

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CR 83.020	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) An Investigation of the Effects of Grain Crushing on the Engineering Analysis of Calcareous Sediments	9. PERFORMING ORGANIZATION NAME AND ADDRESS Ertec Western, Inc. 3777 Long Beach Boulevard Long Beach, CA 90807	5. TYPE OF REPORT & PERIOD COVERED Final Apr 1981 - Dec 1982
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Ertec Western, Inc.	11. CONTROLLING OFFICE NAME AND ADDRESS Naval Civil Engineering Laboratory Port Hueneme, CA 93043	8. CONTRACT OR GRANT NUMBER(s) N62474-82-C-8269
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 42-044; YF60.536.091.01.A206		
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Department of Interior, Mineral Manage- ment Service and Naval Facilities Engineering Command	12. REPORT DATE March 1983	
	13. NUMBER OF PAGES 77	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited	15. SECURITY CLASS. (of this report) Unclassified	
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Calcareous, sand, model, pile, laboratory, crushability, cementation		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Sixteen specially prepared laboratory soil specimens were subjected to model pile driving to induce grain crushing about the pile perimeter and study the effects grain crushing has on the engineering analysis of calcareous sediments. Each speci- ment constituted a particular material, level of degree of cementation, and density. The parameters measured for each test		

DD FORM 1473
1 JAN 73

EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

were the pile driving resistance, pile pullout resistance, and grain size analysis curves determined before and after pile driving for areas next to and remote to the pile surface. The results of this experiment revealed that crushability depends on the interrelated effects of grain harness, pile penetration resistance to driving, cement content, and soil density. A significant finding showed that the pile driving resistance is not a rational parameter in assessing pullout capacity for piles in calcareous sands.

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	1
1.1 General	1
1.2 Background Information	1
1.3 Objective and Scope	3
1.4 Contents	4
1.5 Personnel	4
2.0 TEST SETUP	5
2.1 General	5
2.2 Test Material	5
2.3 Test Equipment and Setup	5
2.3.1 Model Pile and Driving Assembly	6
2.3.2 Sample Retention System	6
2.3.3 Sample Preparation Equipment	7
2.3.4 Pullout Load Test System	7
2.3.5 Instrumentation and Data Acquisition System	8
3.0 TEST PROCEDURES	14
3.1 General	14
3.2 Sample Preparation	15
3.3 Pile Driving	16
3.4 Pile Pullout Test	16
3.5 Subsampling After Pullout Test	16
3.6 Grain Size Analysis	17
4.0 RESULTS, ANALYSES AND DISCUSSIONS	19
4.1 Number of Tests	19

TABLE OF CONTENTS (Cont.)

	<u>Page</u>
4.2 Results	19
4.2.1 Pile Driving	19
4.2.2 Pullout Test	20
4.2.3 Crushability	21
4.3 Data Analyses and Discussions	22
4.3.1 Crushability Versus Cement Content	23
4.3.2 Crushability Versus Pile Penetration Resistance	24
4.3.3 Crushability Versus Pullout Resistance	24
4.3.4 Pullout Resistance Versus Cement Content	25
4.3.5 Pullout Resistance Versus Density	25
5.0 SUMMARY, REMARKS AND CONCLUSIONS	54
5.1 Summary	54
5.2 Remarks	55
5.3 Conclusions	57
6.0 REFERENCES	59

APPENDIX A - TEST EQUIPMENT AND PROCEDURES

LIST OF TABLES

Table No.

- 4-1 SUMMARY OF THE TEST PROGRAM AND RESULTS
- 4-2 CHANGES IN FINES CONTENT

TABLE OF CONTENTS (Cont.)

LIST OF FIGURES

<u>Figure No.</u>	<u>Title</u>
2-1	GRAIN SIZE DISTRIBUTION CURVE OF CALCAREOUS SAND TESTED
2-2	MICROSCOPIC PHOTOGRAPHS OF CALCAREOUS SAND
2-3	GRAIN SIZE DISTRIBUTION CURVE OF THE SILICA SAND TESTED
2-4	SCHEMATIC DIAGRAM OF COMPLETE TEST SETUP
2-5	SCHEMATIC DIAGRAM OF TEST DRUM
3-1	SUBSAMPLING SCHEME AND SEQUENCES
4-1	DRIVING ENERGY VERSUS PILE PENETRATION - HIGHER DENSITY CALCAREOUS SAND
4-2	DRIVING ENERGY VERSUS PILE PENETRATION - LOWER DENSITY CALCAREOUS SAND
4-3	DRIVING ENERGY VERSUS PILE PENETRATION - HIGHER DENSITY SILICA SAND
4-4	DRIVING ENERGY VERSUS PILE PENETRATION - LOWER DENSITY SILICA SAND
4-5	MAXIMUM PULLOUT RESISTANCE VERSUS PILE DRIVING RESISTANCE
4-6	FINES CONTENTS VERSUS DISTANCE OF SPECIMEN FROM THE PILE WALL - HIGHER DENSITY CALCAREOUS SAND
4-7	FINES CONTENT VERSUS DISTANCE OF SPECIMEN FROM PILE WALL - LOWER DENSITY CALCAREOUS SAND
4-8	FINES CONTENT VERSUS DISTANCE OF SPECIMEN FROM PILE WALL - HIGHER DENSITY SILICA SAND
4-9	FINES CONTENT VERSUS DISTANCE OF SPECIMEN FROM PILE WALL - LOWER DENSITY SILICA SAND
4-10	GRAIN SIZE DISTRIBUTION CURVES FOR SPECIMENS AT OR NEAR THE PILE WALL - HIGHER DENSITY CALCAREOUS SAND (CEMENT CONTENT = 0%)
4-11	GRAIN SIZE DISTRIBUTION CURVES FOR SPECIMENS AT OR NEAR THE PILE WALL - HIGHER DENSITY CALCAREOUS SAND (CEMENT CONTENT = 0.5%)

TABLE OF CONTENTS (Cont.)

LIST OF FIGURES

<u>Figure No.</u>	<u>Title</u>
4-12	GRAIN SIZE DISTRIBUTION CURVES FOR SPECIMENS AT OR NEAR THE PILE WALL - HIGHER CALCAREOUS SAND (CEMENT CONTENT = 1%)
4-13	GRAIN SIZE DISTRIBUTION CURVES FOR SPECIMEN AT OR NEAR THE PILE WALL - HIGHER DENSITY CALCAREOUS SAND (CEMENT CONTENT = 2%)
4-14	GRAIN SIZE DISTRIBUTION CURVES FOR SPECIMENS AT OR NEAR THE PILE WALL - LOWER DENSITY CALCAREOUS SOIL (CEMENT CONTENT = 0%)
4-15	GRAIN SIZE DISTRIBUTION CURVES FOR SPECIMENS AT OR NEAR THE PILE WALL (CEMENT CONTENT = 0.5%)
4-16	GRAIN SIZE DISTRIBUTION CURVES FOR SPECIMENS AT OR NEAR THE PILE WALL - LOWER DENSITY CALCAREOUS SAND (CEMENT CONTENT = 1%)
4-17	GRAIN SIZE DISTRIBUTION CURVES FOR SPECIMENS AT OR NEAR THE PILE WALL - LOWER DENSITY CALCAREOUS SAND (CEMENT CONTENT = 2%)
4-18	CHANGE IN FINES CONTENT AT OR NEAR THE PILE WALL VERSUS CEMENT CONTENT - HIGHER DENSITY CALCAREOUS SAND
4-19	CHANGE IN FINES CONTENT AT OR NEAR THE PILE WALL VERSUS CEMENT CONTENT - LOWER DENSITY CALCAREOUS SAND
4-20	CHANGE IN FINES CONTENT AT OR NEAR THE PILE WALL VERSUS CEMENT CONTENT - HIGHER DENSITY SILICA SAND
4-21	CHANGE IN FINES CONTENT AT OR NEAR THE PILE WALL VERSUS CEMENT CONTENT - LOWER DENSITY SILICA SAND
4-22	AVERAGE CHANGE IN FINES CONTENT AT OR NEAR THE PILE WALL VERSUS CEMENT CONTENT
4-23	PILE DRIVING RESISTANCE VERSUS AVERAGE CHANGE IN FINES CONTENT AT OR NEAR THE PILE WALL
4-24	PILE PULLOUT RESISTANCE VERSUS AVERAGE CHANGES IN FINES CONTENT AT OR NEAR THE PILE WALL
4-25	AVERAGE FRICTION RESISTANCE VERSUS CEMENT CONTENT
4-26	PILE PULLOUT RESISTANCE VERSUS DRY DENSITY OF CALCAREOUS SAND

1.0 INTRODUCTION

1.1 General

This report presents the results of a research investigation on the effect of grain crushing on the frictional characteristics of a driven model pile in calcareous and silica sands. Ertec carried out the work under the Naval Civil Engineering Laboratory (NCEL) Contract No. N62474-82-C-8269 dated March 15, 1982, and in general accordance with NCEL's statement of work dated December 2, 1981.

1.2 Background Information

Calcareous sediments consist primarily of calcium carbonate. These sediments differ from terrigenous sediments in several areas (Noorany, 1982b; Datta, et al, 1981; McClelland Engineers, Inc., 1980):

1. They are primarily a product of biological activities.
2. They are softer and have more intra-granular voids, and thus, they are more susceptible to crushing.
3. They are more susceptible to post-depositional physical and chemical alternation.

Various researchers (Datta, et al, 1979, 1980, 1981; Agarwal, 1977; Demars, et al, 1976) have identified the following parameters as being most significant in affecting the behavior of calcareous sediments:

1. Carbonate Content
2. Crushability
3. Degree of Cementation

Because of the behavioral difference, current design methodology for piles in conventional terrigenous soils is not applicable to the design of piles in calcareous sands. An adequate determination of the skin friction characteristics of piles in calcareous sediments requires a thorough understanding of the soil-pile interaction mechanism. This mechanism is complex and poorly understood. There exist considerable experimental evidence to indicate the following observations for piles in calcareous soils:

1. Under static loading conditions, skin friction resistance of the piles can be significantly lower than the piles in terrigenous sands (Angemeer, et al, 1973, 1975).
2. Cyclic loading can cause further reduction of the skin friction value (King, et al, 1980).
3. Grouted piles in calcareous sands potentially yield much higher pile load carrying capacity than driven piles of the same types (Angemeer, et al, 1973, 1975).
4. Current design methodology for piles in calcareous sands is not reliable (Datta, et al, 1980).

Unfortunately, existing experimental information cannot be fully explained by conventional theory. Given the uncertainty in current design methodology, significant judgment is usually introduced in designing piles for calcareous sediments. Where important facilities are planned, it is a normal practice to conduct pile load tests to confirm load predictions. These programs are costly and time-consuming. They are usually impractical for most projects. Instead, large factors of safety are normally introduced to account for design

uncertainty. However, this approach leads to costly over-design in many cases. In other situations, the large safety factor is not sufficient, resulting in unsafe design.

The proceeding summary indicates that the present design framework for piles in calcarous soils requires further improvement. It needs a systematic research and development program aimed towards a better understanding of the soil-pile interaction mechanism which controls the pile behavior in calcareous sediments.

1.3 Objective and Scope

This research investigation is a part of NCEL's effort to improve its understanding of the physical mechanisms controlling the behavior of piles in calcareous sands. The objective of this research investigation was to qualitatively examine the following items related to piles in calcareous sands:

1. The effect of pile driving on the degree of grain crushing
2. The effect of grain crushing on the frictional resistance characteristics of piles in calcareous sands
3. The effect of cementation on the crushability and frictional resistance characteristics.

To accomplish the objective, a series of laboratory experiments were performed using a model pile driven into two sandy soils. These soils include (1) a Florida sand supplied by NCEL, and (2) a uniform silica sand. Samples of each sand were prepared at two (2) different densities and four (4) different

cement contents as specified by NCEL. The scope of work included the following tasks:

- (1) Design and fabrication of test setup and equipment
- (2) Performance of a laboratory testing program which would include sample preparation, pile driving, pile pullout testing, and obtaining specimens for grain size determinations
- (3) Data analysis.

1.4 Contents

Section 2 provides a detailed description of the test setup and test materials. A description of various test procedures is provided in Section 3. The results of this research investigation together with data analyses and relevant discussions are presented in Section 4. Section 5 provides our remarks and conclusions for this research investigation. Appendix A presents a more detailed description of step-by-step test procedures and various equipment utilized in this investigation.

1.5 Personnel

This investigation was performed under the overall direction and management of Dr. Bill Lu. He was assisted by Mr. Apichart Phuhunhaphan who directed the laboratory experiment program and participated in technical evaluation and by Mr. Reynold Jie who assembled the test setup and performed the tests. Mr. Hudson Matlock and Dr. Donald Anderson provided continuous advice as well as technical review of this report.

NCEL's technical representative was Mr. Stephen C. McCarel. NCEL's Contract Administrator was Ms. Ellen Maggard.

2.0 TEST SETUP

2.1 General

This section provides a description of the test materials and test setup utilized in this investigation.

2.2 Test Materials

Two sandy materials were utilized in this investigation; one was a Florida calcareous sand and the other was a natural silica sand. Samples of each sand were prepared at two different densities and four different cement contents.

A total of sixteen 5-gallon drums of Florida calcareous sand was provided by the NCEL. The calcareous sand is a uniformly graded sand with elongated and angular grain particles. It contains variable amounts of shell fragments and little or no fines. The range of grain size distribution of the calcareous sand tested is shown in Figure 2-1. Microscopic examination of this Florida calcareous sand indicates that most of the particles are porous and have a rough texture. Two microscopic photographs of the soil particles, magnified at approximately 30 times, are shown in Figure 2-2. The results of laboratory tests indicated that the specific gravity of this sand ranged from 2.81 to 2.85 with an average value of about 2.82.

The silica sand utilized in this investigation was a commercially available clean coarse to medium sand, commonly referred as the Lone Star No. 1/20 silica sand. Figure 2-3 shows the grain size distribution of this sand. The specific gravity of the silica sand was determined to be about 2.65.

2.3 Test Equipment and Setup

The test setup and equipment utilized in this investigation were specifically designed and built to meet the project requirements. Figure 2-4 shows a

schematic illustration of the complete test setup. The test setup consisted of the following systems:

1. Model pile and pile driving system,
2. Sample retention system (red barrel),
3. Sample preparation system,
4. Pullout load test system, and
5. Instrumentation and data acquisition system.

2.3.1 Model Pile and Driving Assembly

The model pile was a 1.5-inch diameter and 18-inch long flat-ended solid steel rod. This model pile had been utilized by the NCEL in a previous study and was provided for use in this investigation.

The pile driving assembly consisted of a guide rod, a 15-pound steel dead weight, and a guide plate assembly. The guide rod was 0.5 inch in diameter and 4 feet long. The bottom end of this guide rod was concentrically threaded into the top of the model pile. The top end of the guide rod fits through a guide plate which was supported by three vertical steel posts mounted onto the top plate of the sample retention system (red barrel - refer to next section) to provide sufficient rigidity and to ensure the plumbness of the guide rod. Pile driving was achieved by dropping the dead weight from a distance of one (1) foot above the top of model pile.

2.3.2 Sample Retention System

The soil sample (Section 2.3.3) was placed in a test drum, commonly referred as the "red-barrel". The red barrel utilized in this study consisted of a

30-inch diameter and 30-inch high hollow steel cylinder with end plates bolted to both ends of the cylinder, and a pressurization system. A schematic diagram of this test drum is shown in Figure 2-5. This test drum can apply up to 100 psi of stresses to simulate overburden and lateral stress conditions through a series rubber tubes (Figure 2-5) filled with water pumped in by an external pressure source. For this investigation, an overall confining pressure of 20 psi was applied in every test, simulating a pile at about 50 to 60 feet below the seafloor.

2.3.3 Sample Preparation Equipment

Each soil sample was 9 inches in diameter and 18 inches high. Each sample was prepared to the prescribed density, moisture content, and cement content, using a split mold and a rubber membrane. The split mold was capable of applying vacuum to stretch the rubber membrane against the mold wall. After sample preparation, each sample was cured in a moisture room for a minimum of three (3) days prior to testing.

