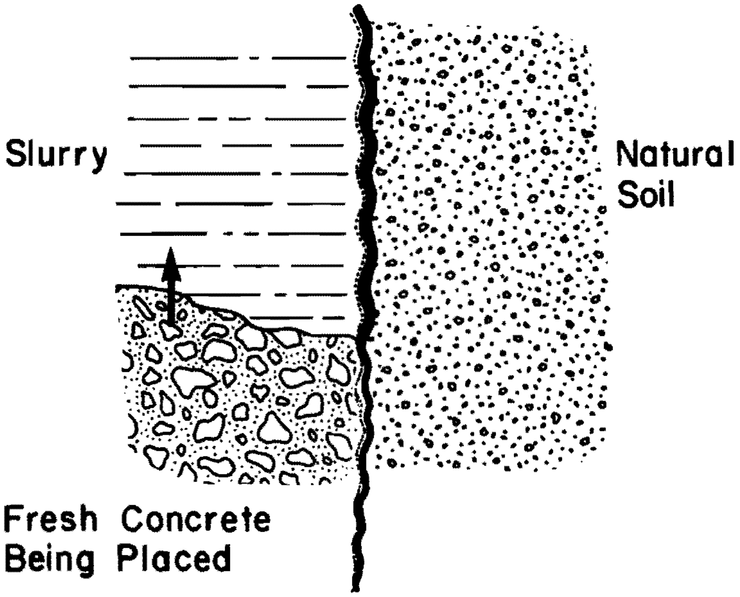


Fig. 1.4. Action of fresh concrete.

shaft capacity. Most of the studies, both in the field and in the laboratory, have concentrated on the effect of bentonitic slurry on skin friction. Weiss (1965), Farmer and Goldberger, (1969) and Wates and Knight (1975) have all conducted laboratory investigations to determine any effects of the slurry. All three investigations were concerned with the effects on skin friction developed between sand and concrete. Weiss (1965) performed his tests on slabs cast horizontally on compacted sands, whereas Farmer and Goldberger (1969) and Wates and Knight (1975) conducted their tests on model piles cast in compacted sand. All three investigations determined that some degree of reduction in skin friction resulted from the presence of bentonitic slurry. Farmer and Goldberger (1969) reported reductions of up to 20%, and Wates and Knight (1975) reported reductions of up to 30%. In addition, both of these studies found that very little filter cake is removed by the scouring action of the rising concrete.

Field investigations, on the other hand, generally have implied that there are no adverse effects on the skin friction of drilled shafts when they are constructed using bentonitic slurry. Fleming and Sliwinski (1977) report on a variety of field investigations. The report includes comparative tests, instrumented-pile tests, and individual tests on piles without special instrumentation. In addition, piles in cohesive soils, granular soils, and chalk were investigated by at least one of the methods. In granular soils, there is an indication that shaft capacity may be reduced by large axial displacements. However, the reductions occurred on a shaft for which the excavation remained filled with contaminated slurry for a long period of time and which was not cleaned prior to concrete placement. Such conditions are not considered as good construction practices. Other tests in granular soils did not show such effects, nor did the tests in cohesive soils or in chalk. Thus, although the testing procedures differ for the various soil types, the general conclusion by

Fleming and Sliwinski from the field investigation is that there are virtually no adverse effects on skin friction resulting from the use of bentonitic slurry.

Touma and Reese (1972) and O'Neill and Reese (1970) report on studies that were carried out at The University of Texas. Several full-sized drilled shafts, instrumented for the measuring of the distribution of axial load with depth, were tested and the influence of the construction method was discussed. It was found that the load transfer in skin friction was about the same for the dry method (hole could be drilled without using any support) and for the slurry-displacement method. However, in at least one case it was found that slurry was trapped in the excavation when the casing method was used.

Experimental Studies

As shown above, there is conflicting evidence as to whether or not the use of bentonitic slurry has any adverse effects on skin friction. It has also been shown that construction practices can impact the slurry effects. The investigation reported in this document consists of both laboratory and field studies. The laboratory work serves primarily as background for the field work. The investigation is concerned with filter-cake development and characteristics. In particular, the slurry properties and construction practices which influence the filter cake are studied. The aim of the investigation is to provide information that will assist in the development of specifications for the construction of drilled shafts when bentonitic slurry is used in the construction technique.

The principal field investigation was done at Lavaca Bay and was in connection with a construction contract at that site.

CHAPTER 2. SLURRY PROPERTIES

Thixotropy

Chemical Structure. As stated earlier, bentonite is a sodium montmorillonite and exhibits thixotropic properties when combined with water. The thixotropic properties of the slurry are a result of bonds formed between the clay particles. A thorough explanation of the chemical structure of the bentonitic suspension can be found elsewhere (Fleming, and Sliwinski, 1977). Briefly, in the presence of water, the clay crystals separate, forming a suspension of thin, plate-like particles. The particles have a negative charge on the surface and a positive charge on the edge. A gel is formed through the three-dimensional bonding of the negative faces with the positive edges. The bonds are weak, so they are easily broken by agitating the slurry. The bonds reform as the slurry is allowed to remain still.

Suspension of Detritus. The ability of bentonitic slurry to gel serves two purposes in the construction of drilled shafts. First, as described earlier, the slurry forms a filter cake on the shaft wall, stabilizing the shaft. Second, the formation of the gel enables the slurry to hold detritus in suspension. Hence, cuttings can be circulated out of the shaft during drilling and detritus settlement will be minimized. The ability of the slurry to hold detritus in suspension is determined in part by the amount of bentonite present.

Laboratory investigations were conducted to determine the effect of the amount of bentonite in the slurry on the ability of the slurry to suspend detritus. Slurries composed of 2% to 10% bentonite were investigated. The percentage of bentonite is based on the weight of bentonite to the weight of water. After the slurry had been thoroughly blended so that optimal hydration of the bentonite was achieved, sand and small pebbles (smaller than 1/2 in.) were added to the slurry in small amounts, and the amount of settlement with time was observed. Slurries composed of less than 3 to 4% of bentonite were virtually ineffective in holding detritus in suspension. The pebbles and a large portion of the sand remained suspended for a few hours in slurries composed of 4 to 4 1/2% of bentonite. Slurries composed of 4 1/2 to 5% of bentonite were very effective in suspending detritus. All of the sand was held in suspension and settlement of the pebbles occurred only after several hours. Slurries composed of greater than 4 1/2 to 5% of bentonite showed virtually no settlement of detritus over time. Large amounts of sand and pebbles were mixed into the slurry without settlement occurring. Hence, 4 to 4 1/2% of bentonite is a turning point in slurry behavior. Below this percentage, detritus settles rapidly, while above that percentage virtually no settlement occurs.

The ability of the slurry to hold detritus in suspension is determined by factors other than the percentage of bentonite present. Thorough mixing of the bentonite is very important. Without thorough mixing, the bentonite will clump so that not all of the particles are exposed to the water and a very non-uniform slurry results. The uniformity or non-uniformity of the slurry affects the ability of the slurry to build up a filter cake and ability of the slurry to hold detritus in suspension. In short, the engineering properties of the slurry are affected.

Engineering Properties

The engineering properties of bentonitic slurry include shear strength, viscosity, and density. Sand content and pH are also of interest. Measurement of these characteristics aids in the determination of the slurry's ability to build up a filter cake and to hold detritus in suspension. These properties are influenced by the amount of bentonite present, the method of mixing, the duration of mixing, the amount of time without agitation, and the amount of contamination.

Density. The density of the slurry is determined by the amount of bentonite and the amount of contamination. Ideally, proper mixing will result in the bentonite being distributed uniformly through the slurry. However, the degree of contamination will most likely vary over the length of the shaft, with the highest percentage at the base. The density of the slurry is of concern for a number of reasons. First, a relatively high density aids in preventing sloughing of the soil surrounding the excavation because as the density increases the pressure of the slurry increases. Second, a very dense slurry can be difficult to circulate if reverse circulation is used, and third, a very dense slurry may be difficult for concrete to displace, possibly resulting in slurry inclusions. With these considerations in mind, the density of slurry should be such that it aids in supporting the shaft walls and in keeping the shaft free of water, while at the same time it allows for circulation and concrete placement.

A mud balance (Fig. 2.1) is typically used to determine the density of the slurry. The density is found by filling the cup with slurry so that when the lid is in place, some slurry is forced out of a hole in the lid. Any excess slurry should then be removed. The density or the specific gravity can then be read from the scale on the balance.

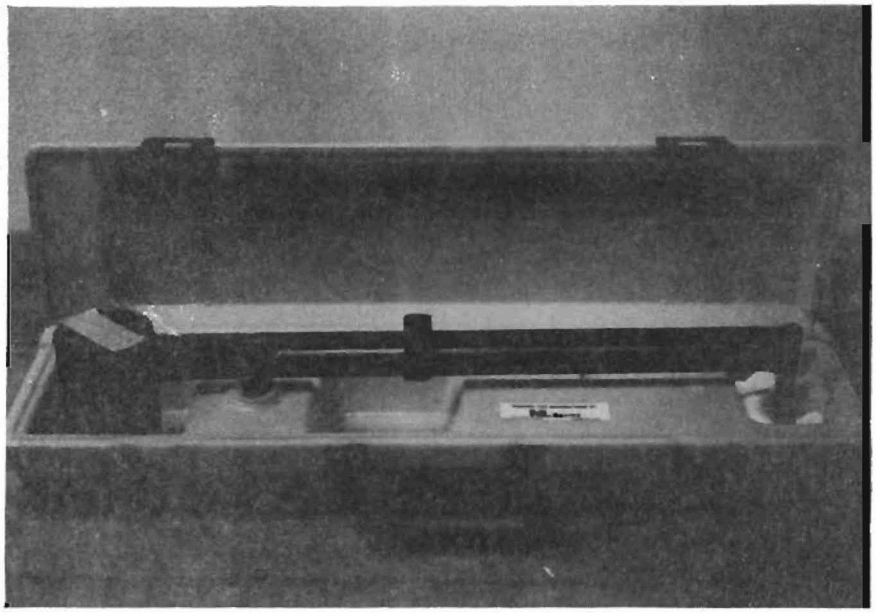


Fig. 2.1. Mud-density balance.

pH. The pH of the slurry can be influenced by minerals present in the water and in the soil. The pH should be kept in a range such that it would have no adverse effects on the shaft reinforcement, casing, or concrete. The pH of the slurry can be determined by pH paper (Fig. 2.2) or an electric pH meter.

Sand Content. The sand content is a means of estimating the amount of slurry contamination. As mentioned above, the presence of detritus will increase the density of the slurry and can cause the slurry to be difficult to circulate and to be displaced. In addition, a high sand content may cause a thick filter cake to build up due to the added particles in the slurry. Also, as the slurry is displaced, sand may collect on the reinforcement if the slurry is highly contaminated and proper bonding between the concrete and reinforcement would be hindered. When slurry is to be circulated and/or reused, it is possible to remove most of the contamination through the use of slurry shakers and desanders.

A sand-content test is performed by mixing a specific amount of slurry with water. The mixture is poured through a No. 200 screen so that sand particles are retained on the screen. The sand particles are then washed into a marked tube. The percentage of sand can be read from the tube once the sand has settled. The testing equipment is shown in Fig. 2.3.

Shear Strength. The shear strength of the slurry is determined by the amount of bentonite present, the thoroughness of mixing, and the amount of time since agitation. Without agitation, the slurry will gel, resulting in an increased shear strength. As the shear strength of the slurry increases, the ability of the slurry to hold detritus in suspension increases. It is possible for the slurry to be satisfactory regarding density, pH, sand content and even viscosity, and have very little shear strength. Hence, determination of shear strength is instrumental in evaluating slurry performance.

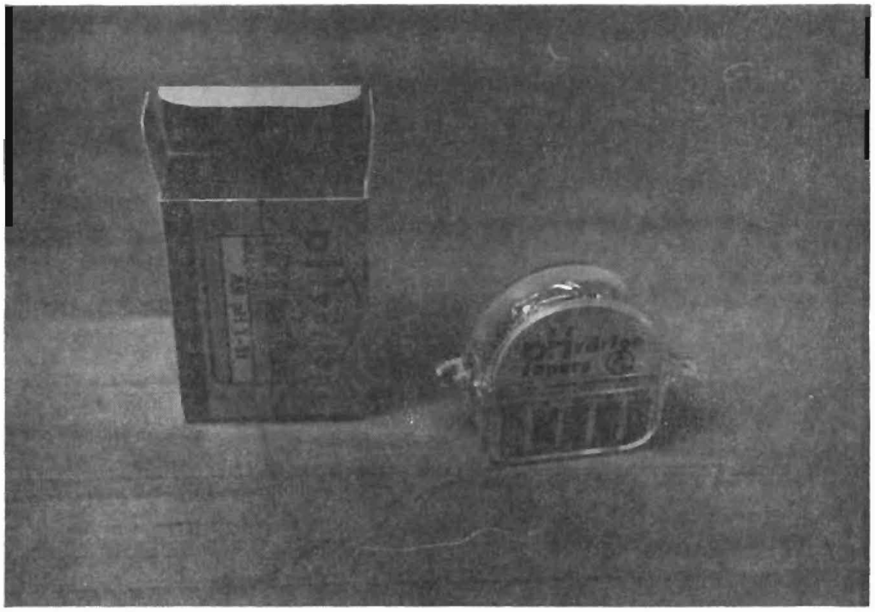


Fig. 2.2. pH paper.

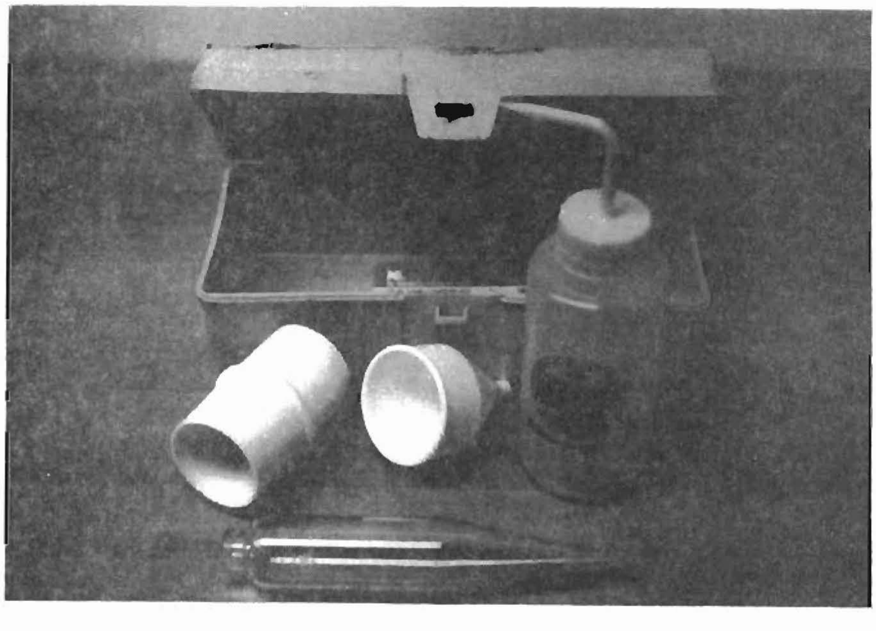


Fig. 2.3. Equipment for sand-content test.

Shear strength can be determined either by a direct indicating viscometer or by a shearometer (Fig. 2.4). The shearometer is more commonly used in construction. The shear strength is determined both initially and after a 10 minute interval. When using a shearometer, the initial shear strength is determined by filling a container to the bottom line on the scale with freshly agitated slurry. A thin metal tube is then lowered over the scale to the slurry surface and released. The tube is allowed to settle for one minute, at which time the shear strength is recorded as the scale reading at the top of the tube. The 10-minute gel strength is determined in the same manner, except that the slurry is allowed to sit in the container for 10 minutes before the tube is lowered.

Viscosity. Viscosity is determined primarily by the amount of bentonite that is present and by the thoroughness of mixing. Contamination of the slurry will also influence viscosity. The viscosity, like shear strength, is a measure of the thixotropic properties of the slurry. As the viscosity increases, the ability of the slurry to hold detritus in suspension increases. However, if the viscosity is too great, the slurry will not flow easily. This would hinder circulation as well as hinder displacement by the concrete. In addition, the slurry might collect on the reinforcement rather than flow around it.