2.3.4 Pullout Load Test System

The pullout load test system comprised of a hydraulic loading system and a load frame. The hydraulic system consisted of a hydraulic actuator, a hydraulic pump, and a flow rate adjuster. This system was used to pull out the pile by displacement control at a slow rate. The load frame consisted of a steel plate which was supported by three (3) vertical steel posts rigidly connected to the top end plate of the red barrel.

2.3.5 Instrumentation and Data Acquisition System

The instrumentation for pullout tests consisted of a strain-gaged load cell to monitor the pullout force and a displacement transducer (LVDT) to monitor the pile displacement. The data acquisition system consisted of a multi-channel conditioner with digital and analog output, and an X-Y-Y recorder.

The load cell and displacement transducer were continuously monitored and results plotted by the X-Y-Y recorder during the pile pullout tests.

Approved by _____

Checked by _____

Drawn by _____

Compiled by _____

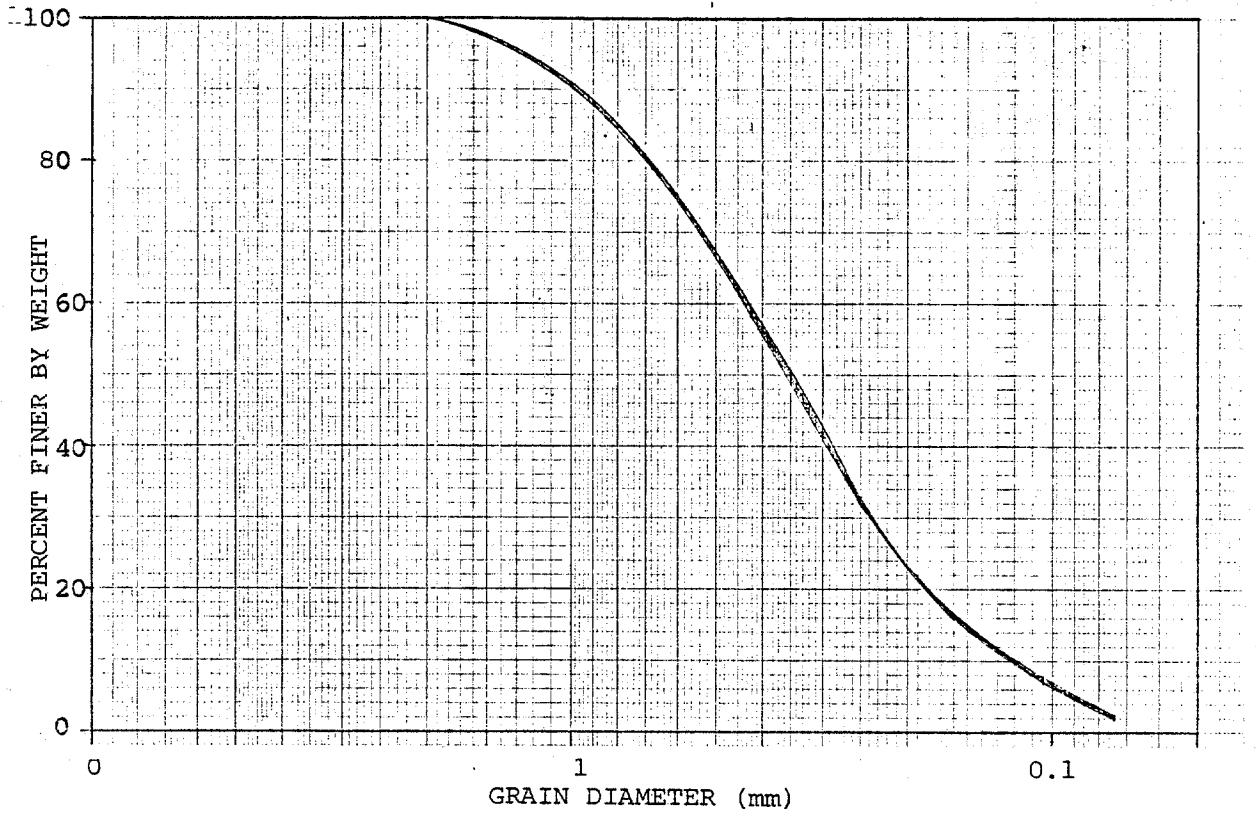


FIGURE 2 - 1

GRAIN SIZE DISTRIBUTION CURVE
OF THE CALCAREOUS SAND TESTED

APPROXIMATE MAGNIFICATION
FACTOR: 30

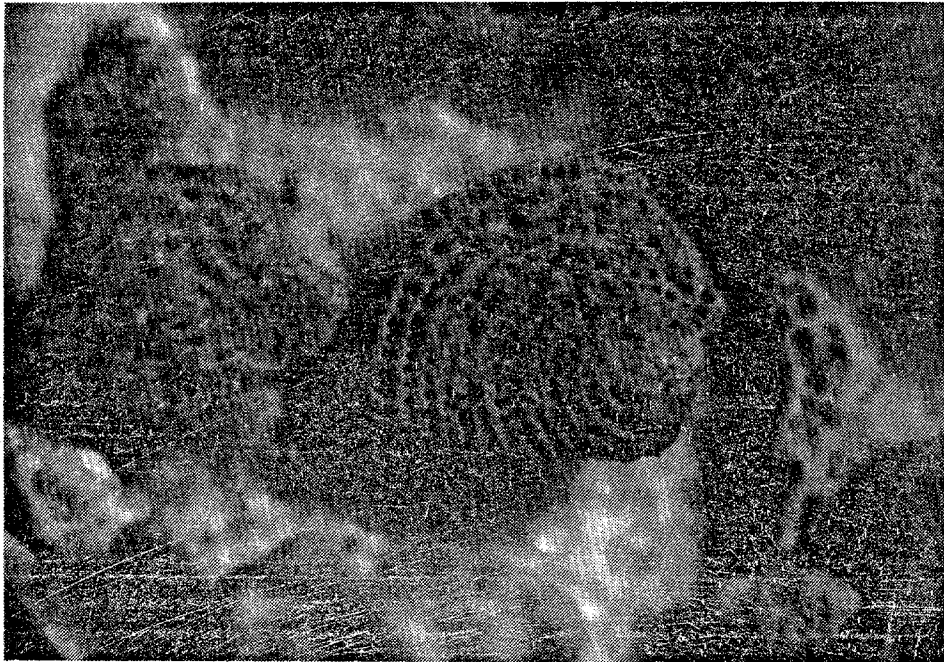
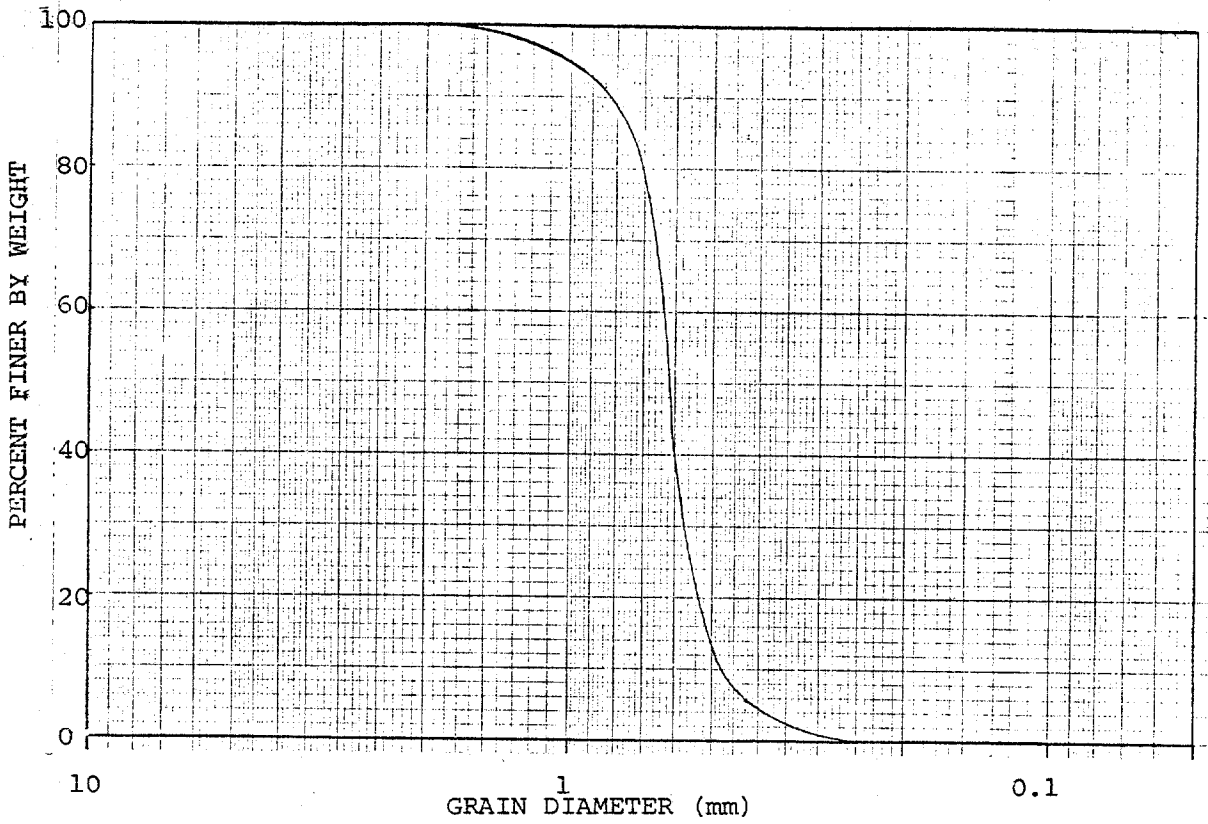



FIGURE 2-2. MICROSCOPIC PHOTOGRAPHS OF CALCAREOUS SAND

Compiled by _____ /
Drawn by _____ /
Checked by _____ /
Approved by _____ /



 <small>The Earth Technology Corporation</small>	FIGURE 2 - 3
GRAIN SIZE DISTRIBUTION CURVE OF THE SILICA SAND TESTED	

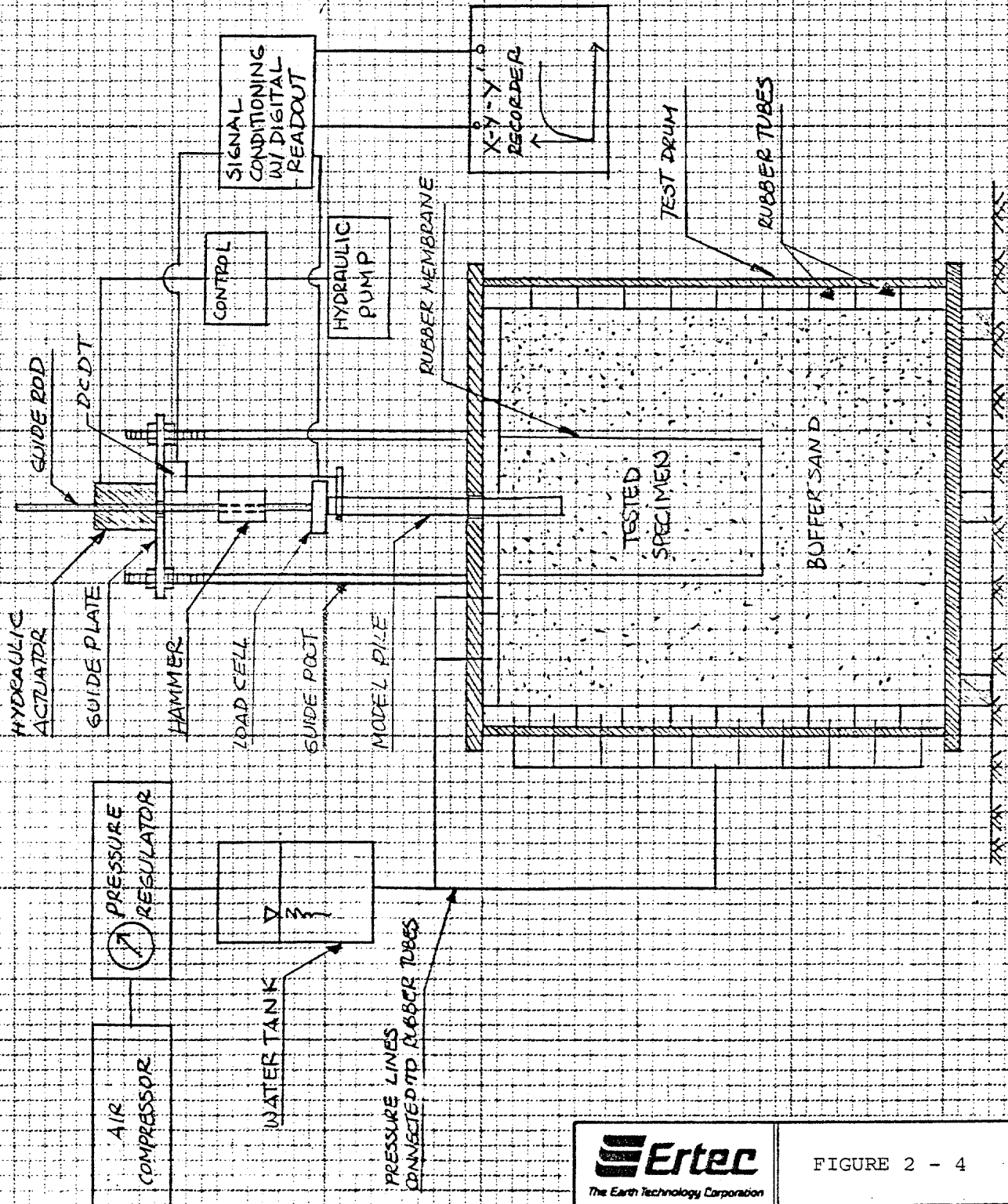
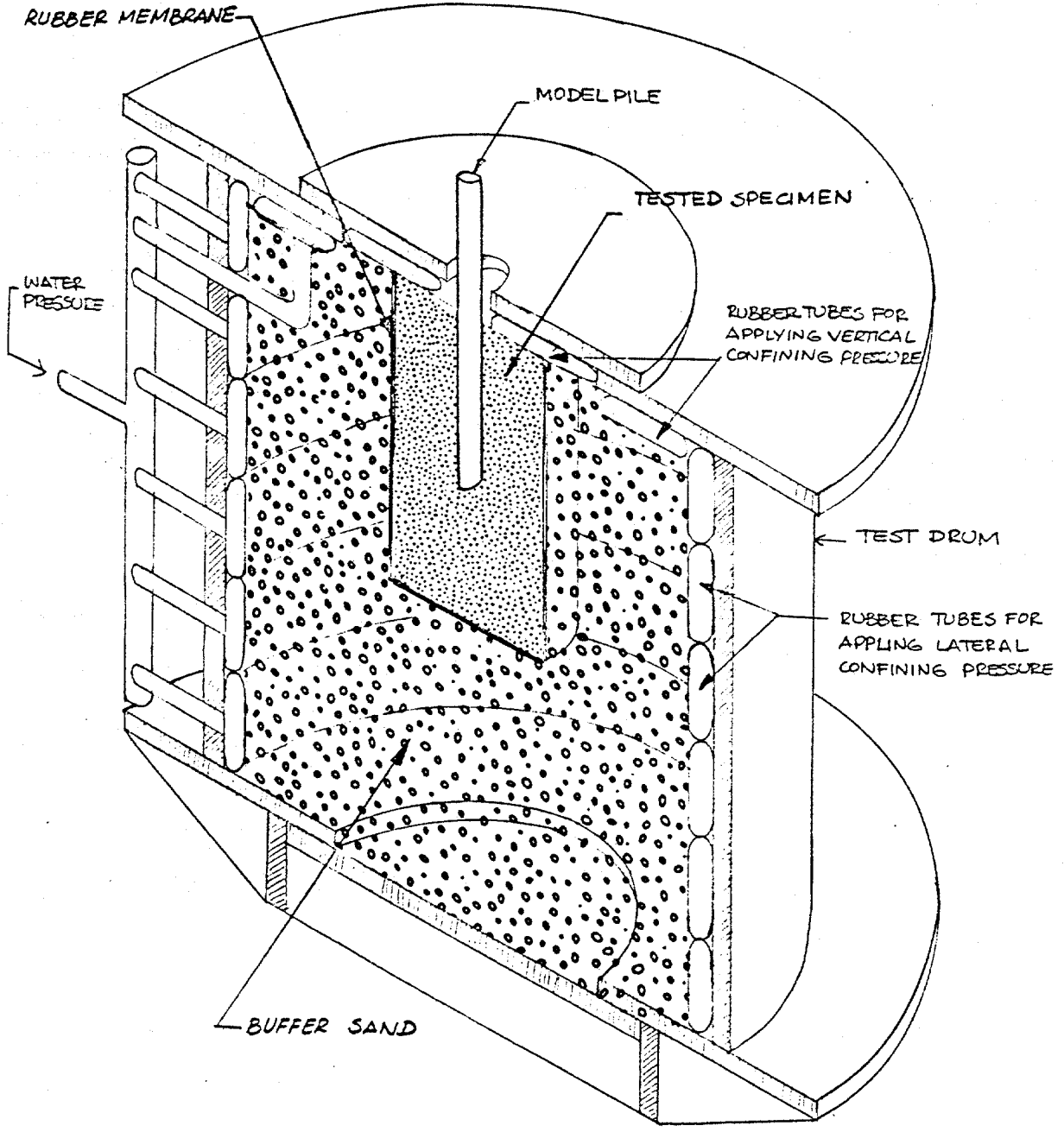


FIGURE 2 - 4

SCHEMATIC DIAGRAM OF COMPLETE TEST SETUP



Approved by _____
Checked by _____
Drawn by _____
Compiled by _____



FIGURE 2 - 5

SCHEMATIC DIAGRAM OF TEST DRUM

3.0 TEST PROCEDURES

3.1 General

A total of 20 laboratory test series was performed on the two different sands prepared at various prescribed densities, moisture contents and cement contents (Section 4.1). Each test generally consisted of the following sequence:

1. Preparing and curing the sample
2. Placing the sample in the red barrel (test drum) and then applying an overall confining pressure of 20 psi
3. Driving the model pile into the soil sample
4. Performing a pullout test
5. Subsampling to obtain soil specimens at various depths and distances from soil-pile interface.