Viscosity of the slurry can be determined either by a direct-indicating viscometer or by a Marsh funnel (Fig. 2.5). The Marsh funnel is the device most commonly used method in construction. The test is performed by placing a finger over the tip of the tube from the funnel and filling the funnel with slurry. When filling the funnel, the slurry should be poured through the screen at the top of the funnel, and the funnel should be filled to the bottom of the screen. The slurry is allowed to flow and the number of seconds required for a quart of

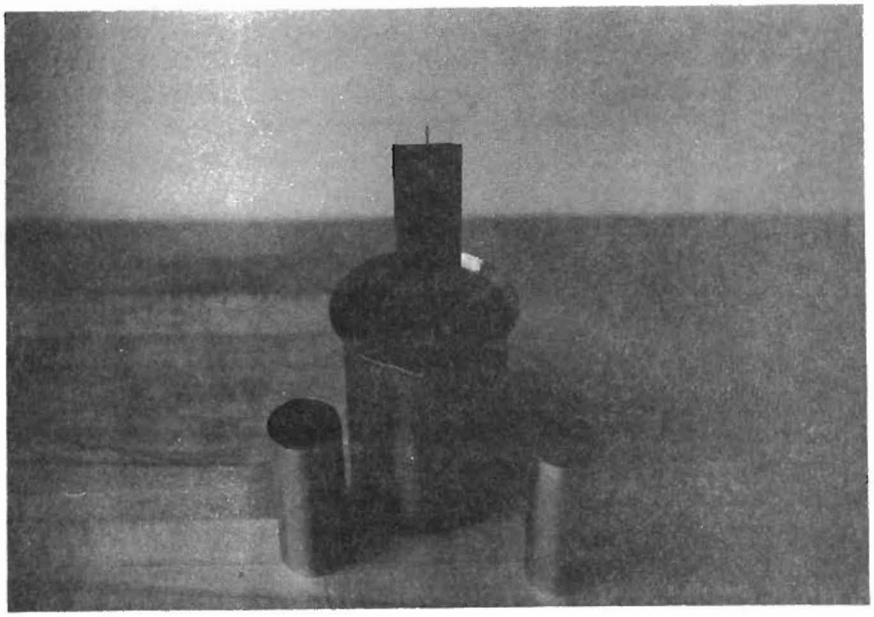


Fig. 2.4. Shearometer.

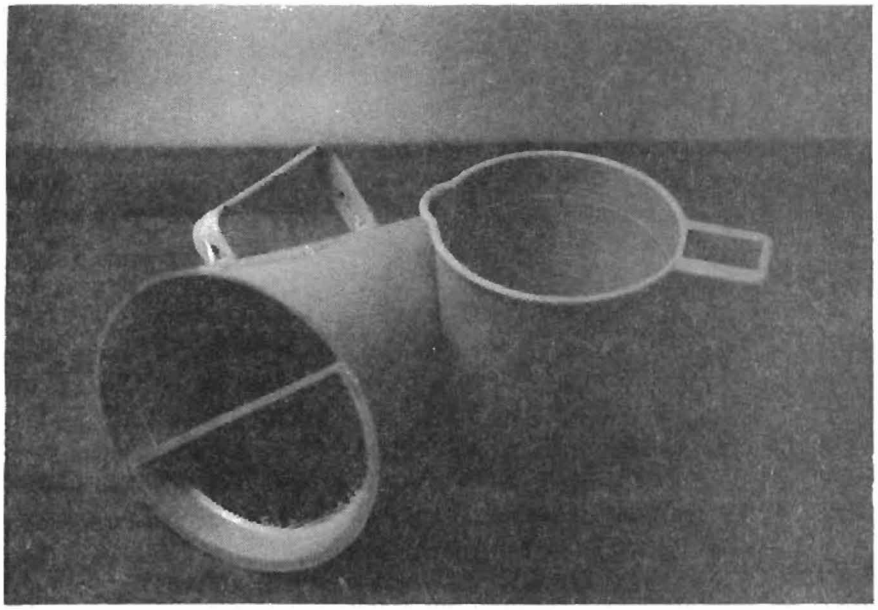


Fig. 2.5. Marsh funnel.

slurry to drain from the funnel is recorded. This measure of time, in seconds, is the viscosity.

Specifications

The above properties can have a wide range of values and in a variety of combinations. The effectiveness of a slurry is determined by the combination of these properties. Because the properties should fall within a range of values, specifications are needed to ensure the effectiveness of a slurry. Various organizations and individuals have developed slurry specifications. A few of these are presented in Chapter 6.

CHAPTER 3. LABORATORY INVESTIGATIONS

Considerations

Laboratory investigations were conducted in which filter-cake growth was observed and the resulting filter cake was analyzed. The purpose of the testing was to gain an understanding of filter-cake development and filter-cake properties as a basis for field investigations. The laboratory investigations were two phase. The first phase of the investigations consisted of filter-cake development on a compacted-sand sample and water-content analysis of the filter cake. Factors influencing filter-cake growth were varied to determine the impact of the factors on filter-cake development. These factors include slurry composition, development time, applied pressure, and initial water content of the sample. The second phase of the investigation consisted of vane-shear tests in the laboratory on sedimented samples of slurry. The samples were of various water contents to allow the determination of the variation of shear strength of the filter cake with water content.

Filter-Cake Growth

Testing Apparatus.

The testing apparatus consisted of a 1/2-in.-thick plastic cylinder, 3 ft in height and 6 in. in inside diameter. The top and bottom plates were plastic, 9 in. in diameter and 1 in. in thickness. The plates were grooved to allow for the cylinder and an O-ring. Four threaded metal rods ran between the plates, holding the system together. Nuts and washers were located on either side of the plates and nuts were tightened to ensure proper sealing of the system. Air pressure was supplied to the system by plastic tubing connected to the top plate. Plastic tubing connected the base plate of the cylinder to the permeameter. The permeameter, shown in Fig. 3.1, consisted of a compaction cylinder, top plate, and base plate. The top plate had an inlet for the slurry and a pressure-release valve. The base plate had a porous stone and outlet for fluid passing through the stone. The system was clamped together with threaded metal rods and wing nuts. An O-ring was located between the top plate and the upper portion of the cylinder, and a flat seal was located between the two portions of the cylinder. Thus, high pressures could be applied to the system without slurry loss. The testing system is shown in Fig. 3.2.

Testing Procedure. Preparation of the sample was the first step of the testing procedure and consisted of mixing the soil with water until a uniform mixture was obtained. Then the sample was compacted into the compaction cylinder. The Standard Proctor Method of compaction was used. A piece of filter paper was placed between the sample and the porous stone in the base of the permeameter. After the soil sample was compacted, the slurry was prepared. A motorized propeller, approximately 4 in. in diameter, was used to blend the slurry. A small portion of the bentonite was added to the water at a time to ensure complete hydration of all of the particles. Mixing continued for 5 to 10 minutes after all of the bentonite was added to ensure that slurry was uniform. Approximately 0.25 cu ft of slurry was mixed at a time.

Once the slurry was mixed, tests were run on the slurry to determine its engineering properties. These tests included density determination with the mud balance, viscosity determination with the Marsh cone, and gel strengths (initial and 10-minute) with the shearometer. Following slurry testing, the cylinder was filled with the slurry through means of a vacuum. A vacuum was

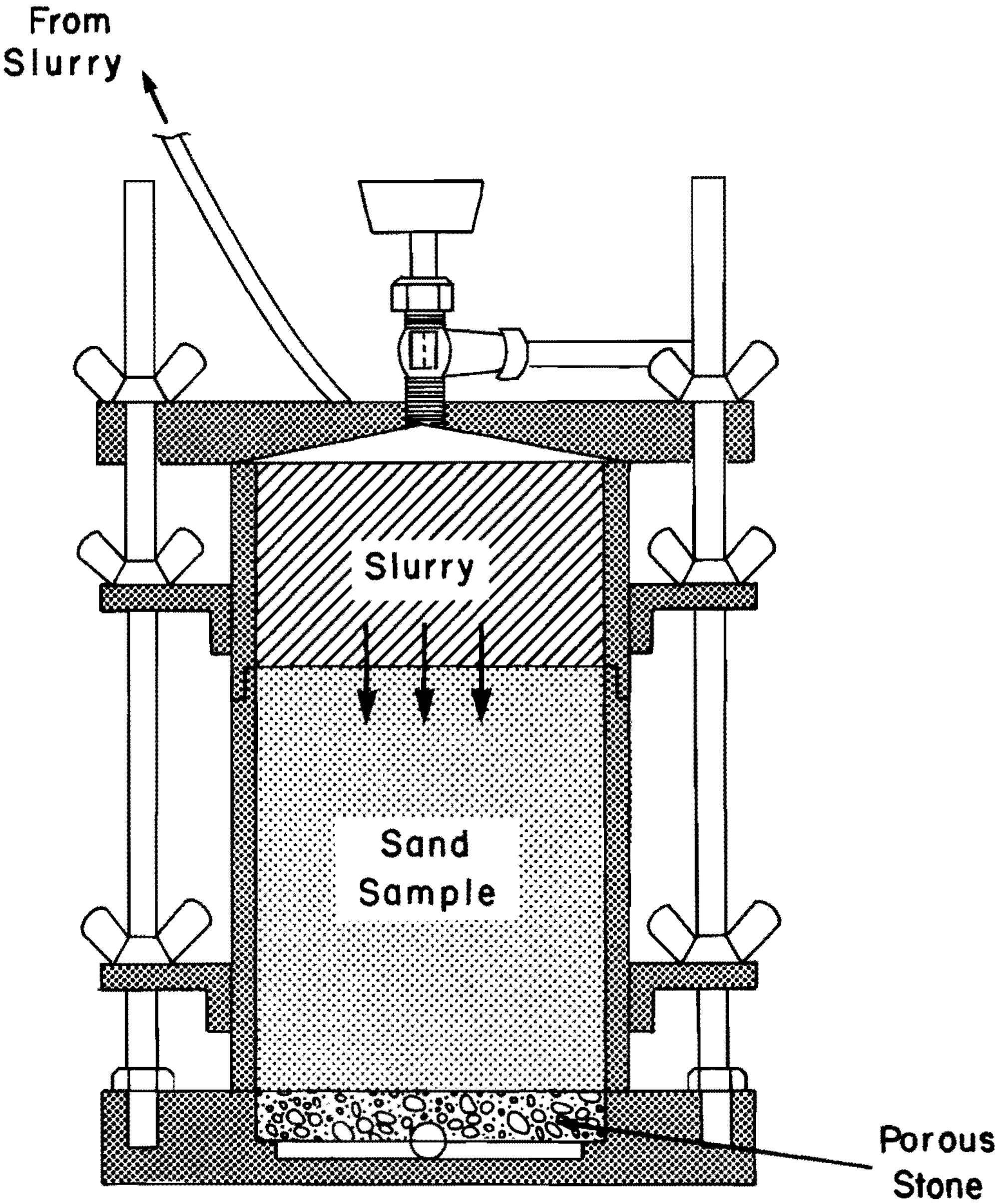


Fig. 3.1. Permeameter.

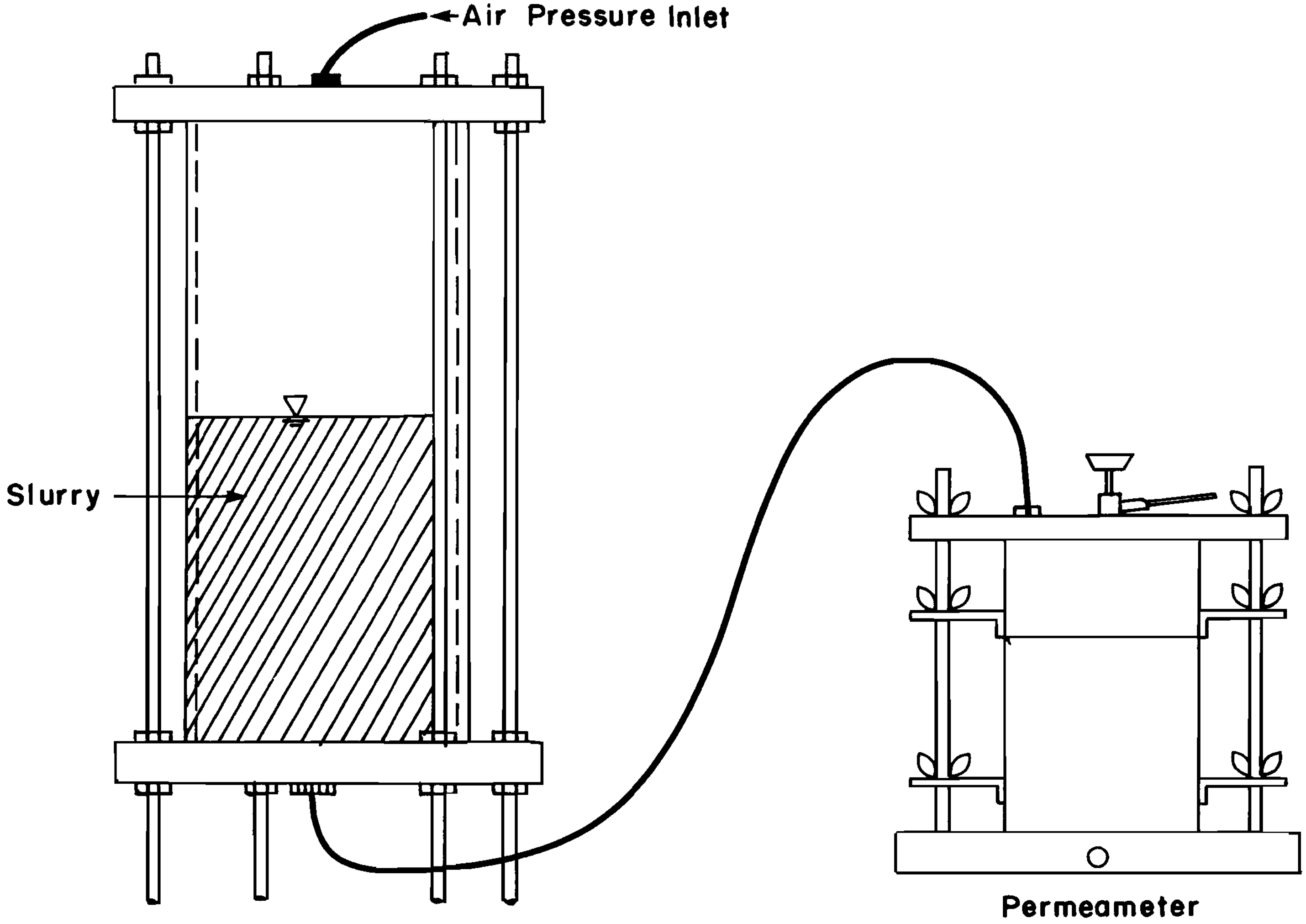


Fig. 3.2. Testing system.

applied to the cylinder at the top and the slurry filled the cylinder through plastic tubing at its base.

After the cylinder was filled, the plastic tubing at the base of the cylinder was connected to the top plate of the permeameter. A small amount of air pressure was applied to the slurry column until the slurry had filled the upper portion of the compaction cylinder. At this time, the permeameter was secured and the pressure-release valve was closed. Additional pressure was then applied to the slurry column, and thus to the slurry in the permeameter, for a period of time. The applied pressure forced the water from the slurry through the compacted sample so that a filter cake was developed on the sample.

Data Accumulation. After the desired period of time had passed, the pressure on the slurry column was released and the slurry supply disconnected from the permeameter. The top plate of the permeameter was then removed, followed by the upper portion of the compaction cylinder. Extreme care was taken so as not to disturb the filter cake. The slurry on top of the filter cake was then carefully removed. The filter cake was determined to be that portion which could not be removed by a thin stream of water. The bottom portion of the compaction cell was then removed from the base plate.

After separating the lower portion of the cylinder from the base, the sample, with filter cake intact, was slowly extruded, using a hydraulic extruder. As the sample was extruded, it was sliced into pieces 1/4 in. in thickness and the water content was determined for each slice. The very top portion of the filter cake was disregarded since it came in contact with the thin stream of water. Also, care was taken to separate the soil and the filter cake at the interface of the sample and the filter cake. Slices of the sample were taken for a distance of 2 in. into the sample.

Data Analysis. A listing of the results of the various tests including test details, filter-cake thickness, and variation in water content throughout the filter cake and into the sample can be found in Appendix A. Figure 3.3 is a plot of the range of results. The variation of water content throughout the filter cake and sample is shown for all of the tests. As can be seen, the sample reached a saturation level at its surface and the water content varied only slightly throughout the 2 in. of sample that was tested. All of the samples that were tested were sand samples. Data on sieve analysis of the sand are presented in Appendix B. Sand was used instead of clay because no filter-cake build-up occurred on the clay sample that was tested.