Prior to the initiation of laboratory testing, a set of preliminary test procedures governing all sequences of testing was developed. These testing procedures as well as test setup (Section 2) were subsequently refined and modified through the knowledge gained from a series of shakedown tests.

The final test procedures adopted for this investigation are provided in Appendix A.

The following sections provide a brief description of various test procedures.

3.2 Sample Preparation

Two methods of sample preparation, including a tamping method and a raining method, were utilized in this investigation. A detailed description of these sample preparation methods is provided in Appendix A. In general the adopted methods were refinements of those methods specified in NCEL's statement of work. They were designed to achieve repeatable, uniform and homogeneous soil samples.

In accordance with NCEL's statement of work, samples were prepared to the following void ratios:

<u>Sand Type</u>	<u>Void Ratios</u>	
	<u>Raining Method</u>	<u>Tamping Method</u>
Calcareous Sand	2.0 ± 0.1	1.4 ± 0.1
Silica Sand	0.75 ± 0.1	0.6 ± 0.1

Based on the average specific gravity values (Section 2.1) and the above requirements, the following dry density values were prescribed for this investigation:

<u>Sand Type</u>	<u>Dry Density (gm/cc)</u>	
	<u>Raining Method</u>	<u>Tamping Method</u>
Calcareous Sand	0.94	1.17
Silica Sand	1.51	1.61

All prepared samples were then cured in a 100% humidity room for a minimum of three days before they were placed in the red barrel for further testing. This curing period was determined on the basis of unconfined compression tests which indicated that 3-day and 7-day strengths of the samples were about the same.

After curing, the test sample was placed on top of a prepared bed of silica sand in the red barrel. The annular space between the test sample and red barrel wall was then filled with silica sand compacted in layers and with an approximate stiffness similar to the test sample to maintain similar compliance. The red barrel was then covered and all pressure lines connected. An all around confining pressure of 20 psi was then applied to the test sample.

3.3 Pile Driving

After the sample was in place and the confining pressure applied, the pile driving assembly was attached. Pile driving was accomplished by manually dropping the 15-pound deadweight hammer from a distance of 12 inches above the pile head. Pile driving continued until a penetration of 12 inches was achieved.

3.4 Pile Pullout Test

Pullout tests were performed using the previously described hydraulic pulling system. The pile was connected to the vertical ram of the hydraulic actuator, and pulled vertically with a speed of about 0.04 inch per second. The pullout test continued until a maximum pullout force was reached. The pullout resistance force and pile displacement were continuously monitored on the X-Y-Y recorder during each pullout test.

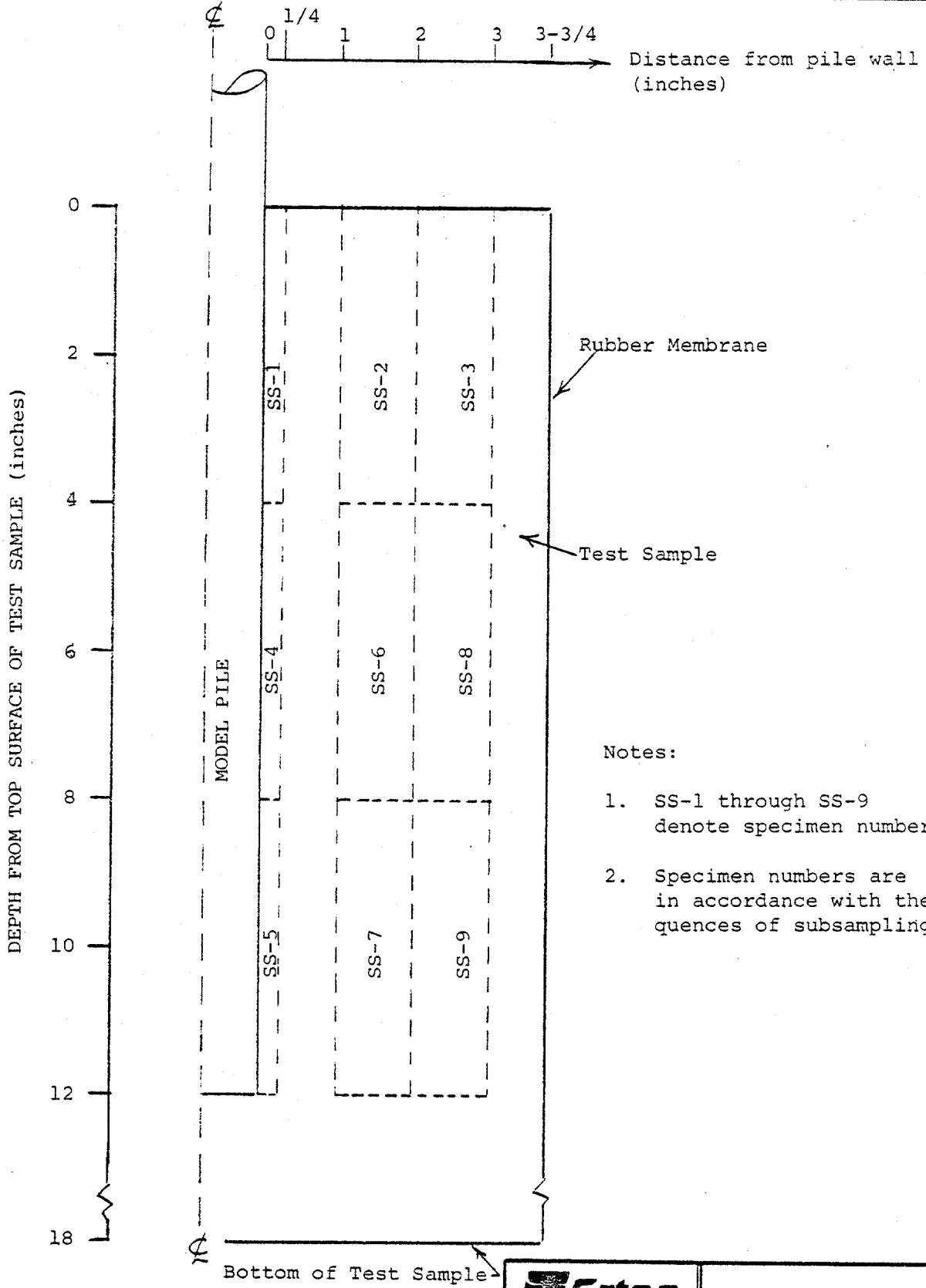
3.5 Subsampling After Pullout Test

It was hypothesized that the degree of grain crushing, if any, would be more severe at or near the pile and significantly decrease as the distance away

from the pile increased. Therefore, it was necessary to obtain soil specimens at or near the pile wall in this investigation. Subsampling of soil specimens was accomplished by using a scraper to carefully scrape around the wall of sand after removing the model pile. Since the samples were moist and mostly cemented, the cavity wall of each sample was able to stand vertically without collapsing. As shown in Figure 3-1, nine (9) soil specimens were taken from each test sample at three (3) horizontal distance intervals of 0 to 1/4, 1 to 2, and 2 to 3 inches from the pile perimeter and at three (3) depth intervals between 0 to 4, 4 to 8, and 8 to 12 inches from the soil surface in each horizontal distance interval.

3.6 Grain Size Analysis

Specimens of cemented sample contained certain cemented lumps. Separation of the cementing agent and sand grains would be necessary for assessing changes in grain size distribution. Regular pulverization method using physical or mechanical force was not acceptable since it would potentially break and crush the soft calcareous sand grains. Pulverization by chemical means was also considered inappropriate since the chemical solution would potentially dissolve the calcareous sand grains as well as the cement agent. Instead, separation was accomplished by lightly rubbing off the cementing agent by hand. Extreme care was taken to prevent crushing of the sand grains. After separation, the specimens were soaked in distilled water for 24 hours. Sieve analyses were then performed on the soil specimens in accordance with ASTM D422 procedures.



Notes:

- 1. SS-1 through SS-9 denote specimen numbers
- 2. Specimen numbers are in accordance with the sequences of subsampling.



FIGURE 3 - 1

SUBSAMPLING SCHEME AND SEQUENCES

4.0 RESULTS, ANALYSES AND DISCUSSIONS

4.1 Number of Tests

A total of 20 tests was performed. These tests included 5 non-scheduled tests and 15 scheduled tests called for in the NCEL statement of work. The non-scheduled tests were categorized as "shakedown tests" to calibrate and modify various test procedures. Relevant data and characteristics of test samples as well as certain test results are summarized in Table 4-1.

In these "shakedown tests", certain areas of emphasis were stressed while little attention was paid to other areas. Thus, the results of the non-scheduled tests could only be used to supplement qualitatively the results of scheduled tests.

4.2 Results

4.2.1 Pile Driving

Plots of driving energy versus pile penetration for the scheduled tests are presented in Figures 4-1 to 4-4. An examination of these results indicates the following:

1. As expected, higher driving energy is required to install the pile into higher density sand samples.
2. For higher density samples of calcareous sand and silica sand, the following observations are made:
 - a. The driving energy required to install the pile increases with increasing cement content.

- b. At each prescribed cement content, pile driving resistances are on the same order of magnitude for higher density silica and calcareous sand samples.
3. For lower density samples of either silica sand or calcareous sand, an increase in cement content does not appear to significantly increase pile driving resistance.

4.2.2 Pullout Tests

The results of maximum pullout resistance and corresponding pile displacement data are summarized in Table 4-1. A summary plot of the maximum pullout force versus the number of blows required to advance the pile 12 inches is provided in Figure 4-5. Several observations can be made:

1. Although the pile driving resistance in higher density silica sand samples is similar to the driving resistance in higher density calcareous sand samples, the pullout resistance in silica sand is two to five times of the pullout resistance in calcareous sand. The difference in pullout resistance appears to increase with the increases of cement contents and pile driving resistance.
2. In lower density calcareous sand, pile pullout resistance appears to increase with the increase of pile driving resistance.
3. In silica sand, pile pullout resistance, in general, increases with the increase of pile driving resistance.

Based on the above observations, it appears that pile driving resistance may not be a rational parameter for use in pullout capacity prediction for piles in calcareous sands.

4.2.3 Crushability

As described in Section 3.5, subsamples of the soil specimens were taken at various depths and distances from the pile wall after each pullout test. Grain size analyses were then performed on these specimens in accordance with procedures described in Section 3.6.

In current practice, the degree of crushability of calcareous sands is usually quantified by a crushability index C_c , defined by Datta, et al (1980) as:

$$C_c = \frac{\text{Percent of sand particles finer than } D_{10} \text{ after being stressed}}{\text{Original percent of sand particles finer than } D_{10}}$$

where

$$D_{10} = \text{particle diameter at which 10 percent of the soil by weight is finer.}$$

This definition was not followed in this investigation because the results of grain size analyses indicated that D_{10} at or near the pile wall for most of the higher density calcareous sand samples was finer than the No. 200 sieve. Therefore, the determination of D_{10} would have required the use of hydrometer testing method. Hydrometer analyses were not performed because of insufficient quantities of specimens. Instead, a "fines content" defined as the percent of soil by weight finer than the No. 200 sieve, was used as a crushability indicator in this investigation.

The fines content versus distance from the pile wall (soil-pile interface) are presented in Table 4-2 and Figures 4-6 to 4-9. As can be noted from these results, most of the grain crushing takes place at or near the pile wall. The degrees of grain crushing decrease significantly with increases in distance away from the pile wall.

For illustrative purpose, "at or near the pile wall" is defined as a distance of 0 to 1/4-inch from the pile wall.

Figures 4-10 to 4-17 present the results of grain size analyses for specimens taken at or near the pile wall after pile driving and pullout test. The gradation curves of the original sample prior to testing are also presented in these figures. Figures 4-10 to 4-17 appear to indicate that:

1. At or near the pile wall, significantly more grain crushing occurs along the bottom eight (8) inches of the pile than the top four (4) inches.
2. Pile driving causes a significant amount of grain crushing in the higher density calcareous sand samples while its effect on grain crushing in silica sand and lower density calcareous sand samples is less pronounced.

The observation in above item 1 appears to be questionable since it is contradictory to the general belief that grain crushing would be more pronounced near the soil surface where more shear stress cycles are imposed by the pile driving. This appears to be caused by the physical limitation of the red barrel and pressurization system (Figure 2-5). The top 4 inches of the pile have been subjected to less complete confinement than the bottom 8 inches of the pile. Thus, it can be hypothesized that grain crushing also depends on the applied confining stress.

4.3 Data Analyses and Discussions

The results of this investigation appear to indicate that there exist certain definitive behavioral patterns which relate to grain crushing (or crushability),

pile driving resistance, pullout resistance (or skin friction resistance), cement content, and soil density. Thus, various analyses and discussions of these test results can be made with respect to the following topics:

1. Crushability versus cement content
2. Crushability versus pile driving resistance
3. Crushability versus pullout resistance
4. Pullout resistance versus cement content
5. Pullout resistance versus density
6. Pullout resistance versus pile driving resistance.

The last of these topics has been described in Section 4.2.2. The following sections provide an analysis and discussion of the first five topics.

4.3.1 Crushability versus Cement Content

Figures 4-18 to 4-21 provide summary plots showing the change in fines content at or near the pile wall versus cement content. The following observations can be made:

1. Crushability generally increases with increasing of cement content for both higher density calcareous sand and silica sand samples.
2. No definite relationship can be established for lower density calcareous sand and silica sand samples.

A summary plot showing average changes in fines content along the model pile at or near the pile wall versus cement content is provided in Figure 4-22. This figure indicates that, for both sands tested, higher density samples exhibit more tendency for grain crushing. This is especially pronounced in

in higher density calcareous sand samples. As will be discussed in a later section, this is thought to be due to the effect of pile driving since higher density samples would require more driving energy to install the pile and thereby yield a higher degree of grain crushing.

4.3.2 Crushability Versus Pile Penetration Resistance

A plot of driving resistance (in terms of number of blows required to drive the pile 12 inches) versus the average change in fines content at or near the pile wall is presented in Figure 4-23. This figure exhibits a definite pattern in which the change of fines content increases with increasing pile driving resistance. As expected, this figure also indicates that silica sand is less susceptible to grain crushing than calcareous sand under the same pile driving energy. This reflects the differences in grain hardness between the two sands.

4.3.3 Crushability Versus Pullout Resistance

A summary plot showing the average change in fines content at or near the pile wall versus maximum pullout resistance, is presented in Figure 4-24. This figure indicates that, for the higher density calcareous sand, the maximum pullout resistance appears to remain essentially constant or decrease somewhat with increasing average change in fines content. This suggests that a significant amount of grain crushing could reduce the pullout capacity, despite an increase in cement content or driving resistance for a pile in denser calcareous sand. In silica sand and lower density calcareous sand, the maximum pullout resistance appears to increase with the changes in fines

content at or near the pile wall. This apparent contradiction to the above observation for higher density calcareous sand samples can possibly be explained by the following way. Since these materials exhibit an insignificant amount of grain crushing, it can be postulated that a slight reduction in pile pullout resistance due to a small amount of grain crushing in these materials is compensated by an increase in soil-pile frictional resistance due to cementation.

4.3.4 Pullout Resistance Versus Cement Content

A summary plot of average unit skin friction resistance versus cement content is presented in Figure 4-25. For piles in silica sands, there is a general tendency for the skin friction resistance to increase as the cement content increases. For piles in calcareous sands, no definite pattern can be established because the effect of increasing the pile pullout resistance is either partially or overly compensated by the effects of increasing in crushability due to driving. An increase in degree of grain crushing can significantly reduce the pile pullout resistance.

4.3.5 Pullout Resistance Versus Density

A summary plot of pile pullout resistance versus dry density of the calcareous sand samples is provided in Figure 4-26. For zero cement content, the pullout resistance increases with increasing density of the calcareous sand. For other cement contents, no regular pattern can be established. This is indicative of the complex, interrelated effects of cementation, grain crushing, and pile driving resistance on the pile pullout resistance.

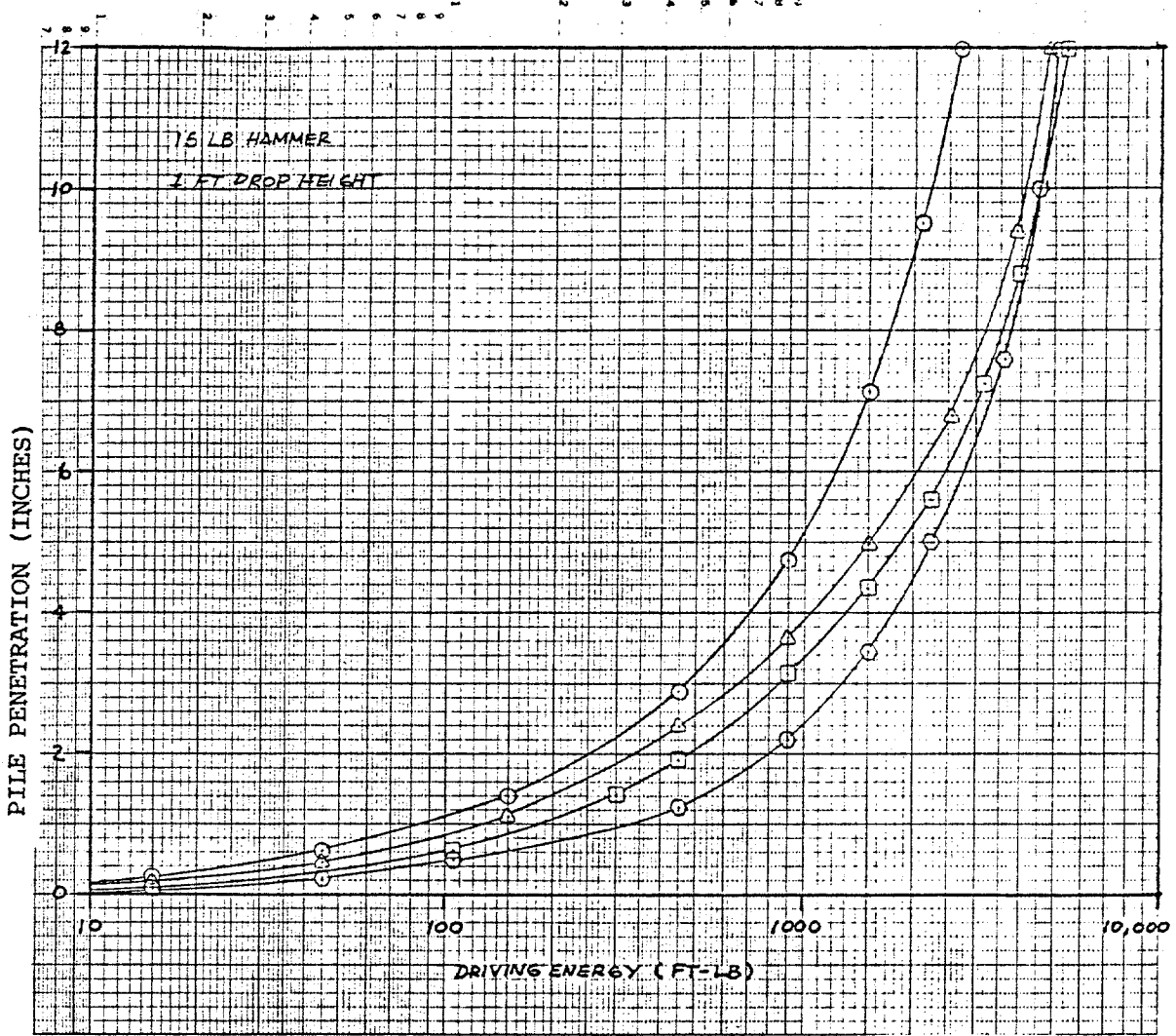
TABLE 4-1. SUMMARY OF THE TEST PROGRAM AND RESULTS

Test Sample No.	Soil Type	Dry Density gm/cc (%)	Moisture Content gm/cc (%)	Sample Preparation Method	Cement Content (%)	Curing Period (days)	Blow-Count	Penetration (Inches)	Maximum Pullout Force (lbs)	Displacement (Inches)
C-1	Calcareous	1.17	19	Tamping	0.0	0	182	12.0	330	2.0
C-2	Calcareous	1.17	19	Tamping	0.5	4	323	12.0	280	2.0
C-3	Calcareous	1.17	19	Tamping	1.0	3	364	12.0	270	2.0
C-4	Calcareous	1.17	19	Tamping	2.0	6	345	12.0	312	1.0
C-5	Calcareous	0.94	19	Raining	0.0	0	29	12.2	105	0.45
C-6	Calcareous	0.94	19	Raining	0.5	3	42	12.2	170	0.70
C-7	Calcareous	0.94	19	Raining	1.0	3	32	12.0	116	0.80
C-8	Calcareous	0.94	19	Raining	2.0	3	45	12.1	176	0.80
S-1	Silica	1.61	10	Tamping	0.0	0	95	12.0	640	1.0
S-2	Silica	1.61	10	Tamping	0.5	4	242	12.0	1200	1.9
S-3	Silica	1.61	10	Tamping	1.0	3	245	12.0	1210	1.2
S-4	Silica	1.61	10	Tamping	2.0	3	353	12.0	1330	1.2
S-5	Silica	1.51	10	Raining	0.0	0	116	12.0	600	1.0
S-6	Silica	1.51	10	Raining	0.5	3	144	12.0	680	1.6
S-8	Silica	1.51	10	Raining	2.0	3	137	12.0	490	0.4
SC-2	Calcareous	1.07	19	Tamping	0.5	4	50	12.1	115	1.2
SC-3	Calcareous	1.07	19	Tamping	1.0	3	110	12.0	340	1.6
SS-3	Silica	1.61	10	Tamping	1.0	4	223	12.0	1460	0.8
SC-8	Calcareous	0.94	19	Raining	2.0	3	31	12.1	60	0.40
SC-1	Calcareous	1.07	19	Raining	0.0	0	47	12.0	145	0.30

NOTES: 1. Test Sample Nos. C-1 through C-8 and S-1 through S-8 are scheduled tests.
 2. Test Sample Nos. SC-1, SC-2, SC-3, SC-8 and SS-3 are non-scheduled tests.

TABLE 4-2. CHANGES IN FINES CONTENT

Test Sample No.	Type of Sample	Dry Density (g/cc)	Water Content (%)	Cement Content (%)	2-3 in. from Pile Wall Average Fines Content	At or Near the Pile Wall			Average Change in Fines Content 0-12 inch (%)
						Change In Fines Content 0-4 inch (%)	Change In Fines Content 4-8 inch (%)	Change In Fines Content 8-12 inch (%)	
C-1	Calcareous	1.17	19	0.0	2.3	2.6	8.2	9.4	6.7
C-2	Calcareous	1.17	19	0.5	2.8	4.2	11.6	12.0	9.3
C-3	Calcareous	1.17	19	1.0	2.6	5.7	12.2	11.1	9.7
C-4	Calcareous	1.17	19	2.0	3.7	7.9	13.2	11.3	10.8
C-5	Calcareous	0.94	19	0.0	2.6	0.5	1.6	0.9	1.0
C-6	Calcareous	0.94	19	0.5	2.5	0.6	2.2	2.0	1.6
C-7	Calcareous	0.94	19	1.0	2.6	0.8	1.1	1.5	1.1
C-8	Calcareous	0.94	19	2.0	2.9	0.3	1.6	2.5	1.5
S-1	Silica	1.61	10	0.0	0.0	0.0	0.3	0.5	0.3
S-2	Silica	1.61	10	0.5	0.5	0.1	1.4	1.5	1.0
S-3	Silica	1.61	10	1.0	0.8	0.4	1.4	1.6	1.1
S-4	Silica	1.61	10	2.0	1.5	0.4	1.8	2.4	1.5
S-5	Silica	1.51	10	0.0	0.0	0.2	0.5	0.6	0.5
S-6	Silica	1.51	10	0.5	0.4	0.2	0.8	0.8	0.6
S-8	Silica	1.51	10	2.0	1.3	0.2	0.8	0.8	0.6



<u>SYMBOL</u>	<u>SAND TYPE</u>	<u>TEST NO.</u>	<u>CEMENT CONTENT (%)</u>
⊙	Calcareous	C-1	0
△	Calcareous	C-2	0.5
□	Calcareous	C-3	1.0
◇	Calcareous	C-4	2.0



FIGURE 4 - 1

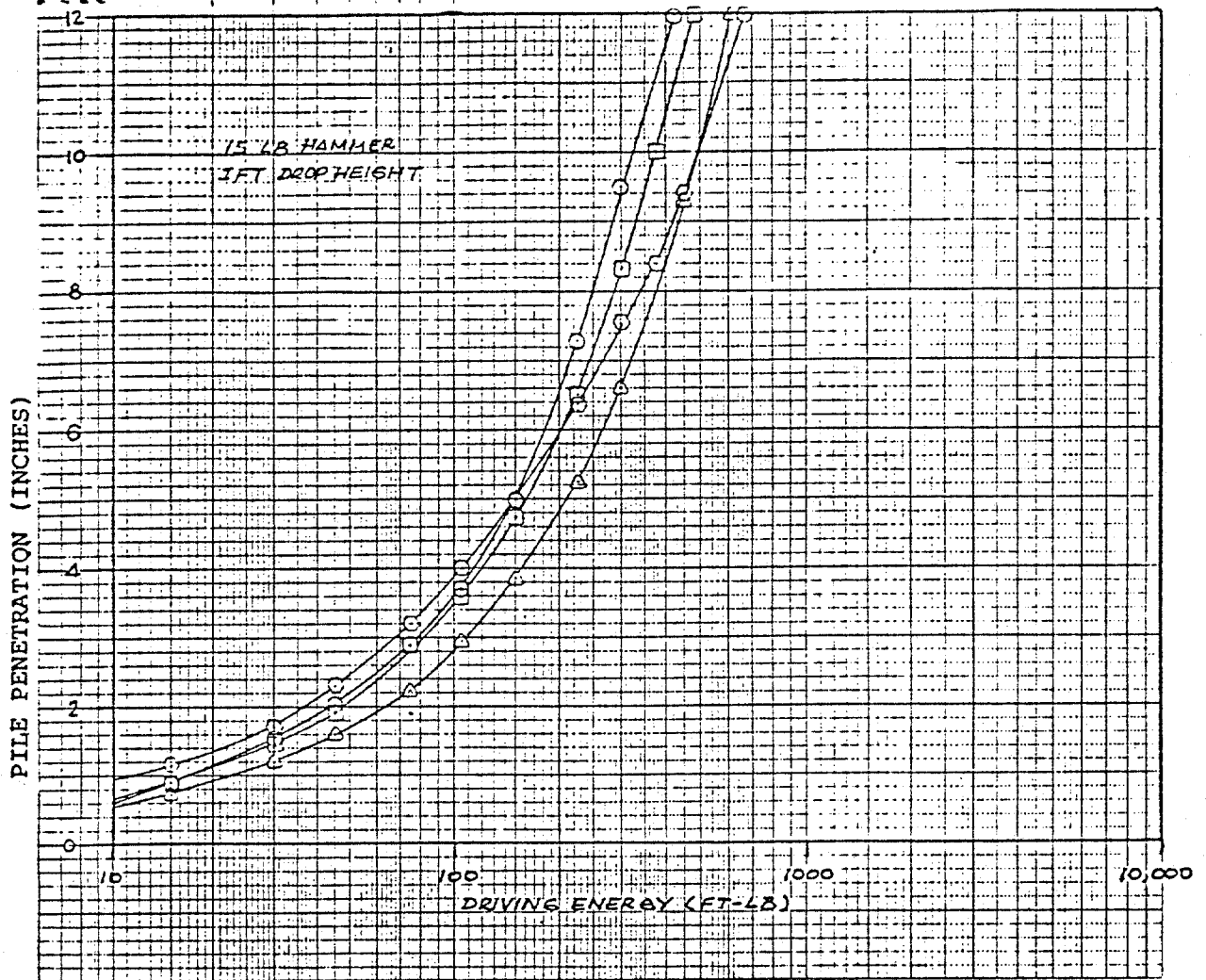
DRIVING ENERGY VERSUS PILE PENETRATION - HIGHER DENSITY CALCAREOUS SAND

Approved by

Checked by

Drawn by

Compiled by



<u>SYMBOL</u>	<u>SAND TYPE</u>	<u>TEST NO.</u>	<u>CEMENT CONTENT (%)</u>
○	Calcareous	C-5	0
△	Calcareous	C-6	0.5
□	Calcareous	C-7	1.0
○	Calcareous	C-8	2.0