In testing, the duration of build-up was varied from 3 hours to 6 days. The applied pressure varied from 3 psi to 30 psi, and slurry concentration varied from 5% to 12.8% bentonite. In addition, some tests were run using "Quik Gel" instead of standard bentonite. Slurries made from "Quik Gel" tended to build up larger filter cakes for a given time period. At low pressures, time had little to no effect on build-up for a given slurry composition. Pressure had very little impact for a given time period on filter-cake build-up when slurries with high bentonite concentrations were used. At medium to high pressures and a given slurry composition, filter-cake build-up increased with test duration. In addition, slurries with higher concentrations of bentonite yielded lower water contents for the same filter-cake thickness when medium to high pressures were used. These results are depicted in Fig. 3.4 to Fig. 3.8.

Sample Sedimentation

Sedimentation Process. The investigations described above determined the effects of various factors on filter-cake build-up and the variation of water content throughout the filter cake. However, the investigations did not

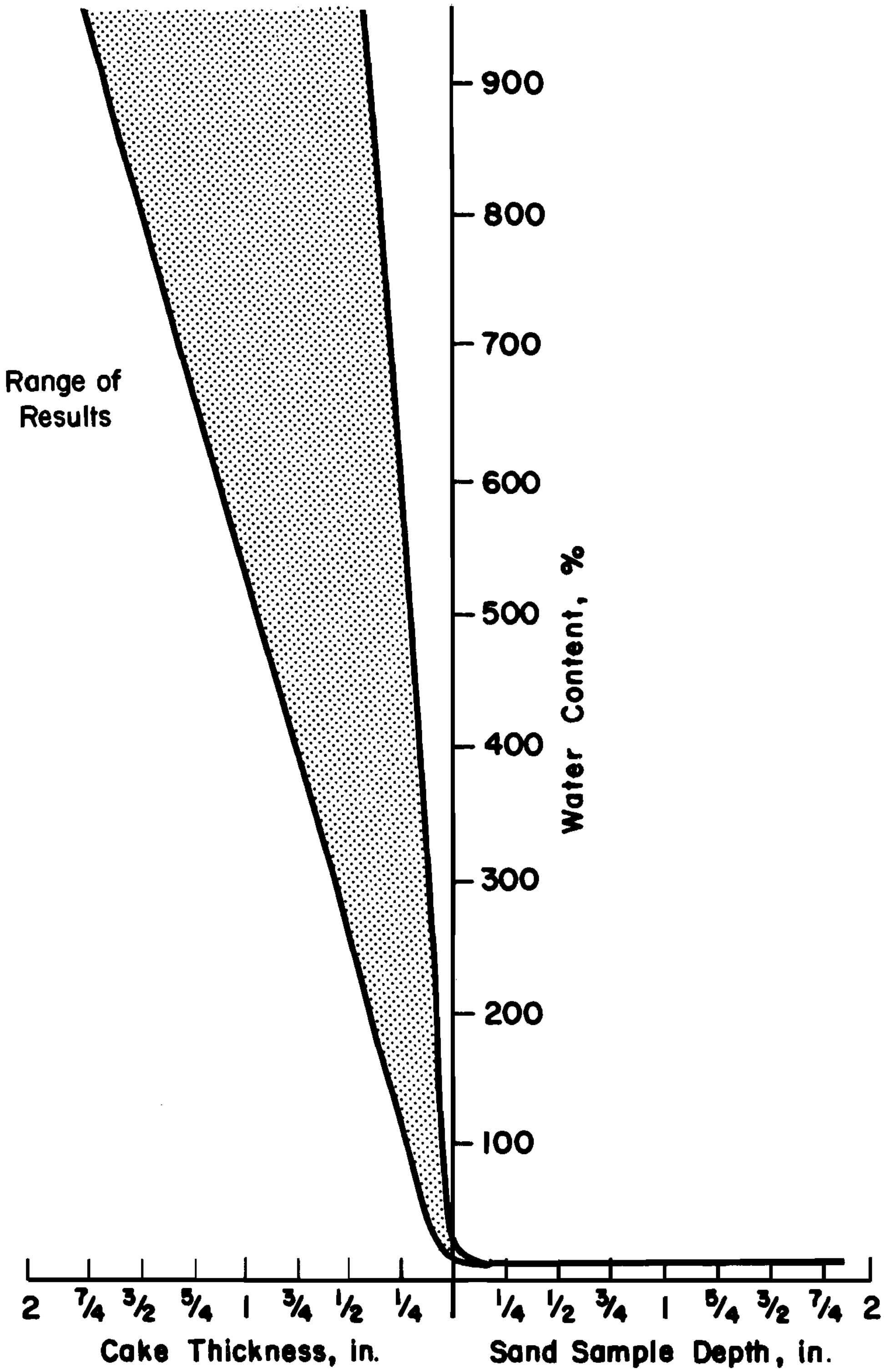


Fig. 3.3. Water content vs. filter-cake thickness.

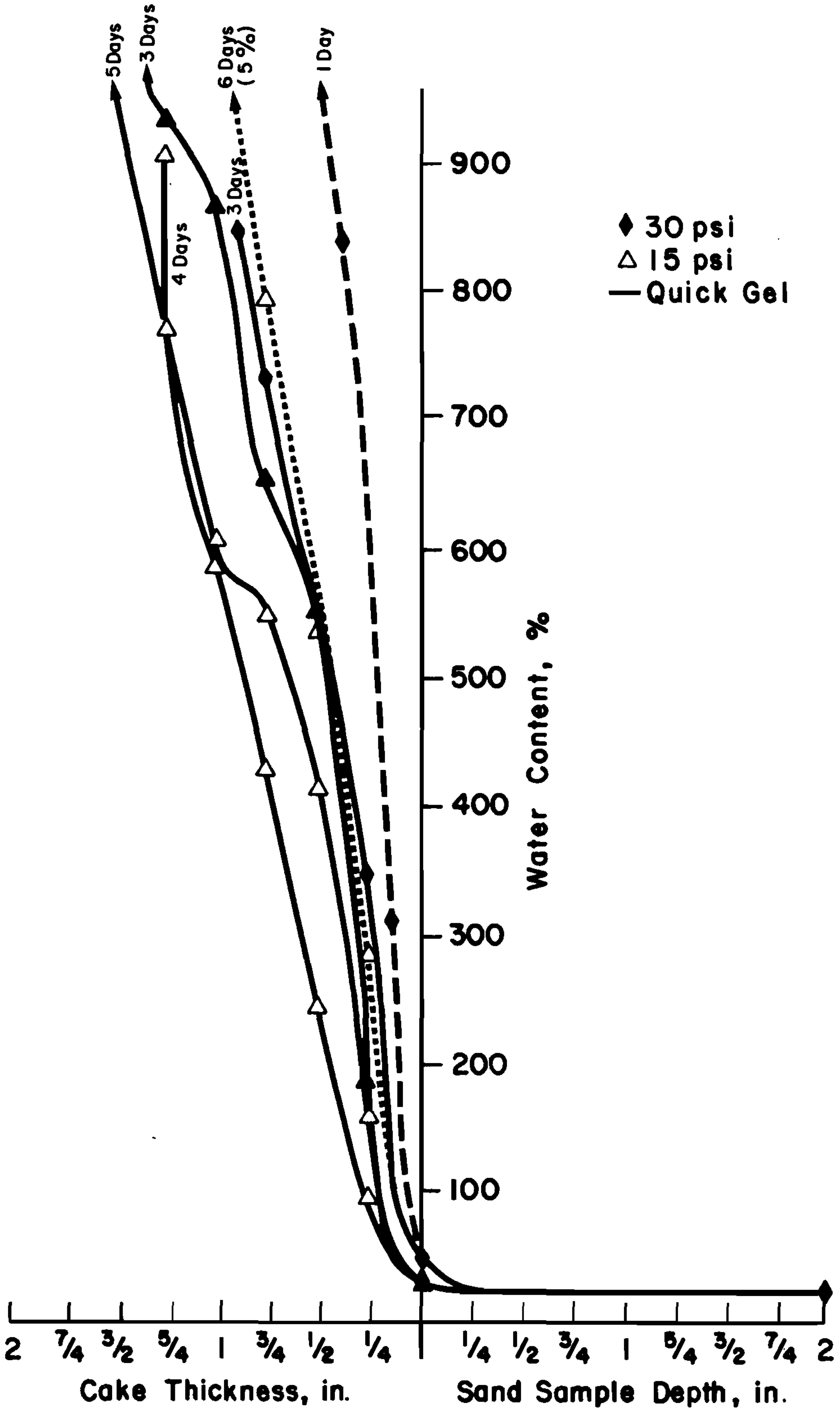


Fig. 3.4. 8% bentonitic slurry.

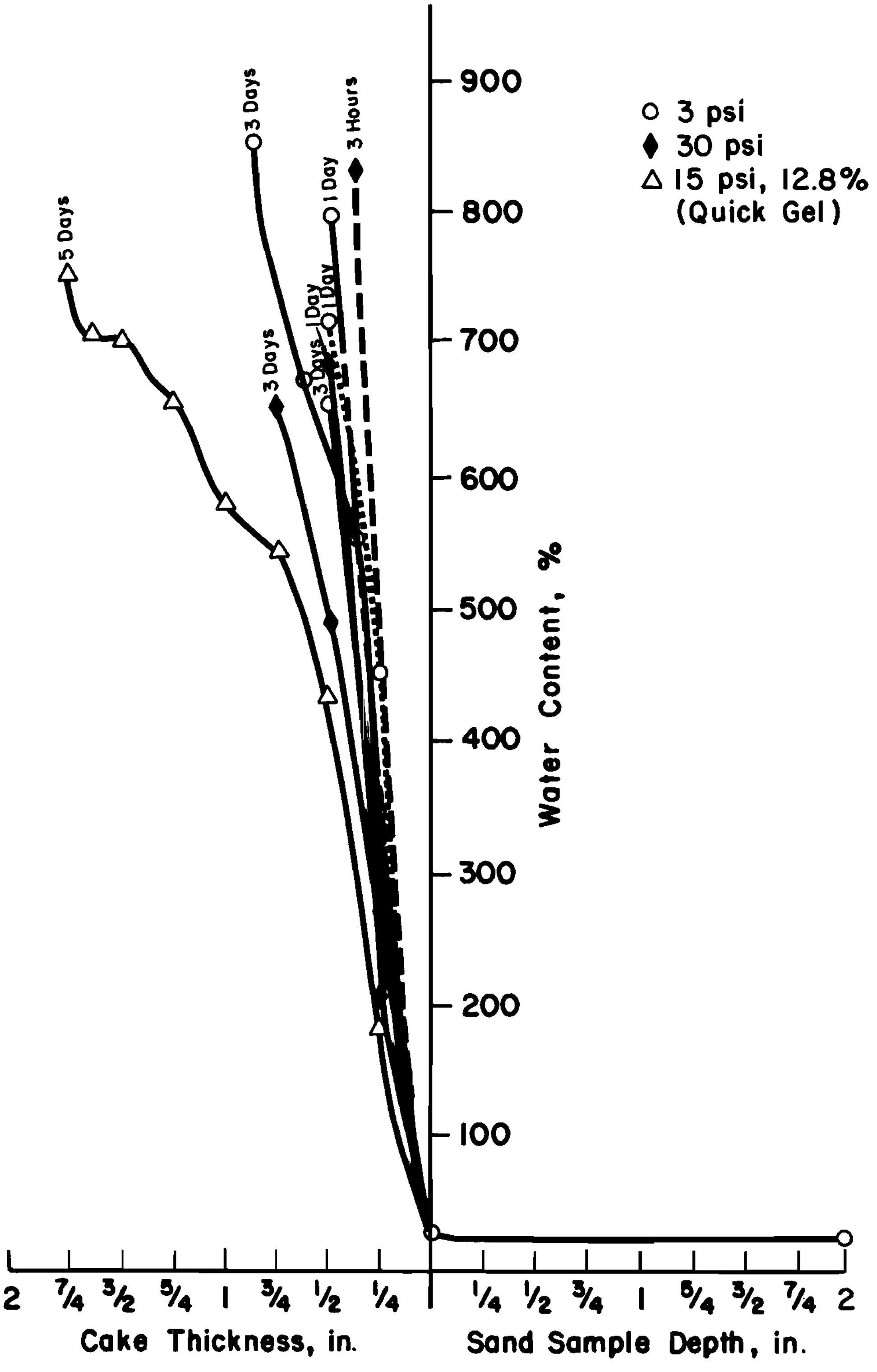


Fig. 3.5. 10% bentonitic slurry.

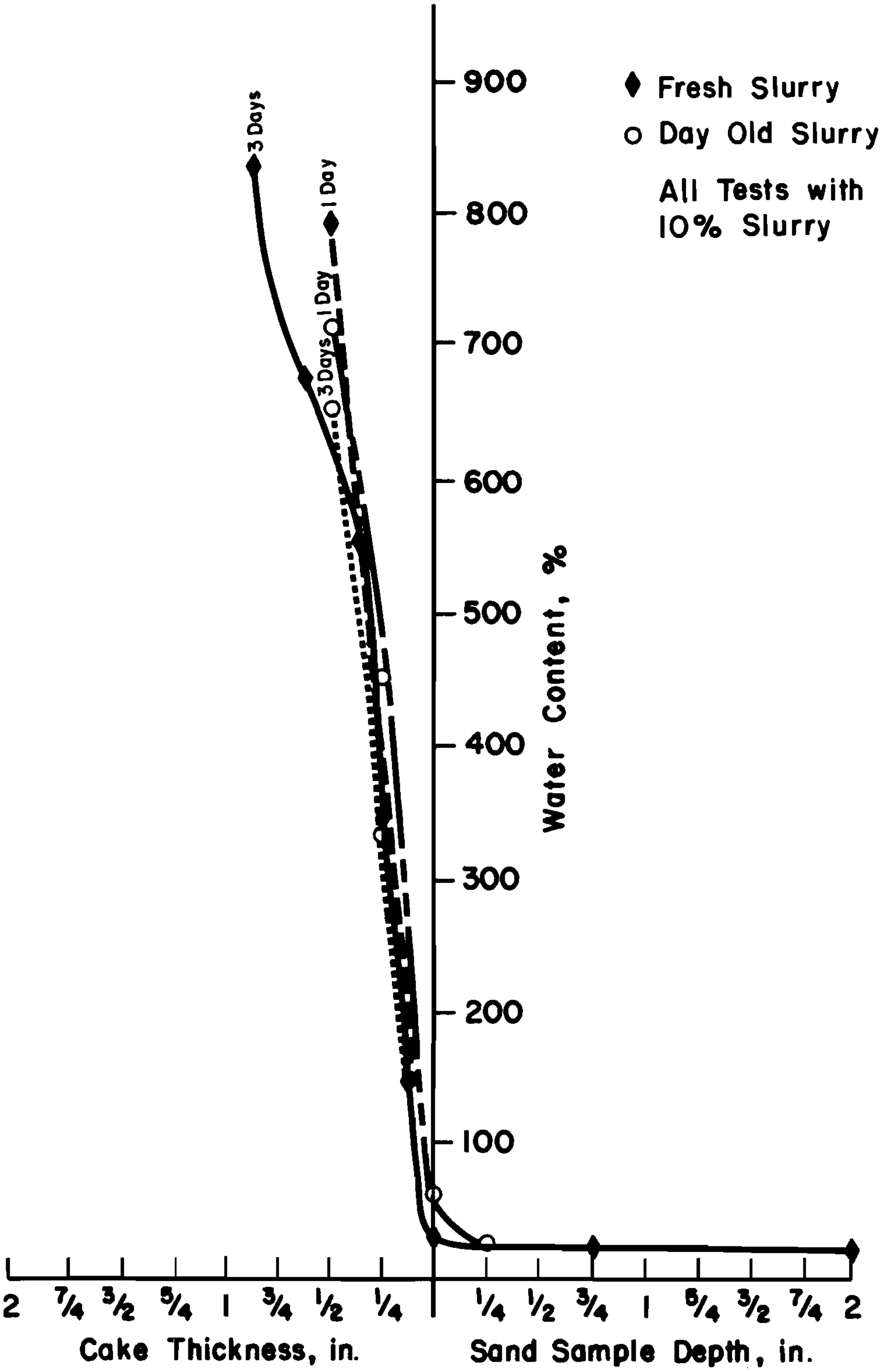


Fig. 3.6. 3 psi development pressure.

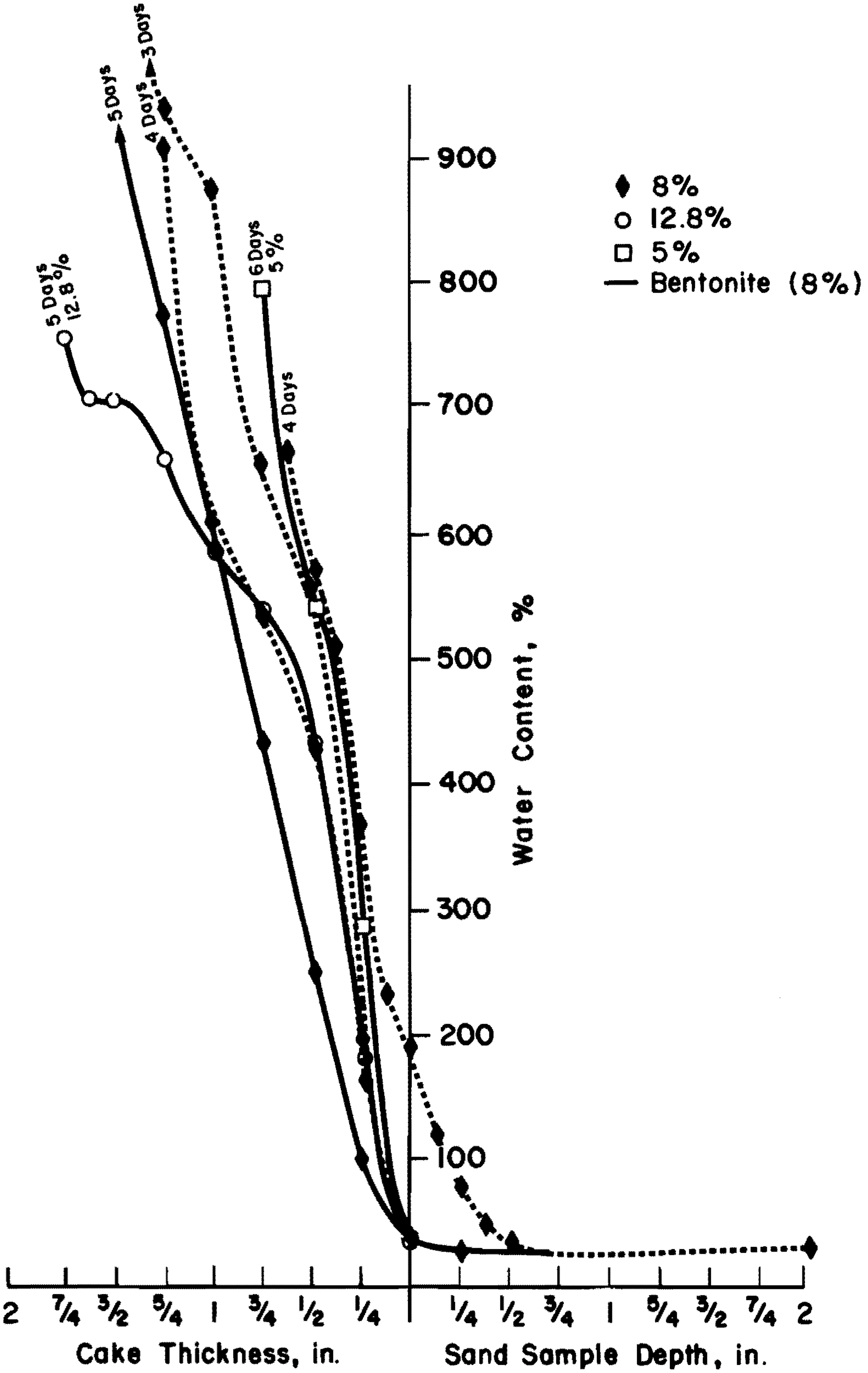


Fig. 3.7. 15 psi development pressure.

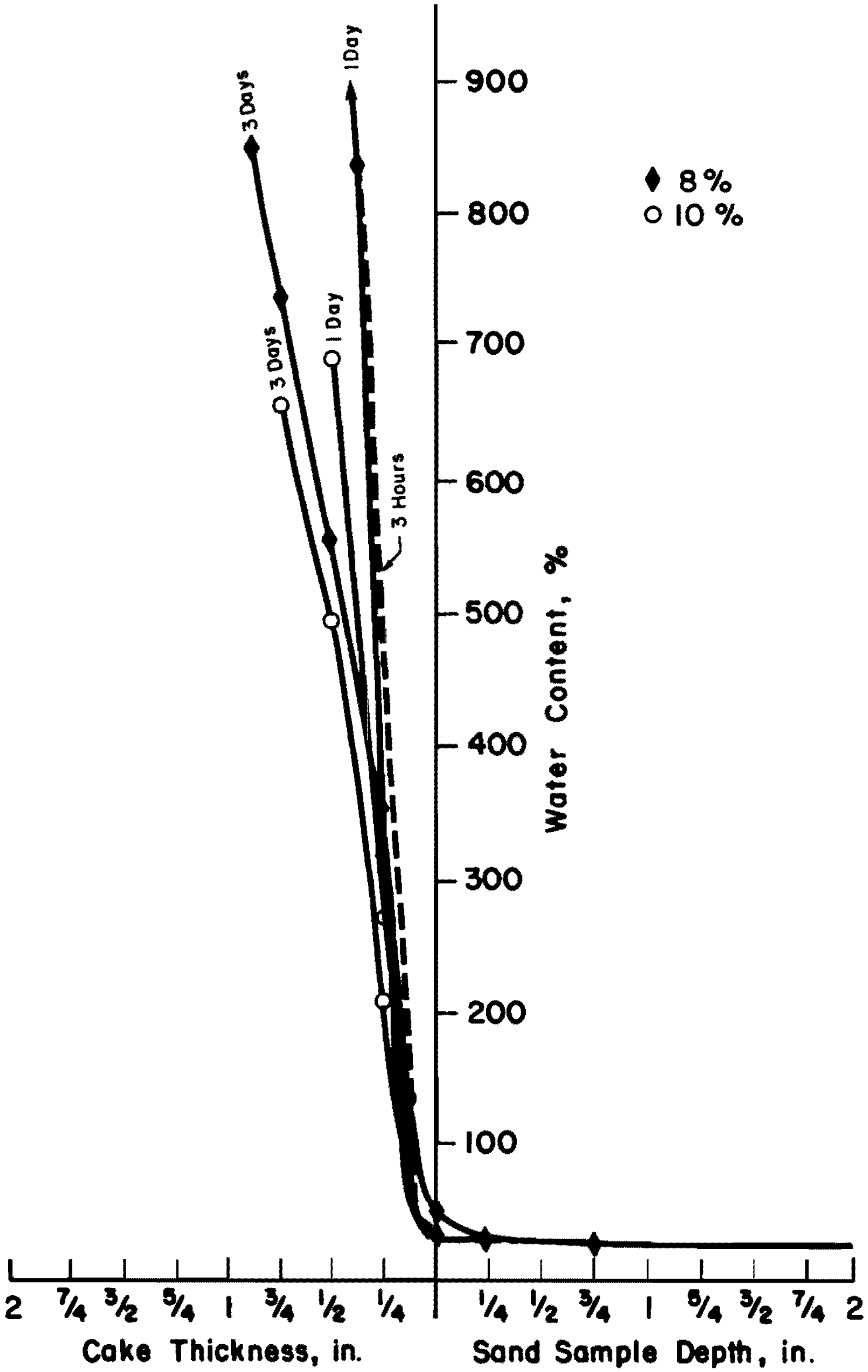


Fig. 3.8. 30 psi development pressure.

provide any information regarding the variation in strength throughout the filter cake. Such testing was not feasible due to the non-uniform nature of the build-up. Hence, a uniform filter-cake sample was required to determine strength characteristics. Uniform samples were produced through sedimentation.

A sedimented sample was produced by application of pressure to a column of slurry, with porous stones and filter paper at top and bottom, so that water passed out of the slurry, leaving the bentonitic particles behind. The sedimentation tubes were of plastic, 1 1/2 in. in inside diameter and 12 in. in height. The top and base plates were plastic, connected by threaded metal rods, and grooved to accommodate the tube. An O-ring was located in the groove of the base plate, and the system was sealed by the tightening of nuts located above the top plate. The base plate was inset with a porous stone and contained a horizontal tube leading from the stone to the exterior, so that water could pass through the stone and out of the base. The top plate contained a hole, 1 in. in diameter, to allow for the piston. The piston fit snugly inside the tube and contained a porous stone, above which were small holes to allow the water to pass through. A collar around the piston rod fit into the top plate and held the piston erect. The top of the piston rod was connected to a flat plate on which weights were set. Thus, pressure was applied to the slurry through the addition of weight to the piston.

The initial step of the sedimentation process was to mix the slurry. The slurry was mixed in small amounts, about 500 ml at a time. Care was taken to ensure optimal hydration of the bentonitic particles. Slurries of concentration of 10 percent were generally used. Slurries of lower concentration contained a large amount of water, while those of higher concentration were extremely viscous, presenting problems in filling the sedimentation tube. When filling the tube, care was taken not to trap any air in the slurry column, thus a fairly fluid slurry was better than a viscous slurry. Initially a vacuum was applied to the slurry before filling the tube in an effort to remove entrapped air. However, due to the thixotropic nature of the slurry, virtually no air was removed by the process and filling of the tube was more difficult due to the more viscous nature of the slurry that resulted from the period of time between mixing and filling the tube. Because only a minimal amount of entrapped air was present in the slurry, the effort to remove the air before filling the tube was abandoned.

The sedimentation tube was filled by slowly pouring the slurry into the tube. The tube was tilted and the slurry forced to run down the side of the tube in a thin, continuous stream to avoid entrapping air. The tube was filled approximately one-half to two-thirds full. The piston, coated with vacuum grease, was inserted and an initial pressure of 1 psi was applied. The pressure was slowly increased to 15 psi, and in some cases to 20 psi, over a period of about 3 days. The slurry remained under pressure for periods ranging from 1 to 6 weeks, so that various water contents were attained. The sedimented samples ranged in height from 2 in. to 4 in., depending on the initial height of the slurry column and on the sedimentation time.

Testing Procedure. The sedimented sample was extruded slowly and sliced into 1-in.-thick pieces. Each portion was transferred to a mold and the shear strength was measured by use of a laboratory vane-shear device. The water content of the soil was then determined. Extreme care was taken while extruding and handling the sample so as not to fail or disturb the sample.

Data Analysis. Results of the soil testing are shown in Table 3.1 and are depicted in Fig. 3.9. The lowest water content that was attained by the sedimentation process, after the loading was maintained for six weeks, was over

TABLE 3.1. SHEAR STRENGTH OF SEDIMENTED-SLURRY SAMPLES USING LABORATORY VANE TEST

Test No. (Date)	w (%)	Spring Const. (in.-lb/deg)	Reading (deg)	Torque (in.-lb)	$(H\frac{D^2}{w} + \frac{D^3}{6})$ (in.^{3})	S (psi)	S (psf)
#1(11/11)	218.5	0.0375	20.5	0.76875	0.2617994	2.94	442.6
#2(11/11)	226.9	0.0375	20.5	0.76875	0.2617994	2.94	442.6
#3(12/8)	421.5	0.01367	15.0	0.20505	0.2617994	0.78	117.4
#4(12/8)	712.5	0.01367	13.0	0.17771	0.2617994	0.68	102.4
#5(12/8)	663.4	0.01367	7.0	0.09569	0.2617994	0.36	54.2
#6(12/8)	424.4	0.01367	22.0	0.30074	0.2617994	1.15	165.6
#7(12/8)	516.5	0.01367	08.0	0.10936	0.2617994	0.42	60.5
#8(12/8)	496.1	0.01367	16.0	0.21872	0.2617994	0.84	120.9
#9(1/26)	225.1	0.01367	20.0	0.27340	0.2617994	1.04	149.8
#10(1/26)	259.8	0.01367	53.0	0.72451	0.2617994	2.77	398.5

200%. The water content of the filter cake at the surface of the soil will perhaps be less than that.

The plot of strength versus water content on the traditional semi-logarithmic plot, as shown in Fig. 3.9, indicates that a straight-line gives a reasonable representation of the relationship between the two variables if Tests 4 and 9 are ignored. The equation of the straight line is

$$w\% = -466(\log_{10} S) + 1432 \qquad (3.1)$$

where

$w\%$ = water content in percent, and

S = shear strength, $\mathrm{lb/ft^2}$.

Equation 3.1 can be used to estimate the shear strength of a bentonitic filter-cake for the kind of bentonite used in the experiments described herein. However, the equation should be used with caution for other bentonites and for water contents that are significantly lower and higher than the ones achieved in these experiments.

Application

The significance of the study of the shear strength of filter cake is that a filter cake with a low water content and a high shear strength might not be ejected as the column of fluid concrete flows upward. Because no quantitative data can be presented at present on the shear stress related to fresh concrete of a given character and flowing with a given velocity in a specific excavation, the data on the strength of bentonitic filter-cake can be used at present only in a qualitative sense. Some further insight to the problem is presented in the following paragraphs.

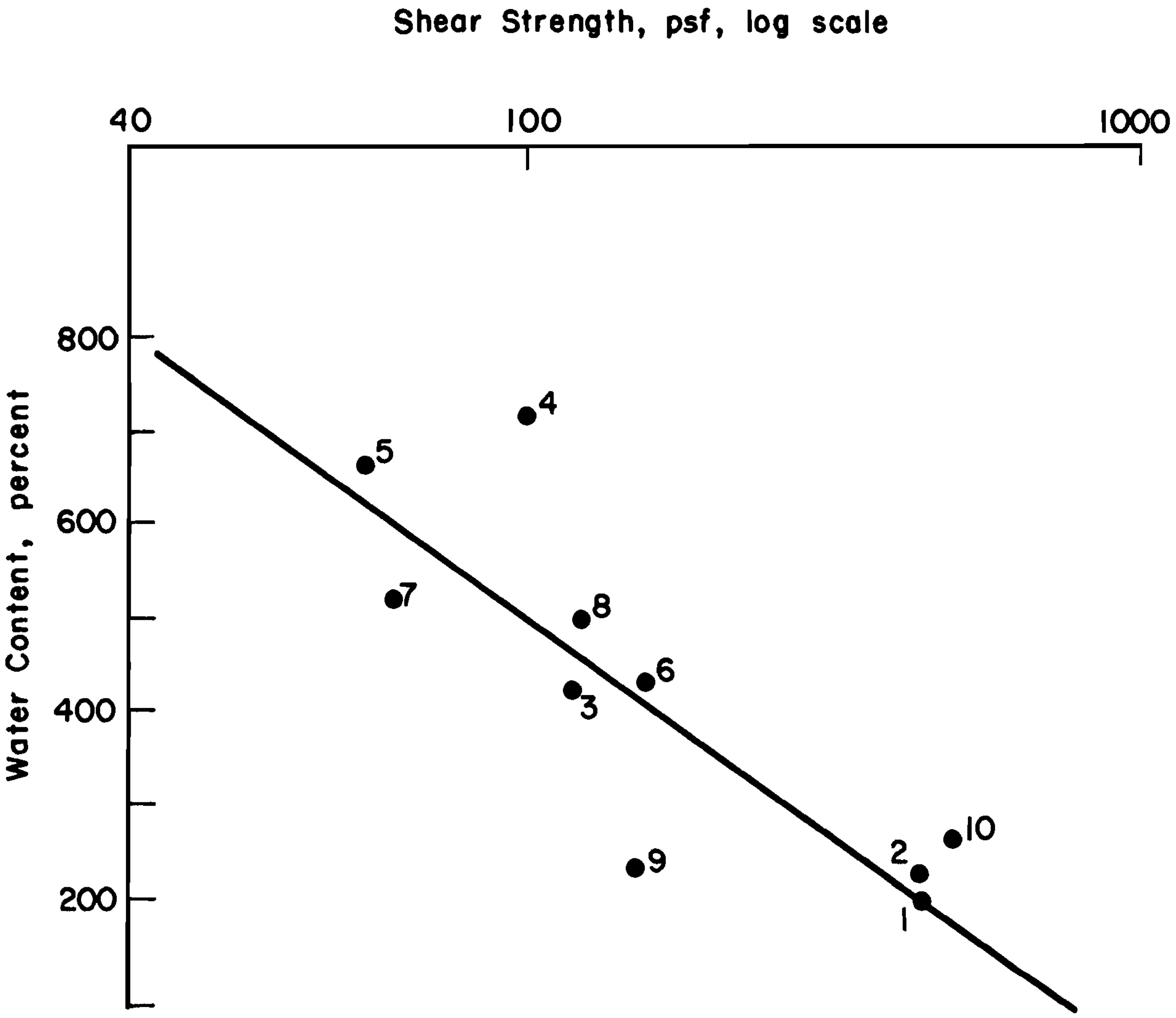


Fig. 3.9. Shear strength vs. water content.

With regard to the nature of the flow of concrete, Tattersall (1976) and others are of the opinion that fresh concrete can be represented as a Bingham fluid where:

$$\tau = \tau_0 + \mu \, dv/dx \qquad (3.2)$$

where

τ = shear stress in the concrete

τ_0 = yield stress in the concrete

μ = plastic viscosity of concrete

dv/dx = shear.