FIGURE 4 - 2

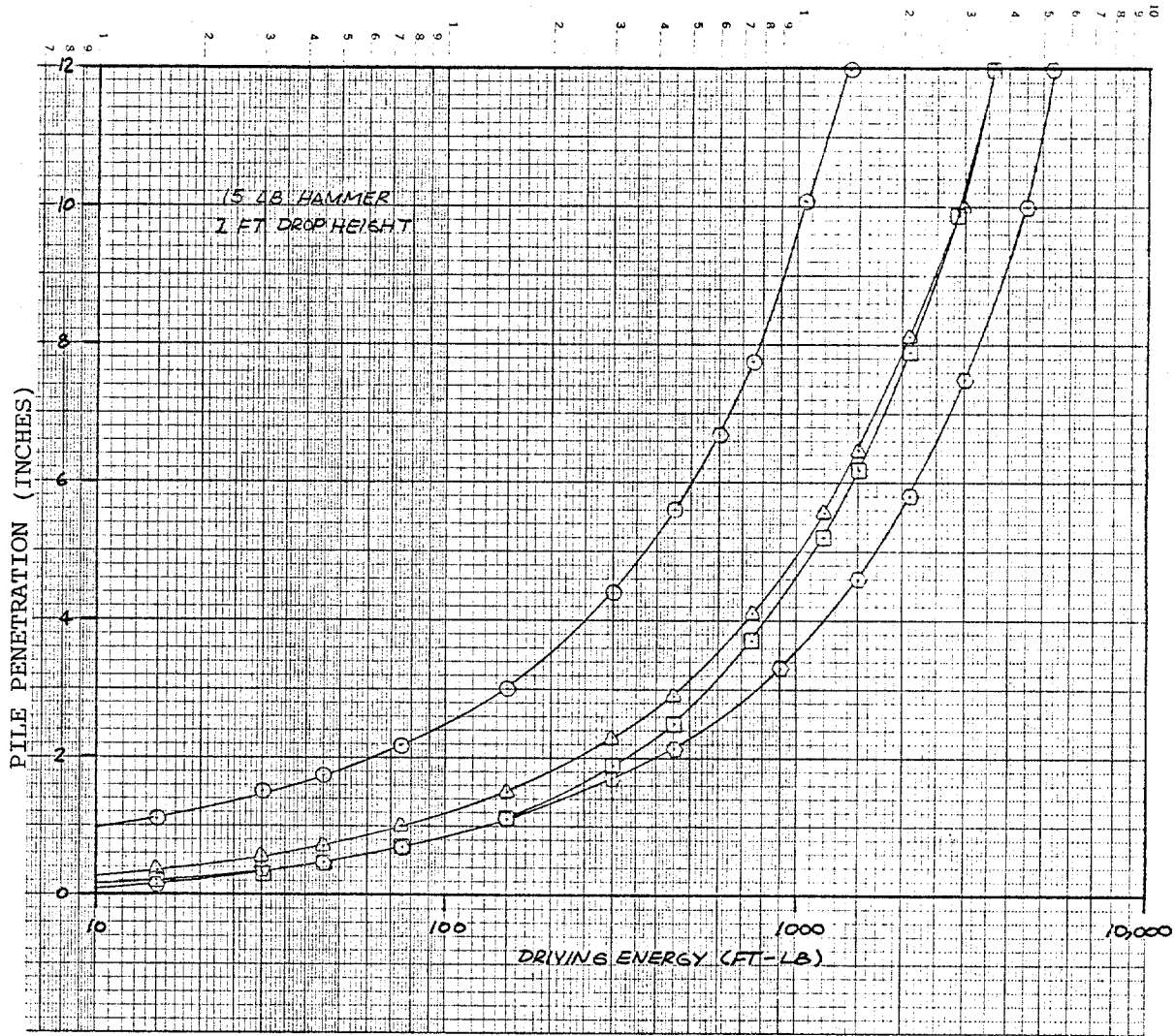
DRIVING ENERGY VERSUS PILE PENETRATION - LOWER DENSITY CALCAREOUS SAND

Approved by

Checked by

Drawn by

Compiled by



SYMBOL	SAND TYPE	TEST NO.	CEMENT CONTENT (%)
⊙	Silica	S-5	0
△	Silica	S-6	0.5
□	Silica	S-7	1.0
◇	Silica	S-8	2.0



FIGURE 4 - 3

DRIVING ENERGY VERSUS PILE PENETRATION HIGHER DENSITY SILICA SAND

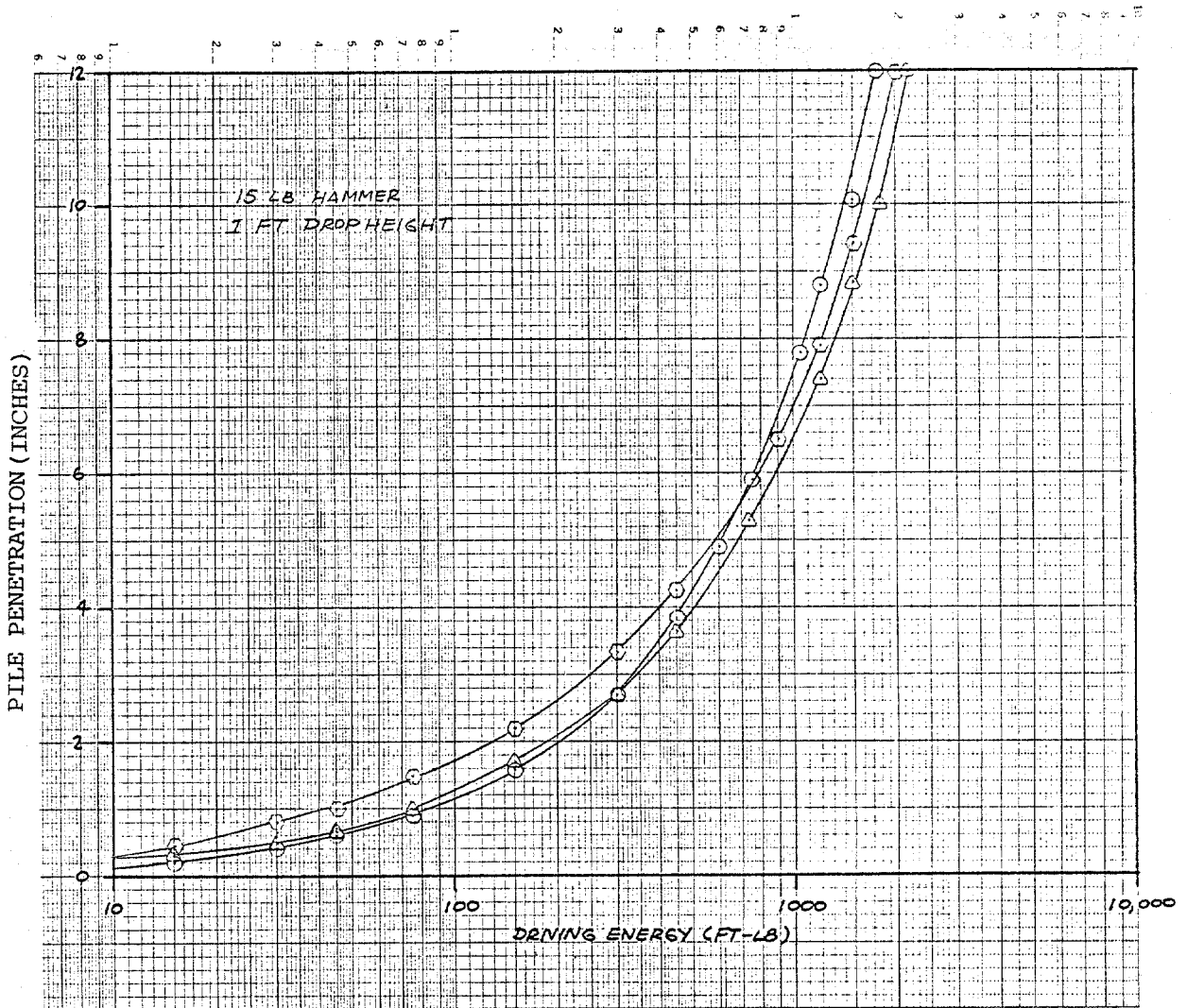
Approved by

Checked by

Drawn by

Compiled by

Approved by _____
 Checked by _____
 Drawn by _____
 Compiled by _____

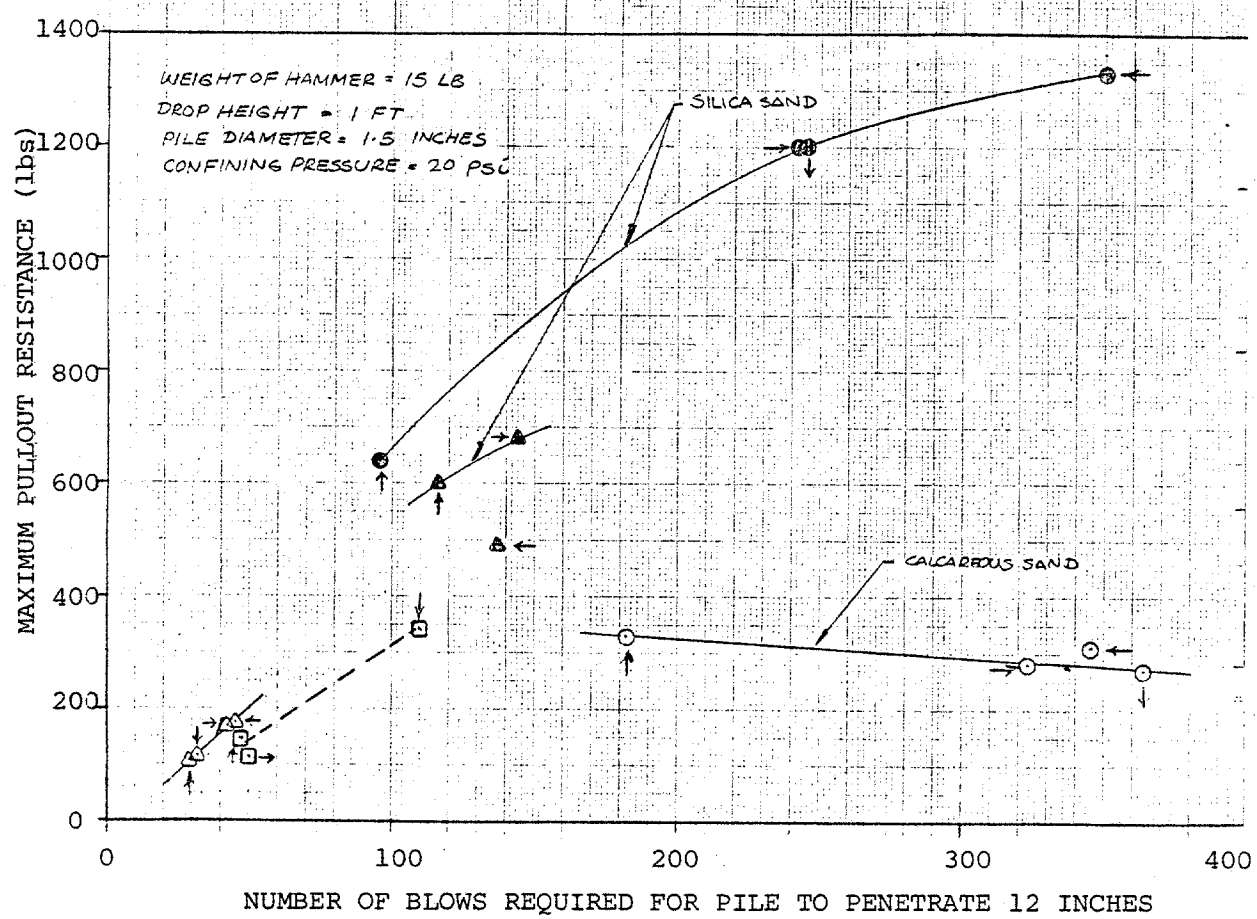


<u>SYMBOL</u>	<u>SAND TYPE</u>	<u>TEST NO.</u>	<u>CEMENT CONTENT (%)</u>
○	Silica	S-5	0
△	Silica	S-6	0.5
⊙	Silica	S-7	2.



FIGURE 4 - 4

DRIVING ENERGY VERSUS PILE PENETRATION - LOWER DENSITY SILICA SAND



<u>SYMBOL</u>	<u>SAND TYPE</u>	<u>DRY DENSITY (g/cm)</u>	<u>PREPARATION METHOD</u>
○	Calcareous	1.17	Tamping
□	Calcareous	1.07	Tamping
△	Calcareous	0.94	Raining
●	Silica	1.61	Tamping
▲	Silica	1.51	Raining

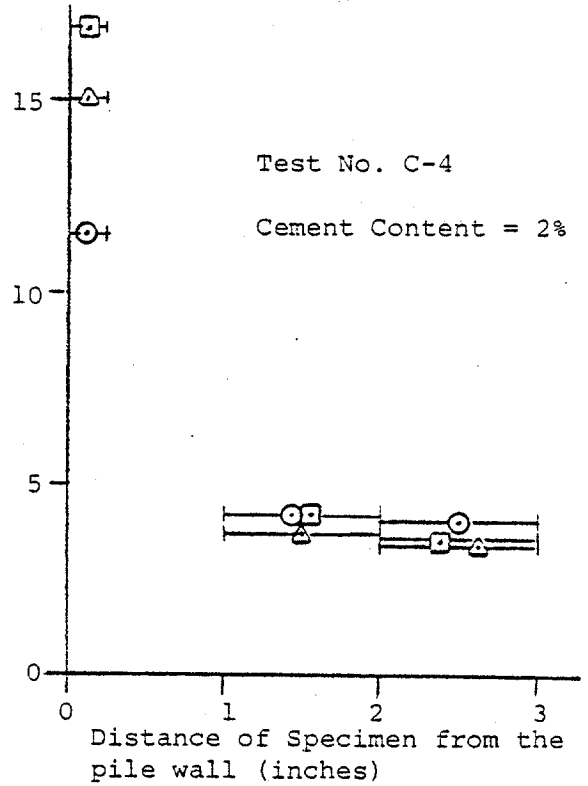
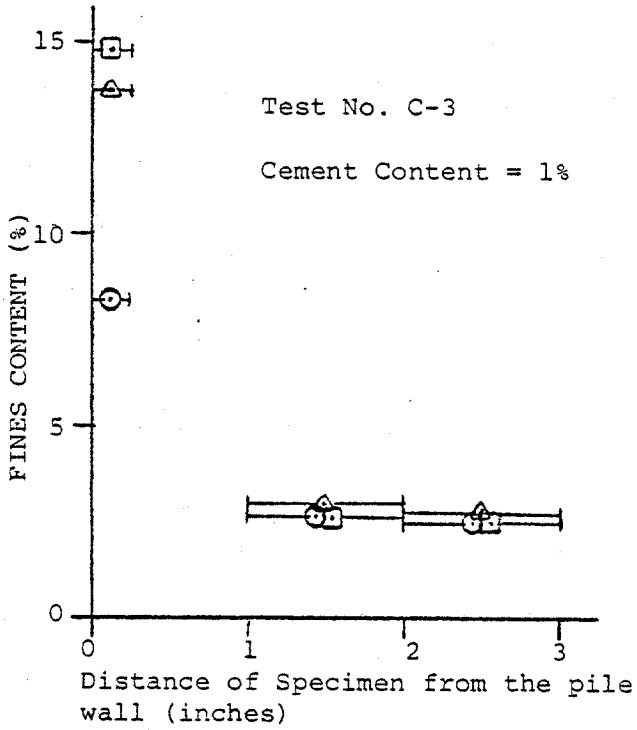
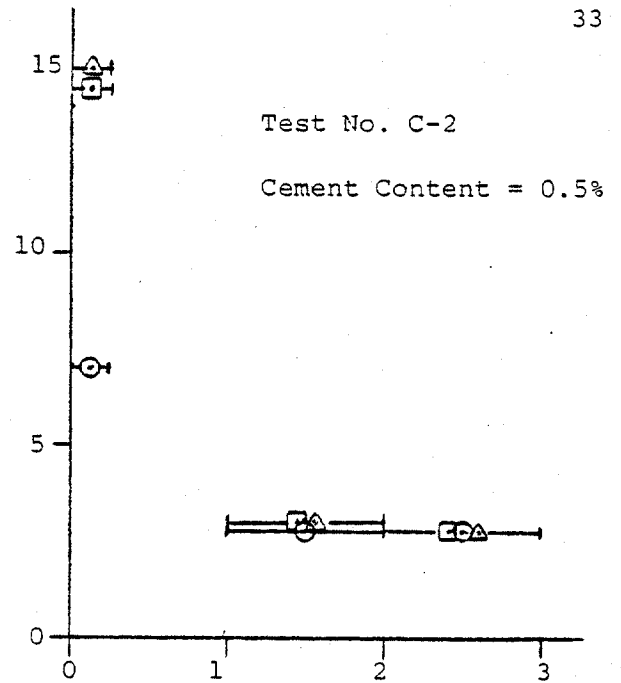
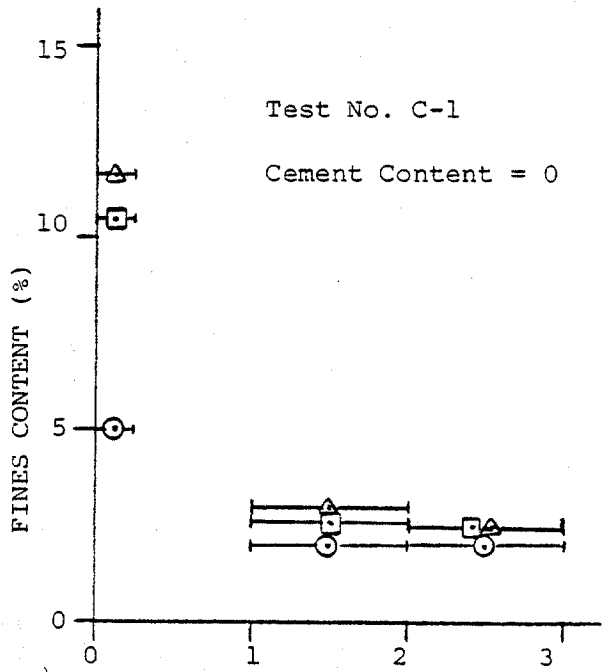
NOTE: Arrow directions indicate cement contents:
 ↑ = 0%, → = 0.5%
 ↓ = 1.0%, ← = 2.0%