Popovics (1982) states that there is no reliable method for the determination of τ_0 and μ, and numerical values for the parameters are not frequently quoted. However, Fleming and Sliwinski (1977) suggest that values of τ_0 are in the range of 5 to 20 lb/sq ft and go on to say that they expect the upward flowing concrete to scour the filter cake from the walls of vertical boreholes.

Recent studies (Bernal and Reese, 1984) give information on the lateral stress from fresh concrete on the sides of a borehole. The studies showed that higher lateral stress came from concrete with higher slump. The shearing stress from the upward-flowing concrete should assuredly depend on this lateral stress as well as on the concrete properties and the velocity of the upward flow.

Additional research can lead to methods of developing the shearing stress against the sides of an excavation from the concrete column as the concrete flows upward. Information from such research can allow an engineer to make computations as to whether or not a particular filter cake could be removed from a borehole by concrete with particular characteristics.

In the absence of a specific analytical technique the recommendations given later should provide sufficient guidance in order to achieve good construction with the slurry-displacement method.

CHAPTER 4. DEVELOPMENT OF SIDE-WALL SAMPLER AND CALIPERS

Objective

The first portion of this study consisted of laboratory work. The second portion consisted of field work which could be compared with the laboratory work and could serve as a basis for recommendations concerning slurry-construction of drilled shafts. The thrust of the field work was similar to that of the laboratory work, monitoring filter-cake build-up and the properties of the filter cake. In order to monitor filter-cake build-up, a tool was needed which would sample the soil-slurry interface at depth. A side-wall sampler was developed for this purpose.

Considerations

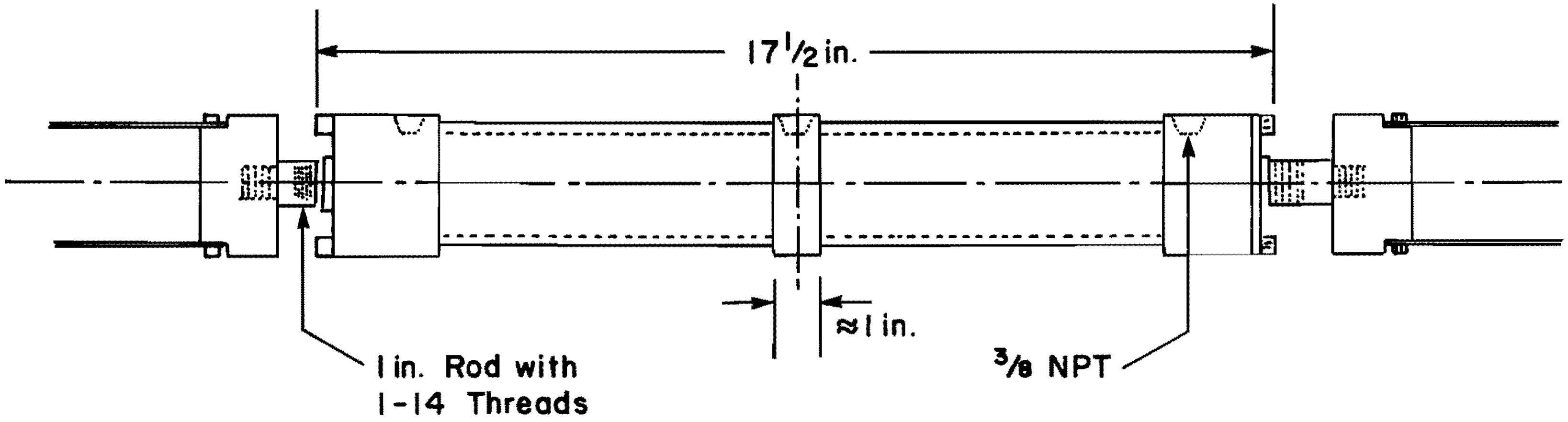
Sampling at Depth. When developing the side-wall sampler, consideration was given to the circumstances under which it would be used. The sample would be taken at depth from the wall of an excavation filled with bentonitic slurry. Thus, the sampler could not be seen or reached and would function horizontally, not vertically, during sampling. These circumstances imposed several requirements on the sampling system. The depth at which the sample was being taken should be known, every caution should be taken to ensure that the sampler did not become stuck or lodged during lowering, sampling, and removing, and the sampler must be controlled from ground level. More specifically, the sampler had to be able to extend and sample, and then retract the sample, all on a horizontal plane, with control being above ground. To ensure that the sampler would not become lodged, it should maintain a horizontal position throughout lowering, sampling and removing, and should remain centered during lowering and removing. Some means was required to ensure that the sampling tube did not become embedded to a point where it could not be removed.

Sample Retrieval. Because the sample was obtained on a horizontal plane rather than on a vertical plane, it would be difficult to twist the sampling tube in order to shear the end of the sample. Hence, some means of retaining the sample during retraction of the sampling tube was required. Also, the slurry in the sampling tube must be provided with an escape route to make room for the sample as the tube was forced into the shaft wall.

Versatility. With the requirements that the sampler be centered, that it not lodge, nor become stuck during sampling, it appeared that a guide would be useful to center the sampler and keep it from lodging. Such a guide would need to be close in size to the diameter of the shaft. Not all shafts, however, are the same size. Thus, it was desired that whatever type of guide and sampler were decided upon, they should be adjustable to be able to sample a variety of shaft sizes.

Sampler Specifics

Hydraulic Cylinders. Two double-acting hydraulic cylinders were used for the body of the sampler. Two cylinders were used so that two samples could be obtained at one time. The two cylinders were mounted end to end to balance the forces developed when the system was activated. Thus, the cylinders remained centered and did not twist. The sampler is shown in Fig. 4.1. Each cylinder was 8 3/4 in. long, with a 2 1/2 in. bore, and with a 4 in. stroke. Each cylinder had a 3.7 ton capacity in extension and 3.1 ton capacity in retraction.



Note:
2½ in. Bore Hydraulic Rams
4 in. Stroke
1550 psi Working Pressure

Fig. 4.1. Side-wall sampler.

Sampling Tubes. Three-in. diameter Shelby tubes, 4 1/2 in. in length were used as sampling tubes. The tubes were mounted to a base as shown in Fig. 4.2. The tubes were attached using four screws. The base had four holes drilled through it to allow the slurry to escape. The base was then attached to the piston by means of a threaded connection. The sampling tubes contained a basket retainer, as shown in Fig. 4.3, to secure the sample in retraction.

Guide. The guide for the sampler is shown in Fig. 4.4. The bearing plates were 4 in. in width and 6 in. in length. The plates were angled on the ends to keep them from hanging up as they were lowered or raised. Bearing plates extended 1/2 in. past the sampling tubes so that the tubes did not come in contact with the wall until the system was activated. The bearing plates kept the cylinders centered in the shaft so that the sampling tubes did not get stuck in the shaft wall. The bearing plates were attached to a metal rod which fit inside a metal tube. The rod was held in place by a bolt and was bored every inch so that it could be adjusted for various shaft diameters. The sampler length was adjusted by adding spacers between the cylinder and sampler-tube base.

Frame and Pump. The sampler was raised and lowered by means of a cable attached to a manual winch. The cable was plastic coated and 140 ft in length. The cable coating was scored every 5 feet. The cut in the coating was then filled with paint. A system was used for marking the cable so that the depth of the sampler was known.

Trial Test

In March of 1983, the sampling system was tested in the yard of Farmer Foundation Company in Houston, Texas. The test shaft was 30 in. in diameter and 10 ft in depth. The soil was a stiff clay. No problems were encountered in

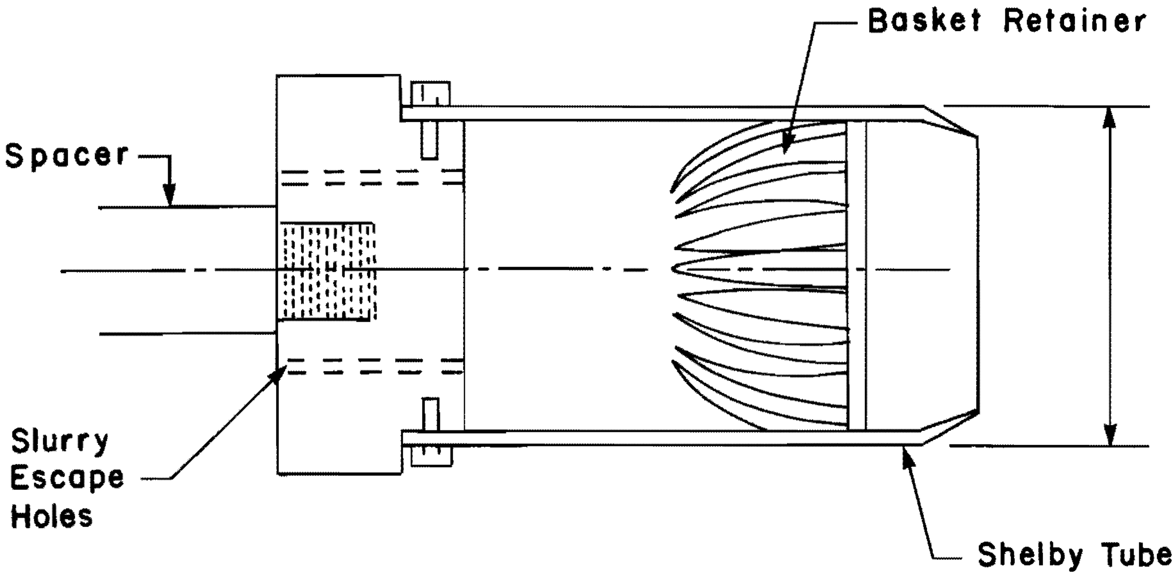


Fig. 4.2. Sampling tube.

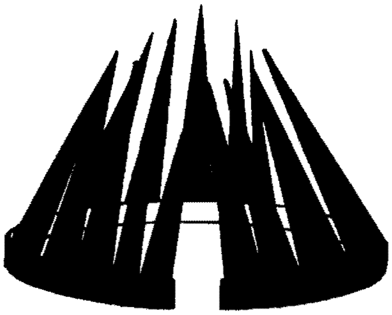


Fig. 4.3. Basket retainer.

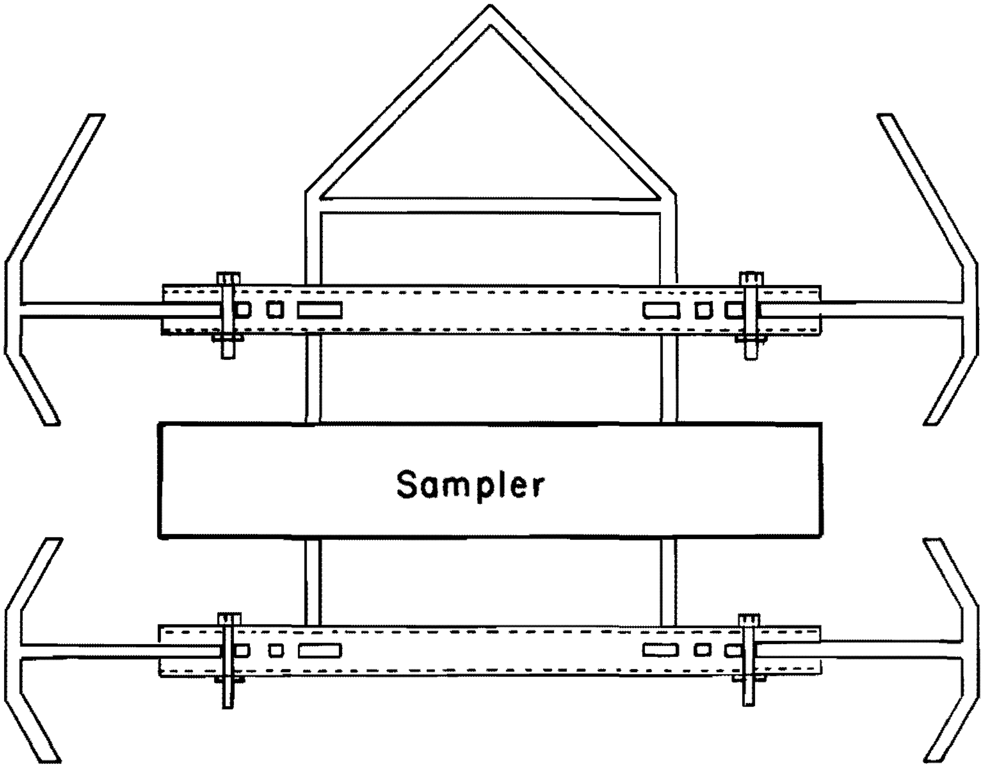


Fig. 4.4. Sampler guide.

testing the system. The guide kept the sampler centered, allowing for sampling and removal of the sampling tubes. Due to the nature of the soil, removal of the samples from the tubes by hand was difficult. Thus, the need was recognized for a mechanical extruder in the field.

Calipers

Objective. The need for calipers arose when some difficulty, which will be addressed in the next chapter, was encountered in lowering the sampler during testing at Lavaca Bay. As a result, determination of the variation in the diameter of the shaft along its length was necessary for proper sizing of the guide and sampler. The uniformity in the diameter of the excavation could be determined, allowing the detection of any caving or expansion of the soil.

Configuration. The calipers developed had four legs, 3 ft in length, and of 1 1/4-in.-square aluminum tubing. A lightweight lawn mower wheel was attached to each leg. The legs were attached to the four sides of a 7-ft-long, 2-in.-square aluminum tube. Screen-door springs ran from the legs to the square tubing, such that when the legs were vertical, the springs were fully extended. The calipers are shown in Fig. 4.5. The legs were held in place by a strap which could be released easily once the calipers were lowered. When the strap was released, the legs moved out from the tubing until they came in contact with the shaft wall. The calipers were raised and lowered by the winch and cable used in raising and lowering the sampler.

Diameter Determination. The configuration of the legs of the calipers allowed the diameter of the shaft to be determined in two complementary directions at one time. Two variable resistors, each with a 10,000-ohm rating, were utilized in determining the shaft diameter. A four-conductor cable ran between the battery, the variable resistors, and the voltmeter. The calipers

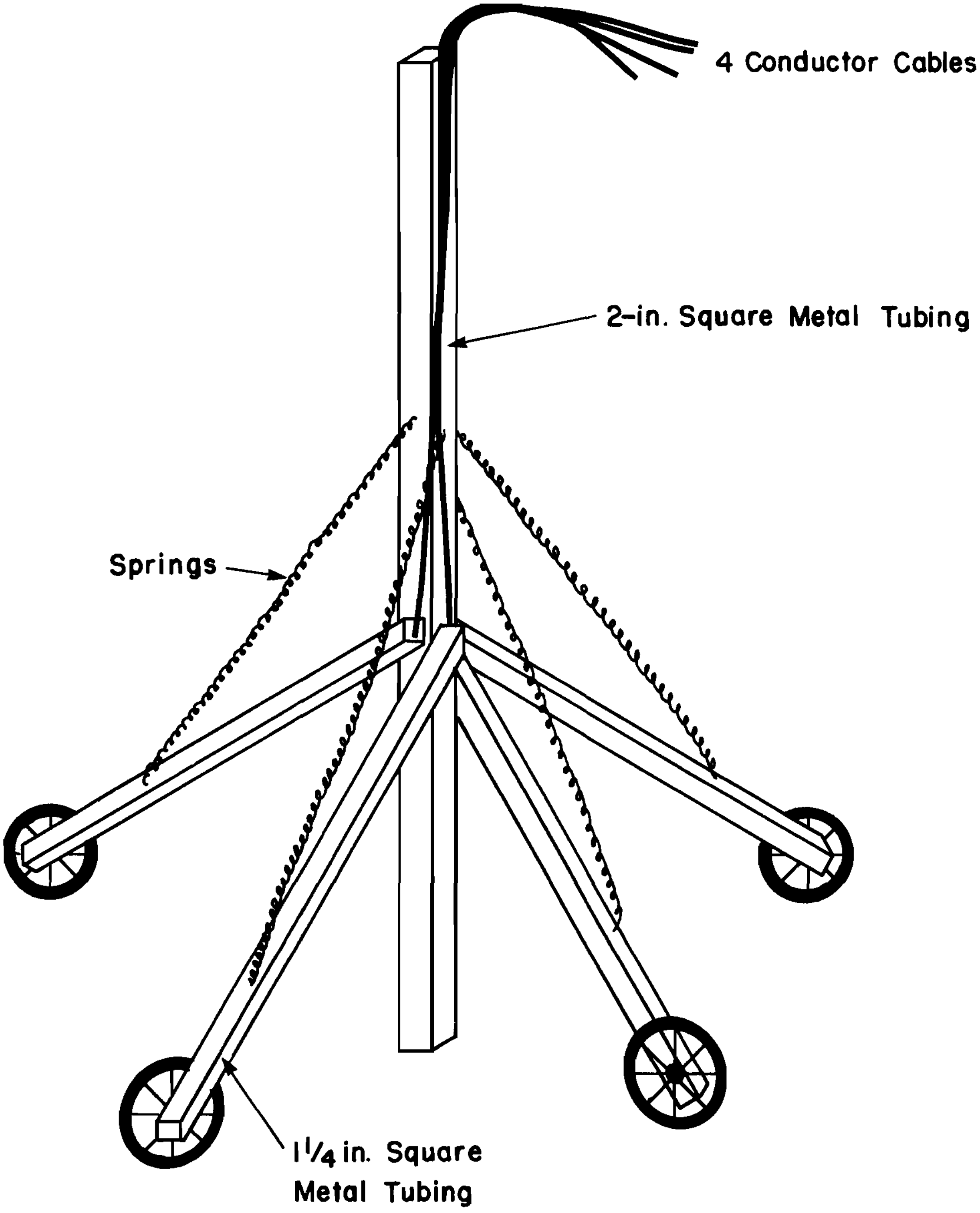


Fig. 4.5. Calipers.

were callibrated such that the voltage reading corresponded to the position of the legs, and, thus, the shaft diameter. Two readings were taken at each level so that the diameter was known in two directions. Table 4.1 gives a sample listing of depth, readings, and the corresponding diameter.

The use of the calipers with production shafts that are constructed by the slurry-displacement method would allow concrete overrun (or underrun) to be investigated as concrete is poured. The level of concrete in the excavation could be measured from point to point and the value of concrete that was placed could be compared with the theoretical volume as determined from measurements with calipers. A graph could be made and would allow the inspector to gain useful information about the probable shaft configuration.

TABLE 4.1. CALIPER READINGS

Depth Below Casing, ft	Diameter, in.
117	27 - 19
116	39½ - 39½
115	39½ - 39½
114	39½ - 39½
112	39½ - 39½
107	40½ - 39½
102	39½ - 39½
97	39½ - 39½
92	40 - 40
87	40 - 40
82	39½ - 39½
77	39½ - 39½
72	40 - 40
67	46 - 42
Casing	40½ - 40½

CHAPTER 5. TESTING AT LAVACA BAY

Site Specifics

Project Specifics. Field work for the filter-cake investigation took place in South Texas where a construction project was underway for the Texas Department of Highways and Public Transportation. The TDHPT project was to replace three deteriorated bents under a bridge between Lavaca Bay and Point Comfort. A test shaft was to be drilled as part of the construction. The total project cost was $750,000 and was to last 125 working days. The tentative starting date was set as October 17, 1983,and the completion date as April 1, 1984.

Construction Sequence. A 41-in.-diameter test excavation was the first item on the construction agenda. The excavation would be drilled using a drill rig mounted on a barge. Support equipment, such as the slurry tanks, would also be located on barges. After completion of the test excavation, drilling for the bent shafts would begin.

Each bent had six drilled shafts; two on each side of the bridge and two beneath the bridge. A beam connected the six shafts. The shafts beneath the bridge were scheduled to be drilled first. The central shafts for all three bents were to be constructed before the exterior shafts and would be drilled from the bridge deck. After they were completed, the drill rig would again be mounted on a barge and the exterior shafts would be constructed. The shafts for all three bents would be constructed on one side of the bridge and then the shafts on the other side would be constructed. Following shaft completion, the beams would be constructed to complete the project.

Construction Problems

Start-Up Delays. Drilling of the test shaft did not begin until October 24, 1983, one week later than scheduled. At this time, discussions took place as to the importance of the exact location of the test shaft. Exact placement would cause further delay, so with the researcher's agreement, the shaft was built within a one foot tolerance of its specified location.

The casing for the test shaft, with an inside diameter slightly less than 41 in., was driven to the specified depth with very little resistance. The contractor suggested that the casing be driven another 5 ft to 10 ft until it was secured. Also, the contractor suggested, with agreement from the researcher, that the working platform for the test shaft be lowered from the level of the bridge deck to a level accessible by boat. This would allow the contractor to rework the shaft without having to remove, and then replace, the platform, since drilling was to be from the water rather than from the bridge. Also, the hazards of working from the bridge during testing would be eliminated. TDHPT agreed to lower the working platform in exchange for driving the casing until it was better seated.

Drilling Delays. The casing was driven an additional 5 ft until it was well seated, followed by rigging for the drilling operation. The shaft was to be drilled using the reverse-circulation process. At the time the drilling bucket was to be connected to the drill stem, it was discovered that the adapter between the bucket and drill stem was the wrong size. Another adapter had to be brought in from Houston, Texas, a three-hour drive from the test site. Shortly after drilling began, the desander for the slurry broke down. A short delay ensued during which time the desander was repaired. Drilling began again, with progress being made in the mud and shale layers composing the top 50 ft of soil. A soil profile of the shaft is shown in Fig. 5.1. Drilling continued at a rate of 10 ft/hour.

Clogging in Clay. Beneath the mud and shale layer was a 5 ft layer of sand followed by a 23 ft layer of stiff clay. Shortly after the clay was encountered, the bucket became clogged with clay and drilling stopped. Over the next several weeks several modifications were made to the drilling bucket in an effort to drill through the clay using reverse circulation. Some of these modifications include changing the cutting teeth, lowering the air lift, shortening the bucket, adding a baffle to direct flow, and modifying the air-lift configuration. An estimated eleven modifications were made to the drilling system, none of which was successful. Consultations with oil drilling companies in the area revealed that the clay layer typically caused drilling delays. Walnut shells and detergents had been added to the slurry by these companies in an effort to form clay "balls" which could be lifted out of the shaft by the air. These attempts had not solved the problem. Because the additives might affect filter-cake development and had not proven entirely successful, they were not used.

After several weeks of effort during which modifications to the drilling system had proven unsuccessful, the attempts to use reverse circulation through the clay layer were abandoned. Negotiations between the TDHPT and the contractor ended in an agreement to use reverse circulation above and below the clay layer. The clay layer would be drilled using an auger. The test shaft was completed in this manner, seven weeks after the project began. Because of the long delay in the completion of the excavation, another excavation was drilled

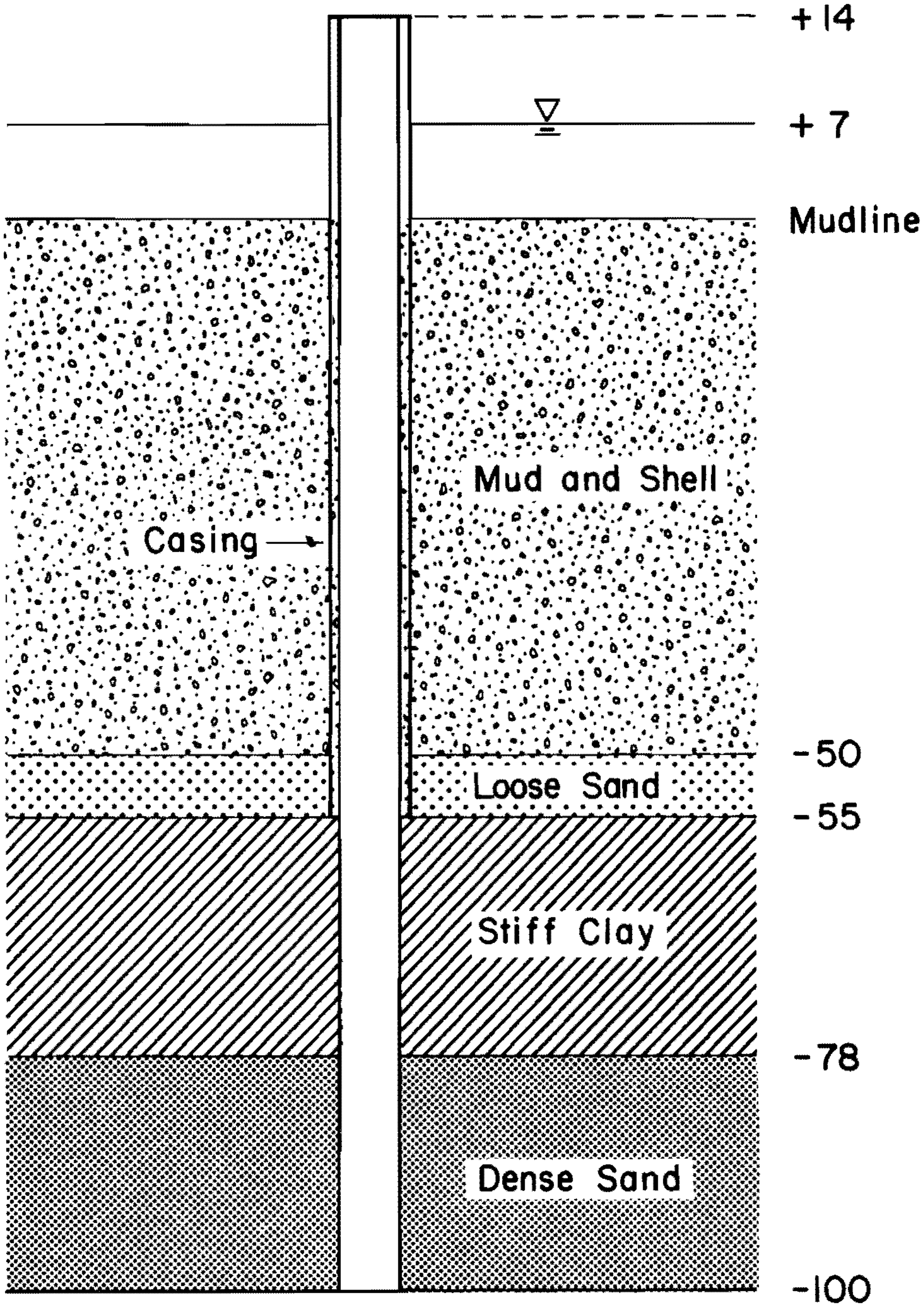


Fig. 5.1. Soil profile at site of test excavation.

on which to run tests. The excavation was 100 ft deep and approximately 40 in. in diameter, rather than 41 inches.

Sampling Problems

Sampling began on December 1, 1983. The slurry supplied to the shaft had a specific gravity of 1.09; the reading with the Marsh cone was 40 sec. The sampler, measuring 39 1/2 in. in length, was lowered down the shaft to a depth of 55 ft below the mudline, but could not be lowered further. The clay layer began at approximately the depth at which the stoppage occurred. Hence, it appeared that the clay had expanded enough so that the sampler was blocked, given the close tolerances of the sampler length and shaft diameter. The decision was made to sample the 5 ft sand above the clay while the sampler was in the shaft. A sample was taken and the sampler raised. However, the sampler was raised only a short distance before it stopped, presumably at the base of the casing. After raising and lowering the sampler several times within the 5 ft space between the clay and the casing, along with working the sampler from side to side, the sampler was retrieved.

The samples obtained from the sand layer a few hours after shaft completion showed no filter-cake build-up. The sand samples did not completely fill the sampling tubes, either. Evidently, the sampler had not been fully extended or the shaft diameter was slightly larger in the sand layer. If the sand layer had been enlarged slightly due to raising and lowering of the auger, it would allow the sampler to move off center and become hung on the base of the casing. In an effort to alleviate the problem of hanging at the base of the casing, an A-frame was attached to the top of the sampler guide to help guide the sampler back into the casing.

The following morning, December 2, 1983, the depth of the shaft was still 100 ft, showing no signs of caving or settling. The clay layer was reworked, using the auger, in an effort to enlarge the diameter of the shaft in the clay layer. The sampler was lowered once again and, again, would not pass through the clay layer. As before, a sample was taken from the sand layer above the clay and the sampler raised. Once again, the sampler became lodged at the base of the casing. After working the sampler back and forth and up and down, the sampler was freed and retrieved. No filter-cake build-up was found on the sand sample, nor did the sample fully fill the sampling tube, as was the case the previous day. At this point, the weather worsened to the point that it was deemed unwise to remain on the bay. The sampler was taken to the contractor's shop in Houston and the guide, which was not adjustable at this time, was shortened approximately 1/2 in. in length. Sampling attempts were resumed on Monday, December 5, 1983.

The depth of the excavation on December 5, 1983, was 20 ft less than on December 2, 1983. In addition, the slurry level in the shaft had fallen several feet. Apparently, either a large amount of settlement of detritus from the slurry had occurred or caving had occurred over the weekend, presumably from the sand layer between the casing and the clay. The casing was immediately driven to the clay layer to avoid any further chances of caving. The sampler was again lowered, but was stopped by the clay as before. Because the casing was now driven to the clay, no sample could be taken.

At this point, the decision was made to return to the University of Texas and modify the sampler. The modifications would be to replace the rigid frame with an adjustable frame, and to add a pressure gauge to the hydraulic pump to ensure that the sampler was fully extended and fully retracted in sampling. The finished product is described in the previous chapter. Also, a set of calipers was developed during this period to determine shaft diameter and to detect any caving which might have occurred. The design of the calipers is also described in the previous chapter.

Testing at Lavaca Bay

Initial Results. Testing resumed on Wednesday, December 14, 1983. The shaft was reworked and drilled an additional two feet. The calipers were used to measure the diameter of the excavation over its length. The results are shown in Table 5.1. A fairly uniform excavation of 39 1/2 in. to 40 in. in diameter was found. The sampler as modified was then lowered and adjusted a total of 3 times before it moved easily in and out of the excavation. The final configuration was such that one side was 1 in. shorter than the other. The guide measured approximately 37 in. in length.

Sand samples were taken at a depth of 91 ft below the mud line at 6, 7 and 24 hours after drilling concluded. Very little filter cake was apparent initially; 1/16 in. to 1/8 in. at most. At the end of 24 hours, 1/8 in. of filter cake was apparent and was slightly firmer than it was the day before. A clay sample was taken after 25 hours and no filter-cake build-up was apparent. The specific gravity of the slurry at the base of the shaft was 1.22 after 24 hours had passed.

After each sample was retrieved, it was slowly extruded from the sampling tube. As it was extruded, it was sliced into layers approximately 1/4 in. in thickness. Each layer was wrapped in plastic wrap and secured with masking tape. The samples were then sealed in wax. At the laboratory at The University of Texas, the water contents of the samples were determined. The results of all of the field testing are shown in Table 5.2.

TABLE 5.1. CALIPER READINGS

Depth Below Casing, ft	Diameter, in.
117	27 - 19
116	39½ - 39½
115	39½ - 39½
114	39½ - 39½
112	39½ - 39½
107	40½ - 40½
102	39½ - 39½
97	39½ - 39½
92	40 - 40
87	40 - 40
82	39½ - 39½
77	39½ - 39½
72	40 - 40
67	46 - 42
Casing	40½ - 40½

TABLE 5.2. RESULTS OF FIELD TESTING

Soil and Depth	Developments		Filter Cake		Soil	
	Date	Hour	Depth, in,	w%	Depth, in.	w%
Sand 105'	12/14/83	6	<1/8	36.1	1/4	32.3
Sand 105'	12/14/83	7	1/8	71.2	1/4	29.6
Sand 105'	12/15/83	24	1/8	71.5	1/4	28.3
					1/2	25.7
Clay 80'	12/15/83	25	0		1/4	63.5
					1/2	54.0
Clay 80'	12/15/83	25	0		1/4	67.1
					1/2	51.7
Sand 105'	1/25/84	1	0		1/4	27.1
					1/2	25.1
					3/4	23/6
Clay	1/25/84	2	0		1/4	26.6
					1/2	22.2
					3/4	21.1
Sand 95'	1/25/84	3	0		1/4	25.2
					1/2	25.0
Sand 105'	1/25/84	4	0		1/4	27.8
					1/2	25.4
Clay 80'	1/27/84	48	0		1/4	44.3
					1/2	35.0
Clay 80'	1/27/84	48	0		1/4	40.1
					1/2	31.9
Sand 100'	1/27/84	48	<1/8	81.5	1/4	44.1
					1/2	26.2
Sand 100'	1/27/84	48	1/8	34.9	1/4	30.4

Weather Problems. Further testing was scheduled to take place weekly over a one month period. The following week, preparations were made to return to Lavaca Bay on December 22, 1983. However, due to bad weather, the job site was closed down for several days. Preparations were then made to return December 29, 1983 for further testing. However, due to abnormally cold weather, the bay had frozen over and the job was shut down. In addition, the barges were forced by the weather move to the inland side of the bridge where they would be better protected. It was not until January 24, 1984 that the barges returned to the gulf side of that bridge and testing resumed.

Final Testing. Testing was attempted January 24, 1984, six weeks after testing began. However, due to thickening of the slurry, the sampler could not be lowered past the casing to obtain samples. The shaft was reworked and sampling initiated. Sand samples at a depth of 91 ft below the mud line were taken at 1, 3, 4 and 48 hours after completion of the shaft. No filter-cake build-up was apparent after 4 hours. After 48 hours, a build up of 1/8 in. was observed. Clay samples were taken at 2 and 48 hours with no build up being observed.