FIGURE 4 - 5

MAXIMUM PULLOUT RESISTANCE VERSUS PILE DRIVING RESISTANCE

Approved by _____
 Checked by _____
 Drawn by _____
 Compiled by _____



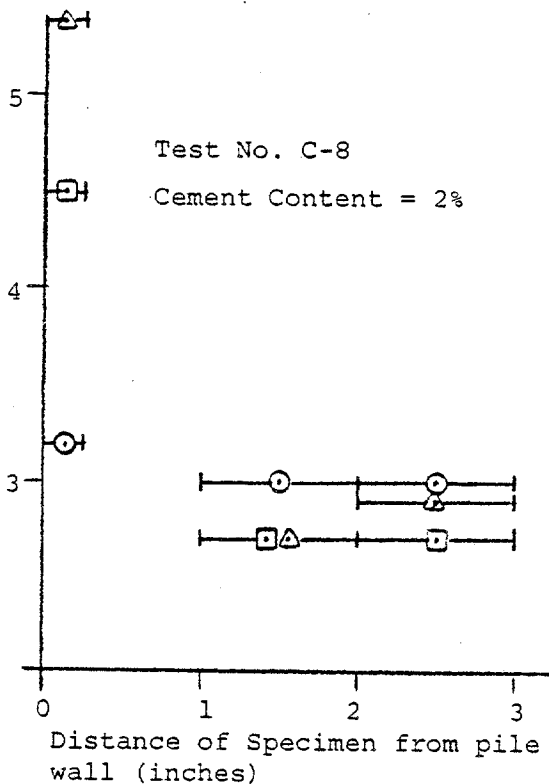
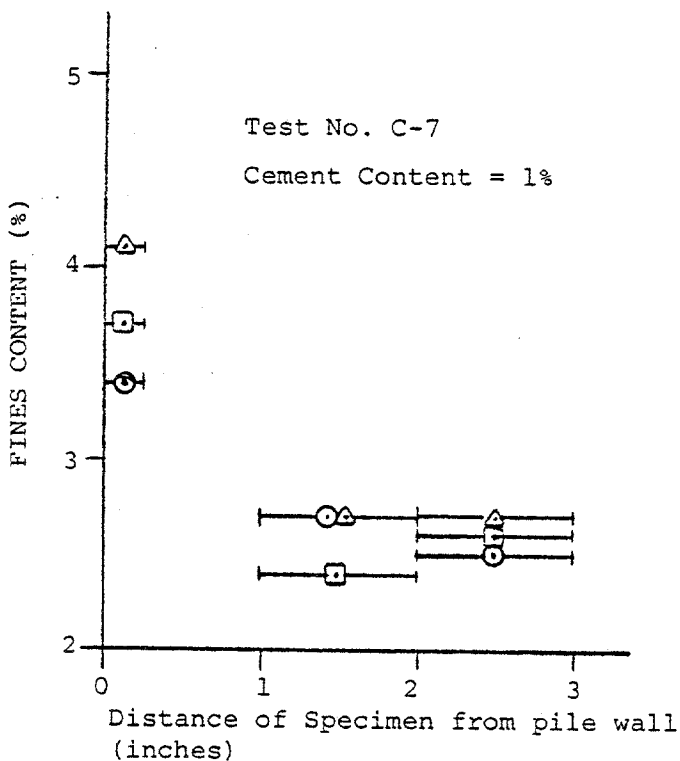
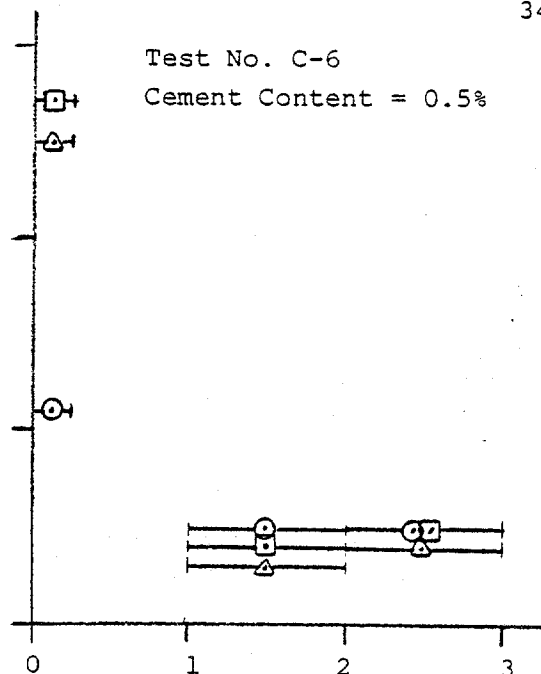
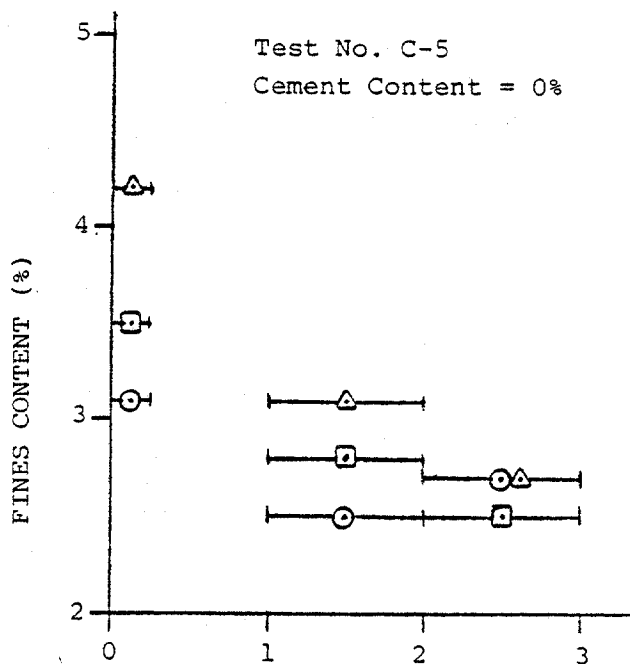
Symbol	Depth Interval (inches)
○	0 - 4
□	4 - 8
△	8 to 12

- Notes: 1. Pile penetration is 12 inches
2. Dry density = 1.17 gm/cc



FIGURE 4 - 6

FINES CONTENT VERSUS DISTANCE OF SPECIMEN FROM THE PILE WALL - HIGHER DENSITY CALCAREOUS SAND



Symbol	Depth Intervals (inches)
○	0 to 4
□	4 to 8
△	8 to 12

- NOTES: 1. Pile Penetration is 12"
2. Dry Density = 0.94 gm/cc



FIGURE 4 - 7

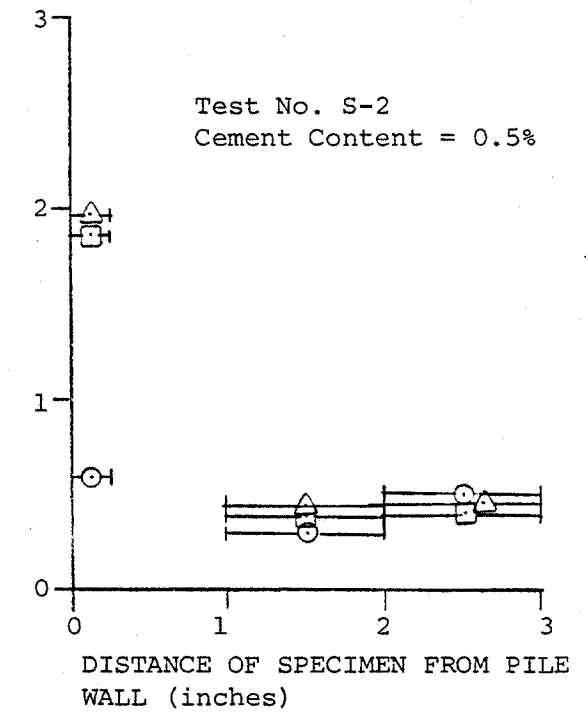
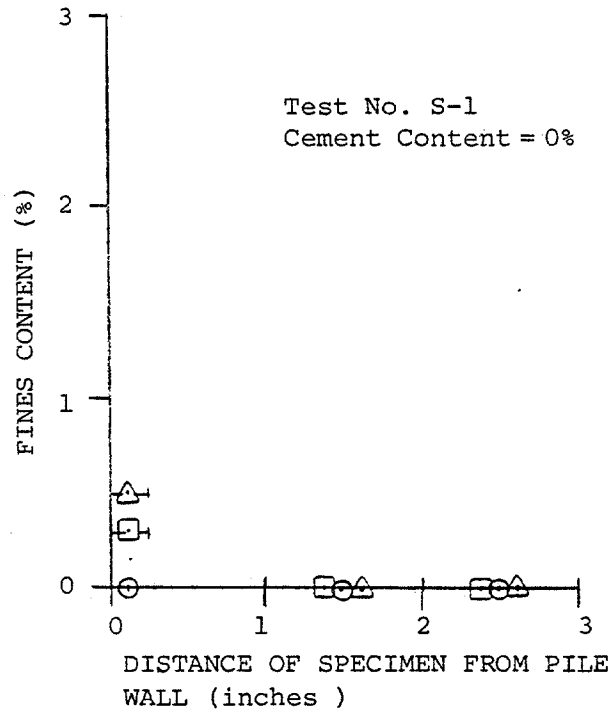
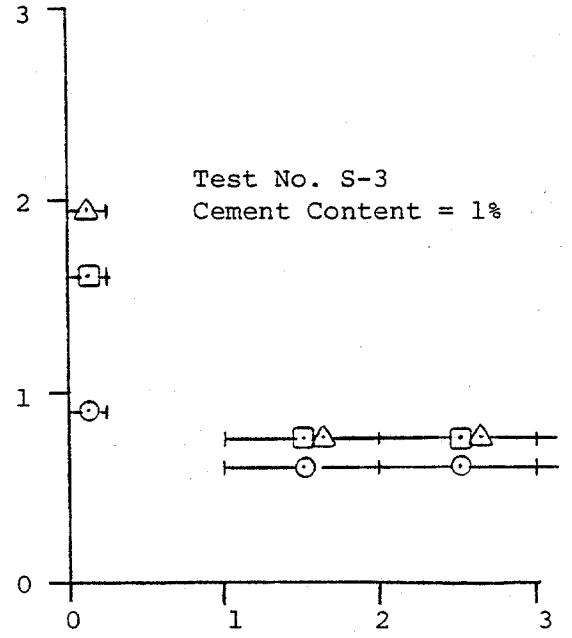
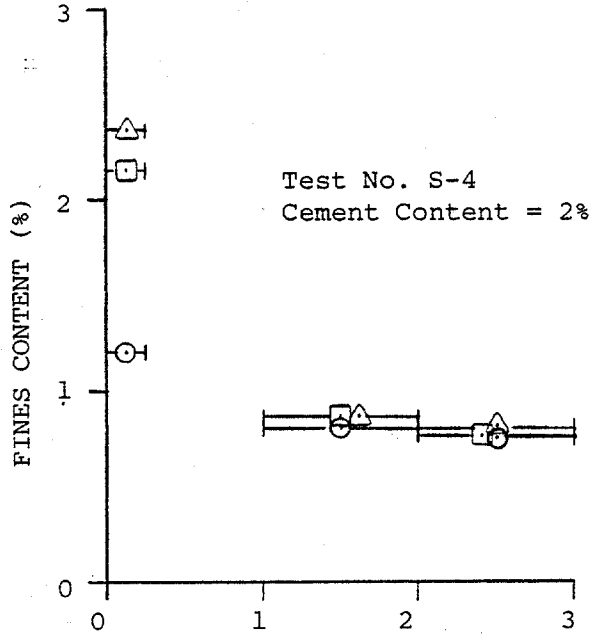
FINES CONTENT VERSUS DISTANCE OF SPECIMEN FROM PILE WALL - LOWER DENSITY CALCAREOUS SAND

Approved by _____

Checked by _____

Drawn by _____

Compiled by _____



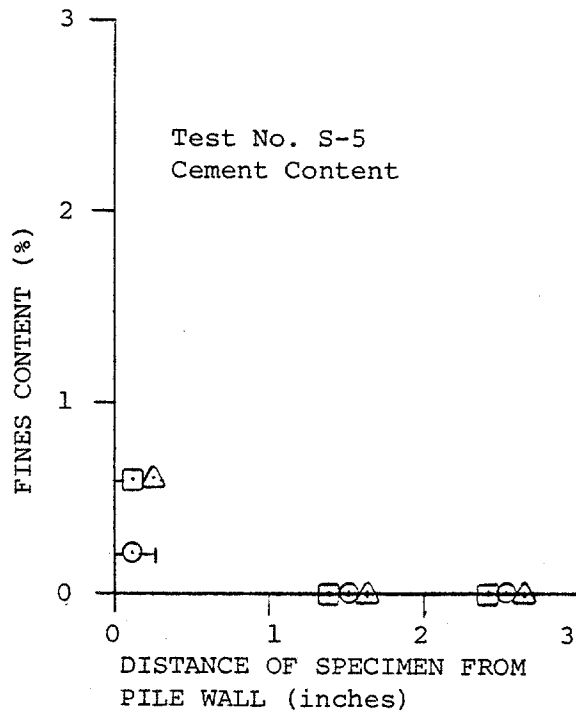
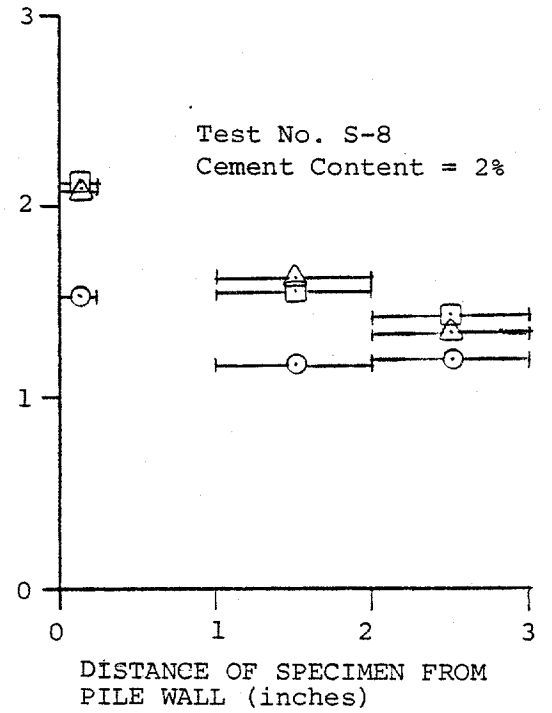
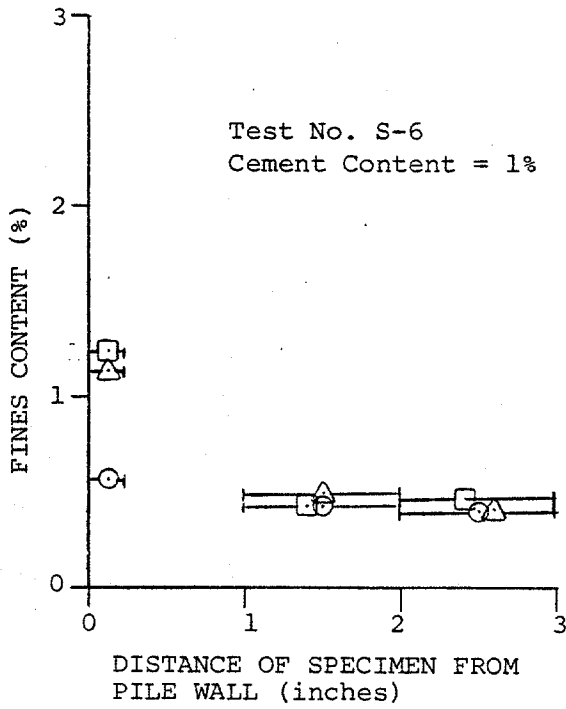
SYMBOL	DEPTH INTERVAL (inches)
○	0 to 4
□	4 to 8
△	8 to 12