A slurry sample was taken from the shaft at a depth of 91 ft below the mud line after 3 hours. The specific gravity was 1.13, the March cone viscosity was 35 seconds, and the sand content was 3 1/2 to 4%. Another slurry sample was taken after 48 hours at 86 ft below the mudline. The specific gravity was 1.1, the Marsh cone viscosity was 34 seconds, and the sand content was 0.25%. Evidently a good deal of settlement had occurred over the two day period.

A photograph of the device used for sampling slurry in the excavation is shown in Fig. 5.2. A weight at the end of a flexible cable is lowered to the depth where a sample is desired. A cylinder with internal guides is then dropped and is guided to a seated position at the top of the lower weight. The upper weight is dropped and slides along the flexible cable and seals the top

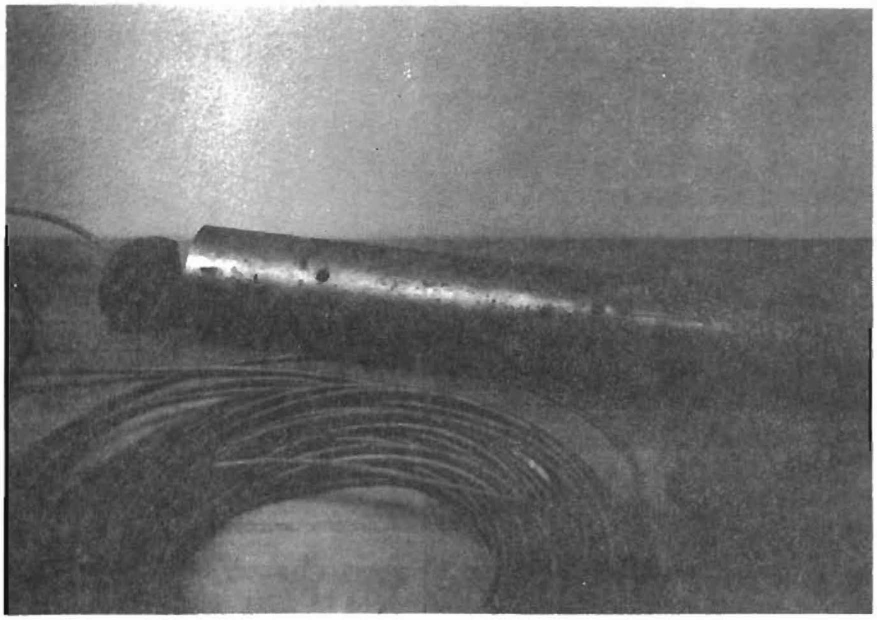


Fig. 5.2. Device for sampling slurry.

of the cylinder. The device is then removed and the slurry contained in the cylinder is available for testing.

CHAPTER 6. SPECIFICATIONS

Need for Specifications

The use of bentonitic slurry in construction has increased over the years. However, its use has not always been under ideal conditions. Many times the slurry has been mixed in the excavation using an auger. If any testing is done, it consists solely of density and viscosity measurements. As a result of the relaxed conditions associated with bentonitic slurry at times, concern has arisen as to the integrity of the slurry and the finished product. This concern has lead to the development in the last ten years of various specifications.

Specifications

Sliwinski and Fleming (1975) suggested general ranges for the various properties of bentonitic slurry. The properties were associated with the function of the slurry. Table 6.1 shows these relationships. As can be seen, the desired values of the properties range from low to high depending on the function. Thus, a slurry which would function ideally at all times must change properties with functions. An ideal slurry, therefore, is impossible. However, an effective slurry is possible with controls. Hutchinson, Daw, Shotton, and James (1975) suggested a more detailed set of specifications as did P. T. Hodgeson (1977). Tables 6.2 and 6.3, respectively, show the suggested specifications. Neither set regards the Marsh Cone as more than a qualitative

TABLE 6.1. SLURRY SPECIFICATIONS FROM FLEMING AND SLIWINSKI (1975)

Function of suspension	Parameter				
	Viscosity	Shear strength	Density	Fluid loss	pH
Form filter cake and stabilize bore by hydrostatic pressure application	Moderate to high	Moderate to high	High	Moderate to low	
Reduce cavitation caused by tool disturbance	High	High	—	Moderate	Low
Minimize loss of fluid in pervious strata	High	High	—	—	Low
Minimize loss of fluid in excavation spoil	Low	Low	—	—	—
Prevent accumulation of dense particles at base of excavation prior to concreting	High	High	High	—	—
Ensure free flow of concrete from tremie and easy displacement of bentonite from excavation and reinforcement	Low	Low	Low	—	Low
Allow easy pumping of bentonite fluid	Low	Low	Low	—	—
Prevent sedimentation in pipes and tanks	Moderate	High	High	—	—

TABLE 6.2. SLURRY SPECIFICATIONS FROM HUTCHINSON, DAW, SHOTTON, AND JAMES (1975)

	bentonite concentration	density	plastic viscosity	apparent viscosity	Marsh cone viscosity	yield strength	10 min gel strength (Fann)	pH	fluid loss	sand content
excavation support	>4½% §13	>1·034 g/cm^3 §16		not a primary parameter	regarded only as a qualitative test	regarded as less important than 10 min gel strength	>36 dyn/cm^2 §15 J		results can be deceptive with present type of test	>1% §14
excavation sealing	>4½% §19									
detritus suspension	>4% §25						>25 dyn/cm^2 §25			
displacement by	<15%	<1·3 g/cm (requires further verification) §28	<20 cP (requires further verification) §28					<11·7 §37		<35%
physical cleaning		<1·21 g/cm^3 §35								<25% §35
pumping							>25 dyn/cm^2 §40 <200 dyn/cm^2 §41			
limits	>4½% <15%	1·034 g/cm^3 1·21 g/cm^3	<20 cP				>36 dyn/cm^2 <200 dyn/cm^2	<11·7		>1% <25%

TABLE 6.3. SLURRY SPECIFICATIONS FROM HODGESON (1977)

Property	Method	Supplied to Trench 3-5	% 5-8	Prior to Concreting 3-5	% 5-8
plastic viscosity	Fann viscometer	3-10	7-20	20	20
10-min-gel strength N/m^2	Fann viscometer	2-20	10-40	20	40
density g/mL	mud balance	1.02-1.07	1.03-1.10	1.02-1.20	1.03-1.15
API sand content % vol	API test	5	5	14	9
fluid loss mL in 30 min	API test	40	40	60	60
pH	pH meter	10.8	10.8	11.7	11.7

measurement. However, its use has continued due to its simplicity and the expense of alternate methods.

The Federation of Piling Specialists (1977) suggested a set of specifications which not only include slurry properties, but also material requirements and construction procedures. Table 6.4 is a summary of the FPS slurry specifications. The FPS specifications are not as extensive as are some others. Holden (1983) found the FPS specifications to be inadequate for a project in Australia. He suggests a much more extensive set of specifications (Table 6.5). He also suggests that the specifications be modified, after further study, to suit the particular equipment, methods, and conditions of a project.

Modification of any specification is necessary for optimal compatibility for a particular project due to the different soil conditions that may be encountered. As the development of specifications is in the early stages, more studies are needed to broaden the scope of specifications. The FPS specifications are a good base on which to build, although they may not always be adequate. The entire FPS specifications are in Appendix C.

TABLE 6.4. SLURRY SPECIFICATIONS FROM F.P.S. (1977)

Item to be Measured	Range of Results at 20° C	Test Method
density	less than 1.10 g/mL	mud density balance
viscosity	30-90 sec or less than 20 cP	Marsh cone method Fann viscometer
shear strength	1.4 to 10 N/m^2 or 4 to 40 N/m^2	shearometer Fann viscometer
pH	9.5 to 12	pH indicator paper strips or electrical pH meter

Prior to concreting: density less than 1.25 g/mL

TABLE 6.5. SLURRY SPECIFICATIONS FROM HOLDEN (1983)

Bentonite Property	Mud Supply during Excavation	Socket Slurry during Interruptions	Socket Slurry during Concreting
bentonite type	sodium bentonite OCMA spec		
bentonite concentration % wt/wt of water	4 min		
density, gm/cc	1.03 min 1.08 max	1.03 min 1.08 max	1.03 min 1.20 max
API sand content, % by vol	0 min 2 max	0 min 2 max	10 max
API fluid loss, mL in 30 min	10 max	10 max	
cake thickness mm	1 max	1 max	
pH (field check with indicator)	8 min 11 max	8 min 11 max	
plastic viscosity (viscometer) cP	4 min 10 max	4 min 10 max	20 max
yield point Pa	14 max	14 max	
10 min gel strength Pa	2 min 10 max	7.5 min	7.5 min 20 max
API marsh funnel viscosity sec (field check)	30 min 40 max	30 min 40 max	
head of bentonite	1 m above water table (min)	1 m above water table (min) 1.5 m above water table (max)	1 m above water table (min)

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

From Literature Research

1. Construction practices dictate the effect of bentonite slurry on the capacity of drilled shafts. Over the years, conflicting reports have been issued as to the effect of bentonitic slurry on skin friction. Laboratory reports indicate that not all of the filter-cake build-up is removed by the scouring action of the concrete. The remaining filter-cake has shown an adverse effect on skin friction. Field studies report that although all of the filter cake may not be removed, rarely does a drilled shaft constructed by use of the slurry-displacement method carry less in skin friction than a drilled shaft constructed dry. The only occasion reporting a reduction was one in which poor construction practices were used; i.e. the excavation remained filled with slurry for a long period of time and was not cleaned prior to concrete placement.

2. Improper construction practices may cause inclusions to occur in the shaft, sand to collect on the reinforcement, and/or heavy filter-cake build-up. Construction practices include the procedure by which the shaft is excavated, the amount of time the shaft remains open, cleaning of the shaft, and properties of bentonitic slurry. Thus, specifications regarding the mixing and cleaning of the slurry as well as the engineering properties of the slurry are needed for proper construction of a drilled shaft using the slurry-displacement and the casing method.

Laboratory vs. Field Investigation

1. The experimental set-ups for the laboratory studies peformed well. The procedure by which filter cakes were developed worked very well. The sedimentation process also worked well, but its range of application was limited by time.

2. No build-up of filter cake was observed on clay soil.

3. The results of the laboratory work indicated that at low pressures, time had little effect on filter-cake build-up on sand for a given slurry composition. However, at medium to high pressures, time had a pronounced effect on filter-cake build-up. Pressure had very little impact for a given time period on filter-cake build-up when slurries with high concentrations of bentonite were used. In addition, slurries with the high concentrations of bentonite yielded lower water contents for the same filter-cake thickness when medium to high pressures were used.

4. The sedimentation process yielded an equation of the shear strength of bentonitic slurry as a function of water content. While there was a considerable scatter in the experimental results, the equation should provide some guidance for estimating whether all of a particular filter cake can be removed by the upward-flowing concrete.

From Field Experiments

1. The instruments, equipment, and procedures employed in the field for investigating the characteristics of slurry and the build-up of filter cake were effective.

The samples of filter cake and soil obtained were of good quality and the method of sealing the samples for transport worked very well. The calipers that were designed and built provided very useful information on the profile of the excavation. Data indicated that reverse circulation produced an excavation of uniform diameter.

2. The filter-cake build-up in the field was much less than that in the laboratory for the same time period. A build-up of 1/8 in. was the maximum observed in the field after two days. Build-up over longer periods was not determined due to the various problems encountered.

3. No filter cake was observed immediately after reworking the shaft. Prior to reworking, the shaft had remained filled with slurry for a period of six weeks. During that period, the slurry was not agitated or altered in any manner. The slurry in the shaft conformed to both FPS specifications (1977) and Holden's specifications (1983) for slurry prior to concreting. The sand content of the slurry, however, was higher than that suggested by Holden during delay periods.

4. Direct comparison of the field and laboratory investigations was difficult due to the limited field data and the difference in soil and slurry composition. The field slurry was contaminated with sand and other detritus whereas the laboratory slurry was composed of bentonite and water only.

Recommendations

1. Further field testing at a variety of sites to investigate the build-up of filter cake is recommended. In this manner, various soil conditions would be encountered. Accumulation of data will allow detailed specifications to be developed which will be applicable to a variety of circumstances.

2. The instruments and procedures employed in the investigation described herein are recommended for use in the field studies.

3. When the slurry-displacement method is employed the use of calipers to detect shaft irregularities and to predict concrete overrun (or underrun) is recommended. Such a practice would give insight as to the integrity of the shaft.

4. Laboratory investigations in which the sand content of the slurry is varied would be informative and more comparable to field work. Other detritus such as clay and soil particles resulting from drilling could also be added to the slurry.

5. Detailed specifications cannot be developed on the basis of the relatively small amount of data gathered in this study. However, the following guidelines are recommended for use in the interim.

A. Specifications should be adopted provisionally for the mixing of bentonitic slurry and for the condition of the slurry prior to placing concrete for the slurry-displacement method and prior to placing casing for the casing method. The FPS Specifications (1977) in Appendix C, with the addition of a requirement on sand content, should be given strong consideration. (Note: Such specifications may require the contractor to use de-sanders and to circulate clean slurry into the excavation to displace sand-laden slurry.)

B. Concrete should be poured during the same day a slurry-stabilized excavation is made or the excavation should be re-worked prior to concrete placement.

C. High-slump concrete, which gives higher lateral pressures against the sides of the excavation than low-slump concrete (Bernal and Reese, 1984), should be employed in the construction of drilled shafts. (Note: This recommendation is aimed particularly at the slurry-displacement method and at the casing method but it is also beneficial if the dry method of construction is used.)

REFERENCES

1. Bernal, Juan B. and L. C. Reese, "Study of Lateral Pressure of Fresh Concrete as Related to the Design of Drilled Shafts," Report to Center for Highway Research, The University of Texas at Austin, May 1984.

2. Boyes, R. G. H., Structural and Cut-Off Diaphram Walls, Barking, Essec, England, 1975.

3. Everett, J. and C. M. McMillan, "Bentonite Piles in Durban," Soil Mechanics and Foundation Engineering, Proceedings of the Sixth Regional Conference for Africa, Vol. 1, Capetown, Africa, 1975, pp 155-159.

4. Farmer, I. W., P. J. C. Buckley, and Z. Sliwinski, "The Effect of Bentonite on the Skin Friction of Cast in Place Piles," Behavior of Piles, Proceedings of the Conference organized by the Institution of Civil Engineers in London, September 1970, pp 115-120.

5. Farmer, I. W. and M. Goldberger, "Effect of Bentonite on the Skin Friction of Bored Piles," Cementation Research Ltd., Internal Report, 1969.

6. Federation of Piling Specialists, "Specification for Cast in Place Piles Formed under Bentonite Suspension," Ground Engineering, Vol. 8, No. 2, London, March 1975.

7. Fleming, W. K. and Z. S. Sliwinski, The Use and Influence of Bentonite in Bored Pile Construction, London, September 1977.

8. Holden, J. C., "The Construction of Bored Piles in Weathered Sedimentary Rock," Fourth Autralian-New Zealand Conference on Geomechanics, Perth, May 1984.

9. Hodgeson, P. T., "Design and Control of Bentonite/Clay Suspensions and concrete Diaphragm Wall Construction," A Review of Diaphragm Walls, 1979.

10. Hutchinson, M. T., G. P. Daw, P. G. Shotton, and A. N. James, "The Properties of Bentonite Slurries used in Diaphragm Walling and their Control," Diaphragm Walls and Anchorages, London, 1975, pp 33-39.

11. O'Neill, Michael W. and Lymon C. Reese, "Behavior of Axially Loaded Drilled Shafts in Beaumont Clay," a Research Report conducted for the Texas Highway Department, in cooperation with the U.S. Department of Transpotation, Federal Highway Administration, Bureau of Public Roads, December 1970.

12. Popovics, S., "Fundamentals of Portland Cement Concrete," Fresh Concrete, Vol. I, Wiley & Sons, New York, 1982.

13. Tattersall, G. H., "The Workability of Concrete, Cement and Concrete Association," Wexham Springs, Slough, U.K., 1976.

14. Touma, Fadlo T. and Lymon C. Reese, "Load Tests of Instrumented Drilled Shafts Constructed by the Slurry Displacement Method," a Research Report conducted for the Texas Highway Department by the Center for Highway Research, The University of Texas at Austin, January 1972.

15. Sliwinski, Z. J., "The Effect of the Bentonite Displacement Method of Construction on the Boring Capacity of Piles and Diaphragm Wall Elements," London, October 1977.

16. Sliwinski, Z. J., and W. G. K. Fleming, "Practical Considerations Affecting the Construction of Diaphragm Walls," Diaphragm Walls and Anchorages, London, 1974, pp 1-10.

17. Wates, J. A., and K. Knight, "The Effect of Bentonite on the Skin Friction in Cast-in-Place Piles and Diaphragm Walls," Sixth Regional conference on Soil Mechanics and Foundation Engineering, Vol. 1, Cape Town, Africa, 1975, pp 183-188.

18. Weiss, F., "Die Wandreibung von im Konstraktionsverfahren unter Bentonite Suspension Sgeschutteten Betonwaden," Die Bautechnik, 1965.

APPENDIX A

RESULTS OF LABORATORY TESTS

APPENDIX A. RESULTS OF LABORATORY TESTS

Test Details	Filter Cake		Soil	
	Depth (in.)	w (%)	Depth (in.)	w (%)
	+5/8	660	0	190
8.4% bentonite	+1/2	586	-1/8	115
15 psi	+3/8	506	-1/4	74
4 days	+1/4	362	-3/8	43
	+1/8	230	-1/2	30
			-5/8	24
			-3/4	26
			-1	32
			-5/4	26
			-3/2	22
	+1/4	748	0	16
12.8% bentonite	+3/2	700	-1/4	15
15 psi	+5/4	657	-1/2	17
5 days	+1	579	-3/4	20
	+3/4	542	-1	21
	+1/2	431	-5/4	21
	+1/4	183	-3/2	21
			-7/4	21
			-2	21
8% bentonite	+3/2	587	0	31
15 psi	+5/4	773	-1/4	25
5 days	+1	609	-1/2	23
	+3/4	431	-3/4	21
	+1/2	245	-1	19
	+1/4	99	-3/2	20
			-3/2	20
			-7/4	20
			-2	19
8% bentonite*	+3/2	1071	0	27
15 psi	+5/4	930	-1/4	26
3 days	+1	867	-1/2	25
	+3/4	653	-3/4	24
	+1/2	553	-1	22
	+1/4	191	-5/4	21
			-3/2	21
			-7/4	28
			-2	23

* Quik Gel

Test Details	Filter Cake (in.)	w (%)	Sand (in.)	w (%)
5% bentonite	+1	1065	0	27
15 psi	+3/4	789	-1/4	26
6 days	+1/2	539	-1/2	24
	+1/4	282	-3/4	22
			-1	20
			-5/4	18
			-3/2	18
			-7/4	18
			-2	17
8% bentonite*	+5/4	904	0	25
15 psi	+1	583	-1/4	21
4 days	+3/4	550	-1/2	20
	+1/2	416	-3/4	21
	+1/4	160	-1	22
			-5/4	22
			-3/2	22
			-7/4	21
			-2	22
8% bentonite	+5/8	1081	0	48
30 psi	+3/8	836	-1/4	26
1 day	+1/8	314	-1/2	25
			-3/4	20
			-1	19
			-5/4	19
			-3/2	18
			-7/4	18
			-2	20
8% bentonite	+7/8	844	0	28
30 psi	+3/4	731	-1/4	25
3 days	+1/2	551	-1/2	23
	+1/4	347	-3/4	22
			-1	19
			-5/4	18
			-3/2	18
			-7/4	19
			-2	19
10% bentonite	+1/2	682	0	29
30 psi	+1/4	273	-1/4	22
1 day			-1/2	24
			-3/4	21
			-1	20
			-5/4	19
			-3/2	19
			-7/4	19
			-2	18

* Quik Gel

Test Details	Filter Cake (in.)	w (%)	Sand (in.)	w (%)
10% bentonite	+3/4	648	0	28
30 psi	+1/2	487	-1/4	26
3 days	+1/4	207	-1/2	24
			-3/4	21
			-1	18
			-5/4	18
			-3/2	18
			-7/4	18
			-2	18
10% bentonite	+3/8	836	0	29
30 psi	+1/8	129	-1/4	26
3 hours			-1/2	23
			-3/4	20
			-1	19
			-5/4	18
			-3/2	18
			-7/4	18
			-2	18
10% bentonite	+1/2	649	0	28
3 psi	+1/4	333	-1/4	24
3 days			-1/2	20
			-3/4	19
			-1	19
			-5/4	19
			-3/2	18
			-7/4	19
			-2	19
10% bentonite	+1/2	714	0	63
3 psi	+1/4	450	-1/4	24
1 day			-1/2	25
			-3/4	21
			-1	19
			-5/4	19
			-3/2	19
			-7/4	19
			-2	18
10% bentonite	+1/2	788	0	30
3 psi	+1/4	344	-1/4	26
1 day			-1/2	22
			-3/4	19
			-1	18
			-5/4	18
			-3/2	18
			-7/4	19
			-2	19

Test Details	Filter Cake (in.)	w (%)	Sand (in.)	w (%)
10% bentonite	+7/8	835	0	29
3 psi	+5/8	670	-1/4	25
3 days	+3/8	550	-1/2	23
	+1/8	144	-3/4	23
			-1	19
			-5/4	19
			-3/2	19
			-7/4	19
			-2	19

APPENDIX B

SAND SIEVE ANALYSIS

APPENDIX B. SAND SIEVE ANALYSIS

Sieve No.	Amt. Retained (gm)	Amt. Passing (gm)	% Passing
40	61.5	938.5	93.8
60	673.0	265.5	26.6
80	207.5	58.0	5.8
100	20.0	28.0	3.8
pan	38.0	0.0	0.0

APPENDIX C

SPECIFICATION FOR CAST IN PLACE PILES FORMED UNDER BENTONITE SUSPENSION

Federation of Piling Specialists
(whose copyright is retained
in the specification)

**GROUND
ENGINEERING**

Specification for Cast in Place Piles formed under Bentonite Suspension

Preface

THE USE OF bentonite in the formation of piles has now become a normal and accepted practice, though one which involves rather different technical skills from those known in traditional bored piling.

Bentonite may be used in a variety of ways, but the most important at the present time are for

(*i*) The process of "mudding in",
(*ii*) The maintenance of the stability of an unlined boring until a temporary or permanent casing, or concrete, has been installed within it.

The process of "mudding in" is one which is used to assist the insertion of temporary or permanent casing as a normal part of pile construction. It involves using a rotary boring machine, usually fitted with an auger, to penetrate the ground.

Bentonite and water are mixed into the ground by rotation and vertical motion of the auger, until a column of slurry has been formed. Casing may then be inserted, the slurry baled out, and pile construction can proceed in the normal manner.

This process is not covered by this specification.

The other process is one in which a bentonite suspension is used instead of casing to retain the ground during boring. This process is based on digging out soil from the base of the excavation, avoiding contamination of a bentonite suspension which is contained within it excepting in so far as it may be used to transport excavated material to a screening system in the case of plant based on the "reverse circulation" principle. The process is akin to that of forming cast in place diaphragm walls and, following from the preparation of a diaphragm wall specification by this Federation, the time would now seem to be opportune to introduce a series of specification clauses which can be used for piling work in this class in conjunction with the existing FPS SPECIFICATION FOR CAST IN PLACE PILING.

One of the most important aspects of the method is that the concrete must fully displace the bentonite suspension in each pile. The bentonite suspension and the concrete both exhibit shear strength characteristics, and the conditions of displacement might be said to be governed by the "active" and "passive" pressure states of the two materials involved. The "active" pressure of flowing concrete reduces as the mix becomes less workable, and the "passive" pressure of the bentonite suspension increases as it becomes denser and more viscous through contamination. Displacement will cease when a balance condition is reached, and it is essential to prevent such a situation arising. Much that is written in the following clauses is aimed at achieving the optimum displacement conditions.

Specification clauses

for addition to the normal FPS Specification for Cast in Place Piles, when the piles are to be bored under bentonite suspension and the concrete placed by tremie

Design

1.* The minimum pile diameter shall generally be 600mm unless otherwise approved.

2. The assumptions made in design regarding load carried by end bearing and by shaft friction are to be clearly stated.

3. The minimum cover to the main bars of steel reinforcement is to be 75mm and the minimum clear spacing between main bars shall be 100mm where aggregates of over 20mm size are used. This spacing may be reduced to not less than 75mm where aggregates of 20mm size or less are used.

Materials

4.* The concrete mix shall be designed to flow easily in the tremie pipe and to give a dense concrete when placed without the aid of any mechanical method of compaction. Aggregates shall comply with gradings in Zones 2, 3, or 4 of BS 882 and shall preferably be of naturally rounded gravel and sand.

5.* Water cement ratio shall not exceed 0.6.

Bentonite

6. Bentonite, as supplied to the site and prior to mixing, shall be in accordance with Specification No. DFCP.4 of the Oil Companies Materials Association, London.

7.* A certificate is to be obtained by the Specialist Contractor from the manufacturer of the bentonite powder, stating from which manufacturer's consignment the material delivered to site has been taken, and showing properties of the consignment as determined by the manufacturer. This certificate shall be made available to the engineer on request.

8.* The bentonite powder shall be mixed thoroughly with clean fresh water. The percentage of bentonite used to make the suspension shall be such as to maintain the stability of the pile excavation.

9.* Control tests are to be carried out on the bentonite suspension, using suitable apparatus, to determine the following parameters:

(i) * Freshly mixed bentonite suspension

The density of the freshly mixed bentonite suspension shall be measured daily as a check on the quality of the suspension being formed. The measuring device is to be calibrated to read within ± 0.005g/ml.

(ii) * Bentonite suspension supplied to pile boring

In average soil conditions the following tests shall be applied to the bentonite supplied to the boring and the results shall generally be within the ranges stated in the table below:

Item to be measured	*Range of results at 20 deg C*	*Test method*
Density	Less than 1.10g/ml	Mud density balance
Viscosity	30-90 seconds	Marsh Cone method
Shear strength (10 min gel strength)	1.4 to 10N/m^2	Shearometer
pH	9.5-12	pH indicator paper strips

Tests to determine density, viscosity, shear strength and pH value shall be carried out initially until a consistent working pattern has been established, taking into account the mixing process, any blending of freshly mixed bentonite suspension and previously used bentonite suspension, and any process which may be employed to remove impurities from previously used bentonite suspension.

When the results show consistent behaviour, the tests for shear strength and pH value may be discontinued, and tests to determine density and viscosity only shall be carried out as agreed with the Engineer. In the event of a change in the established working pattern, the additional tests for shear strength and pH value shall be reintroduced for a period if required by the Engineer.

(iii) * Bentonite suspension in boring prior to placing concrete

Prior to placing concrete in any pile the Specialist Contractor shall ensure that heavily contaminated bentonite suspension, which could impair the free flow of concrete from the tremie pipe, has not accumulated in the bottom of the trench. The proposed method for checking this item is to be stated with the tender, and is to be agreed with the Engineer prior to the commencement of the contract. If the bentonite suspension is found to exhibit properties outside the agreed appropriate range, then it shall be modified or replaced until the required agreed condition is achieved.

10. The temperature of the water used in mixing bentonite suspension, and of the suspension supplied to the trench excavation, is to be not less than 5 deg C.

11. During construction, the level of bentonite suspension in the pile shall be maintained within cased or stable bore, and at a level not less than 1.0m above the level of external standing ground water.

12. In the event of a sudden loss of bentonite suspension, the boring shall be backfilled without delay and the instructions of the Engineer shall be obtained.

13. Where saline or chemically contaminated ground water occurs, special measures shall be taken by agreement with the Engineer to modify the bentonite suspension.

14. All reasonable steps shall be taken to prevent spillage of bentonite suspension on the site away from the immediate vicinity of the pile. Discarded bentonite suspension which has been pumped from the boring is to be removed from the site.

Construction

15.* The proposed method of excavation is to be stated by the Specialist Contractor at the time of tendering.

16. Concrete shall be placed continuously by tremie pipes fed by gravity or under pressure, and care shall be taken during placing to avoid contamination of the concrete.

17. The tremie pipe shall be clean, watertight and of adequate diameter to allow the free flow of concrete. The tremie shall extend to the bottom of the pile boring prior to the commencement of concrete pouring, and care shall be taken to ensure that all bentonite suspension is expelled from the tube during the initial charging process. Sufficient embedment of the tremie pipe in concrete shall be maintained throughout concrete pouring to prevent re-entry of bentonite suspension into the pipe.

18. The concrete pour for any pile shall be completed in such a manner and within such time that the concrete above the foot of the tremie remains workable until the casting of the pile is complete.

**See Notes for Guidance*

Specification for Cast in Place Piles formed under Bentonite Suspension
Pub. 1975

Modifications 1977

Clause 9 Delete the Table and insert the new table shown for insertion in Clause 26 of the Diaphragm Walling Specification

Clause 26 Delete the Table and insert

Item to be measured	Range of Results at 20 deg C	Test Method
Density	Less than 1.10 g/ml	Mud density balance
Viscosity	30-90 second	Marsh Cone Method
	or	
	Less than 20 cP	Fann Viscometer
Shear Strength	1.4 to 10 N/m^2	Shearometer
	or	
	4 to 40 N/m^2	Fann Viscometer
pH	9.5 - 12	pH Indicator paper strips or electrical pH meter

Notes for guidance

Clause 1. *Where piles of less than 750mm diameter are proposed or specified, the Specialist Contractor should, at the tender stage, state any precautionary measures which he proposes to employ in order to safeguard the integrity of the pile.*

Clauses 4 & 5. *The desirable range of slump is from 175mm to 200mm.*

Clause 7. *The properties which should normally be given by the manufacturer are the apparent viscosity range (Centipoises) and the gel strength range* (N/m^2) *for solids in water.*

Clause 8. *In the case of certain estuarine clays of very low strength, it may not be possible to produce a suspension which alone will maintain the stability of borings. Care also needs to be taken in very permeable ground.*

Clause 9. *Details of apparatus and test methods referred to may be obtained from the following publications:*
Recommended Practice: Standard by American Petroleum Institute, New York City, 1957. Ref. API RP29. Sections I, II and IV relate to the above mentioned tests. Alternative source API. RP13B, Second Edition, April 1969.
The control figures given in this clause relate to a typical bentonite material of British origin.
(i) A satisfactory way of measuring the density of a bentonite suspension is by means of a mud balance.
The following table shows the relationship between the concentration, expressed as a percentage by weight, and density:

Concentration per cent	*Density g/ml*
3	1.017
4	1.023
5	1.028
6	1.034

(ii) Freshly mixed bentonite suspension should comply with the requirements of the table consistently, provided a normal concentration has been selected. Where bentonite suspension is used once only and then discarded, the tests set out in the table should not be necessary beyond a short initial period, unless some alteration is made to the concentration or mixing procedure.
Where bentonite suspension is re-used, or is blended with freshly mixed suspension, or has chemical additions made to preserve its properties, there will be a need for routine checking throughout the work, particularly in regard to the tests for density and viscosity. The frequency of testing may initially need to be on a pile by pile basis where bentonite suspension becomes heavily contaminated during its first use (e.g. fine sand soil conditions) and may in other cases (e.g. mainly clay soil conditions) be on a daily basis where contamination is slight. Subsequent frequency will need to be agreed between the Engineer and Specialist Contractor in the light of the test results obtained.
In those cases where a mechanical process is employed to remove contaminating solids from the suspension, the frequency of testing will depend on the circumstances and the equipment employed. The Specialist Contractor should indicate to the Engineer, prior to the commencement of the contract, that he intends to employ such a method, and tests should be carried out as for re-used and blended suspensions.
In certain cases, with the approval of the Engineer, the Specialist Contractor may elect to carry out additional or alternative tests such as the measurement of sand content and fluid loss.
Where the process of "reverse circulation" is used it may be useful to use the sand content measurement, in which case an upper limit of about 6 per cent by weight of fluid would normally be applied
Some Engineers consider the fluid loss measurement difficult to interpret because of the difficulty experienced in relating it to the varied ground conditions.
In the event of either of these tests being proposed, the limiting value of the resulting measurements should be agreed between the Engineer and the Specialist Contractor.
(iii) One method of identifying contaminated bentonite suspension is to take a sample of the suspension from near the bottom of the pile excavation (say about 0.2m above the base of the pile) and to carry out a density test on this using a mud balance. Where this method is employed, the density determined should not normally be greater than 1.25g/ml to enable satisfactory concrete placing.
The results of tests on bentonite suspension referred to throughout Clause 9 should be related to a temperature of 20 deg C approximately.

Clause 13. *The modification required depends on the nature of the contamination. In saline conditions it is frequently necessary to ensure that the bentonite is fully hydrated in fresh water before supplying it to the pile.*

Clause 15....*The use of chiselling to overcome obstructions may cause difficulty in maintaining the stability of the boring and it is therefore an item to be treated with caution. It should also be allowed for in preparing the Bill of Quantities, where the possibility of its use is apparent.*

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