NOTE: 1. Pile Penetration is 12 "
2. Dry Density = 1.61 gm/cc



FIGURE 4 - 8

FINES CONTENT VERSUS DISTANCE OF SPECIMEN FROM PILE WALL - HIGHER DENSITY SILICA SAND



SYMBOL	DEPTH INTERVAL (INCHES)
	0 to 4
	4 to 8
	8 to 12

NOTE: 1. Pile Penetration is 12 inches
2. Dry Density = 1.51gm/cc



FIGURE 4 - 9

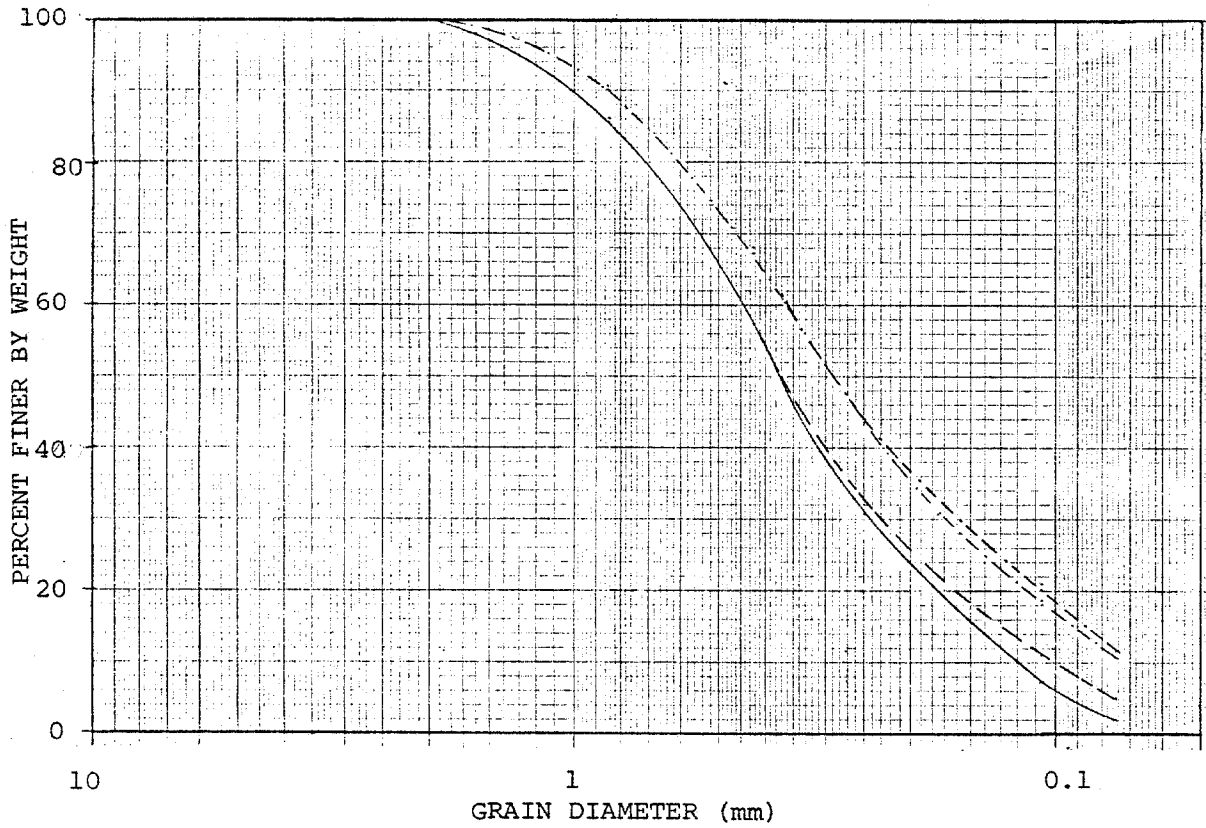
FINES CONTENT VERSUS DISTANCE OF SPECIMEN FROM PILE WALL - LOWER DENSITY SILICA SAND

Approved by

Checked by

Drawn by

Compiled by



- Original Sample
- - - - - Specimen at Depth Interval between 0 and 4"
- Specimen at Depth Interval between 4" and 8"
- · - · - Specimen at Depth Interval between 8" and 12"

Notes:

Test No. : C-1
 Sand Type : Calcareous
 Dry Density (gm/cc) : 1.17
 Cement Content (%) : 0
 Water Content (%) : 19



FIGURE 4 - 10

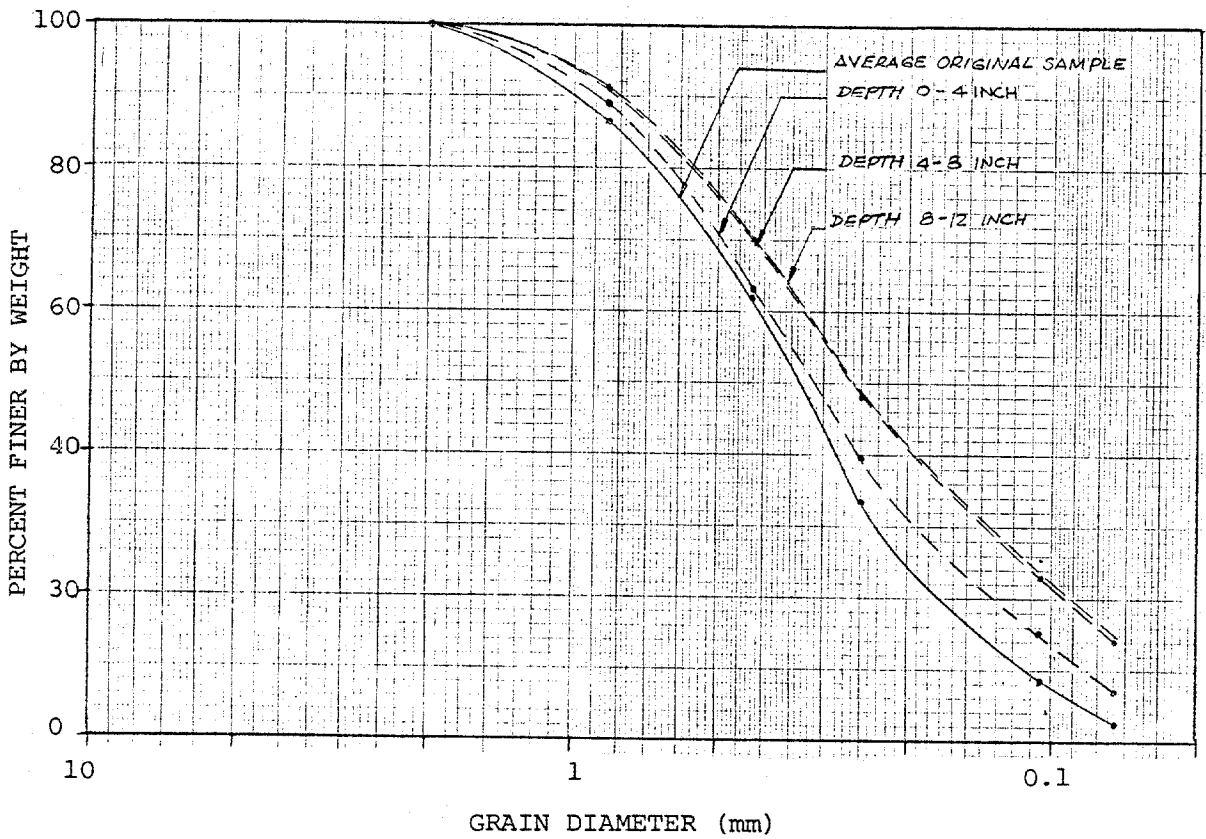
GRAIN SIZE DISTRIBUTION CURVES FOR
 SPECIMENTS AT OR NEAR THE PILE WALL
 - HIGHER DENSITY CALCAREOUS SAND
 (CEMENT CONTENT = 0 %)

Approved by

Checked by

Drawn by

Compiled by



- Original Sample
- Specimen at Depth Interval between 0 and 4"
- . - . - Specimen at Depth Interval between 4" and 8"
- Specimen at Depth Interval between 8" and 12"

Notes:

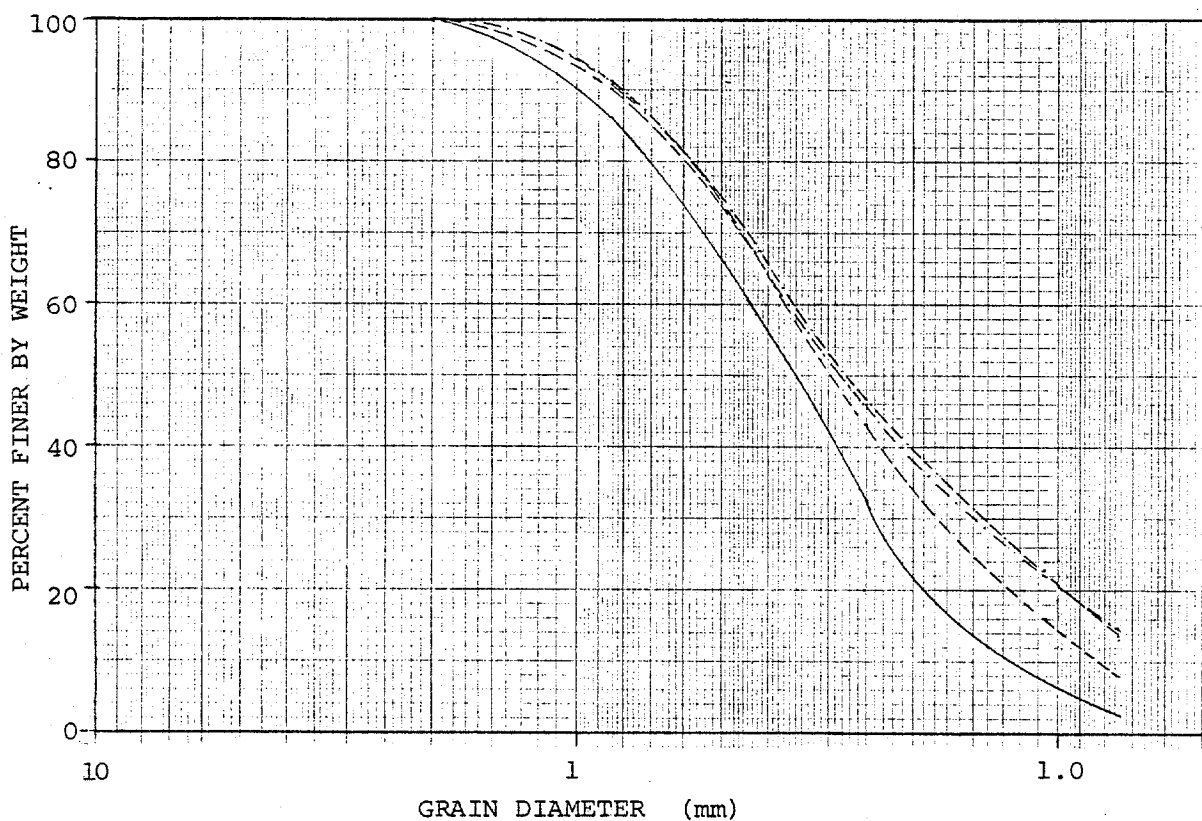
Test No. : C-2
 Sand Type : Calcareous
 Dry Density (gm/cc) : 1.17
 Cement Content (%) : 0.5
 Water Content (%) : 19



FIGURE 4 - 11

GRAIN SIZE DISTRIBUTION CURVES FOR SPECIMENS AT OR NEAR THE PILE WALL - HIGHER DENSITY CALCAREOUS SAND (CEMENT CONTENT = 0.5%)

Approved by _____
 Checked by _____
 Drawn by _____
 Compiled by _____



- Original Sample
- - - Specimen at Depth Interval between 0 and 4"
- · - · - Specimen at Depth Interval between 4" and 8"
- · · · · Specimen at Depth Interval between 8" and 12"

Notes:

Test No. : C-3
 Sand Type : Calcareous
 Dry Density (gm/cc) : 1.17
 Cement Content (%) : 1.0
 Water Content (%) : 19

Ertec
 The Earth Technology Corporation

FIGURE 4 -12

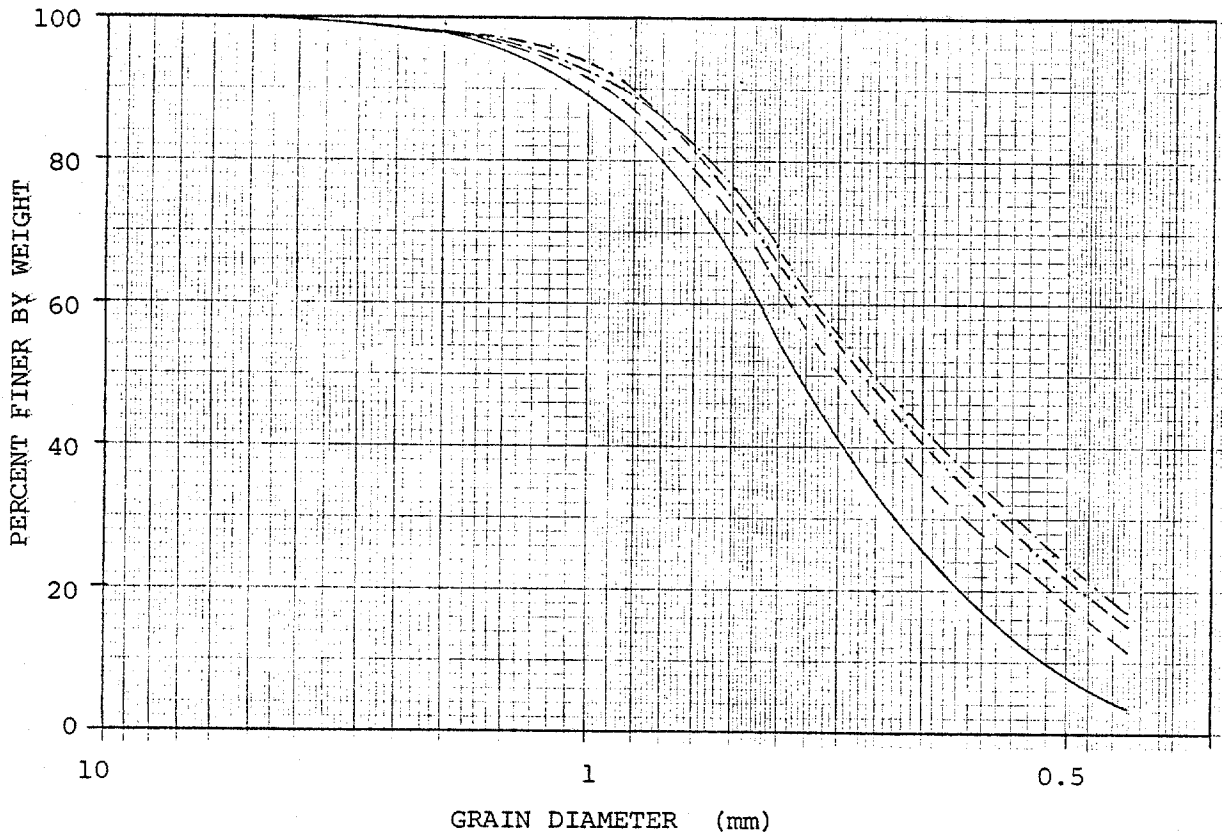
GRAIN SIZE DISTRIBUTION CURVES FOR
 SPECIMENS AT OR NEAR THE PILE WALL -
 HIGHER DENSITY CALCAREOUS SAND
 (CEMENT CONTENT = 1%)

Approved by

Checked by

Drawn by

Compiled by



- Original Sample
- Specimen at Depth Interval between 0 and 4"
- .-.-.- Specimen at Depth Interval between 4" and 8"
- .-.-.-.- Specimen at Depth Interval between 8" and 12"

Notes:

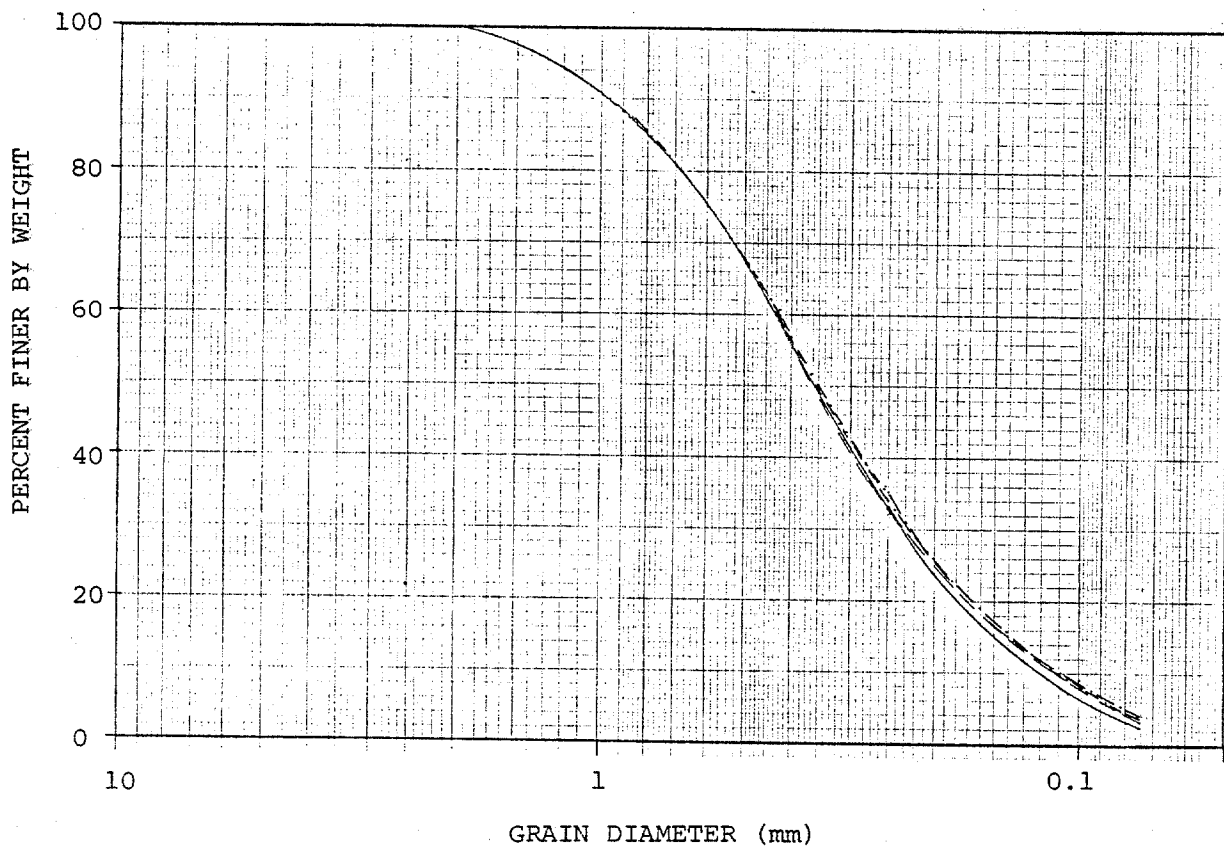
Test No. : C-4
 Sand Type : Calcareous
 Dry Density (gm/cc) : 1.17
 Cement Content (%) : 2.0
 Water Content (%) : 19



FIGURE 4 - 13

GRAIN SIZE DISTRIBUTION CURVES
 FOR SPECIMEN AT OR NEAR THE PILE
 WALL - HIGHER DENSITY CALCAREOUS SAND
 (CEMENT CONTENT = 2%)

Approved by _____
 Checked by _____
 Drawn by _____
 Compiled by _____



- Original Sample
 - - - - - Specimen at Depth Interval between 0 and 4"
 - - - - - Specimen at Depth Interval between 4" and 8"
 - - - - - Specimen at Depth Interval between 8" and 12"

Notes:

Test No. : C-5
 Sand Type : Calcareous
 Dry Density(gm/cc) : 0.94
 Cement Content(%) : 0
 Water Content(%) : 19



FIGURE 4 - 14

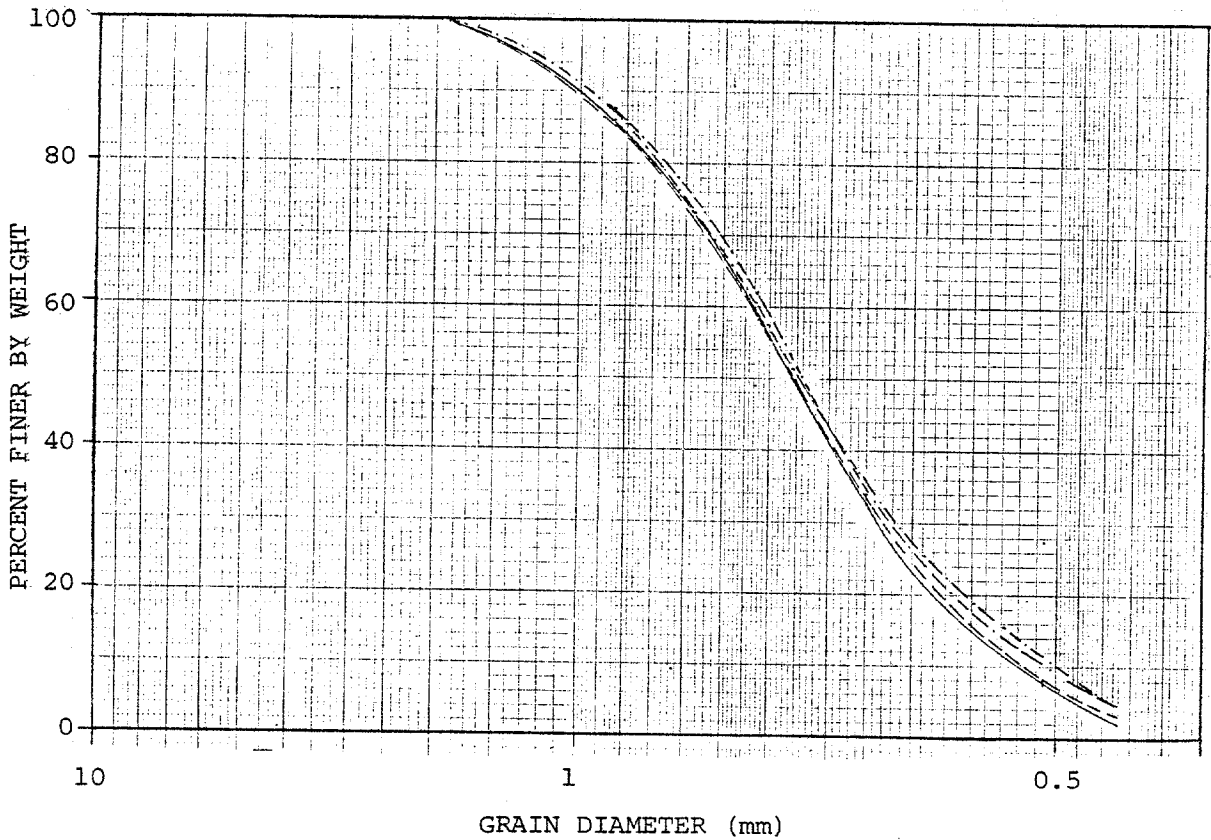
GRAIN SIZE DISTRIBUTION FOR SPECIMENS
 AT OR NEAR THE PILE WALL - LOWER
 DENSITY CALCAREOUS SOIL
 (CEMENT CONTENT = 0%)

Approved by

Checked by

Drawn by

Compiled by



- Original Sample
- Specimen at Depth Interval between 0 and 4"
- · - · - · Specimen at Depth Interval between 4" and 8"
- - - - · Specimen at Depth Interval between 8" and 12"

Notes:

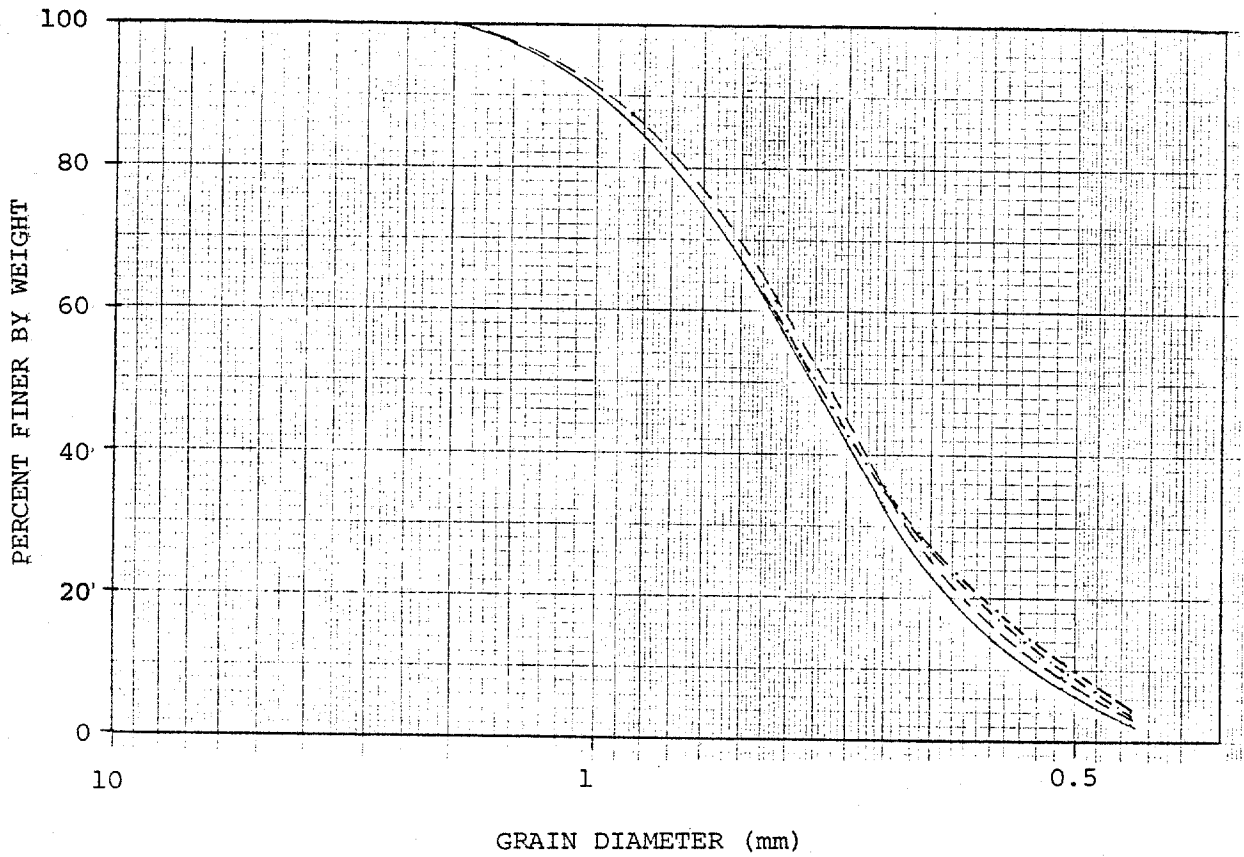
Test No. : C-6
 Sand Type : Calcareous
 Dry Density(gm/cc) : 0.94
 Cement Content(%) : 0.5
 Water Content(%) : 19



FIGURE 4 - 15

GRAIN SIZE DISTRIBUTION CURVES FOR SPECIMENS AT OR NEAR THE PILE WALL - LOWER DENSITY CALCAREOUS SAND (CEMENT CONTENT = 0.5%)

Approved by _____
 Checked by _____
 Drawn by _____
 Compiled by _____



- Original Sample
- - - - Specimen at Depth Interval between 0 and 4"
- · - · - Specimen at Depth Interval between 4" and 8"
- · - - - Specimen at Depth Interval between 8" and 12"

Notes:

Test No. : C-7
 Sand Type : Calcareous
 Dry Density (gm/cc) : 0.94
 Cement Content (%) : 1.0
 Water Content (%) : 19



FIGURE 4 - 16

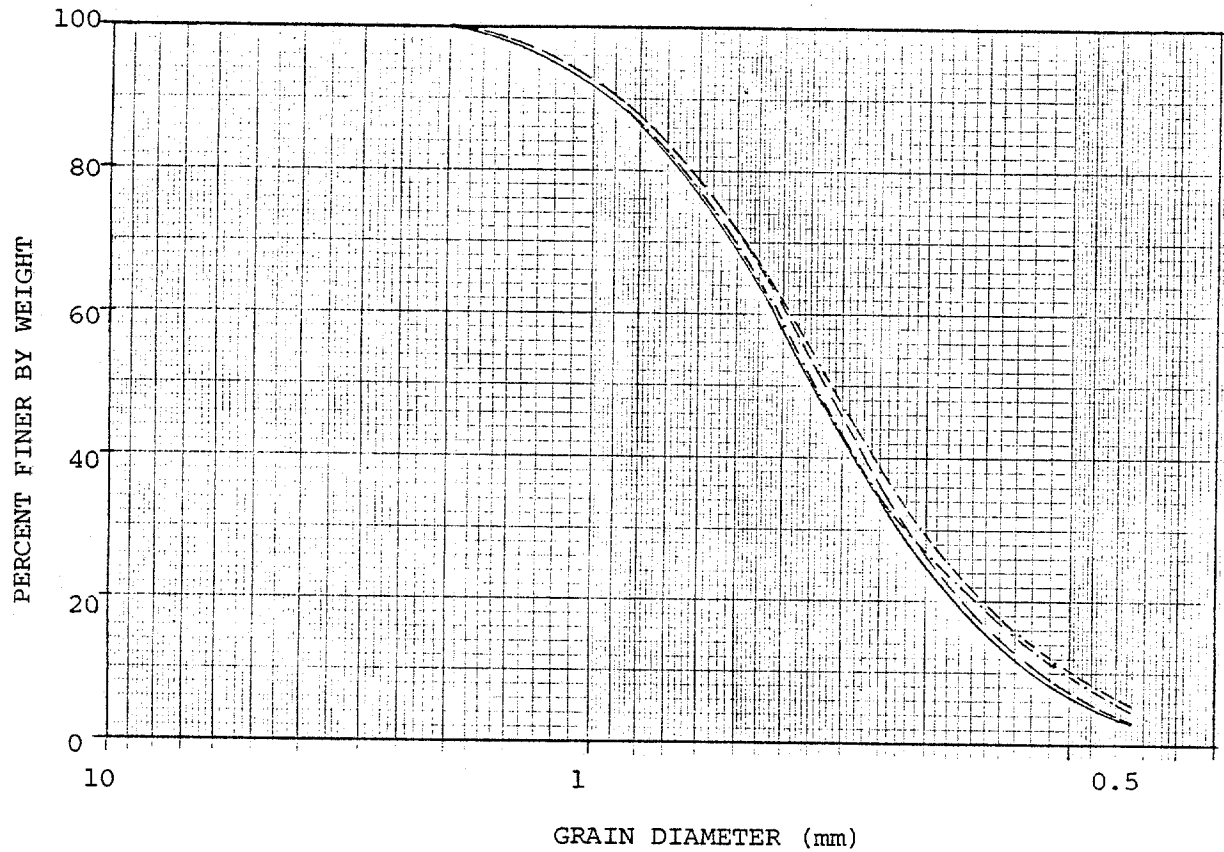
GRAIN SIZE DISTRIBUTION CURVES FOR
 SPECIMENS AT OR NEAR THE PILE WALL -
 LOWER DENSITY CALCAREOUS SAND
 (CEMENT CONTENT = 1%)

Approved by

Checked by

Drawn by

Compiled by



- Original Sample
- Specimen at Depth Interval between 0 and 4"
- - - - - Specimen at Depth Interval between 4" and 8"
- Specimen at Depth Interval between 8" and 12"

Notes:

Test No. : C-8
 Sand Type : Calcareous
 Dry Density(gm/cc) : 0.94
 Cement Content(%) : 2.0
 Water Content(%) : 19

Ertec
 The Earth Technology Corporation

FIGURE 4 - 17

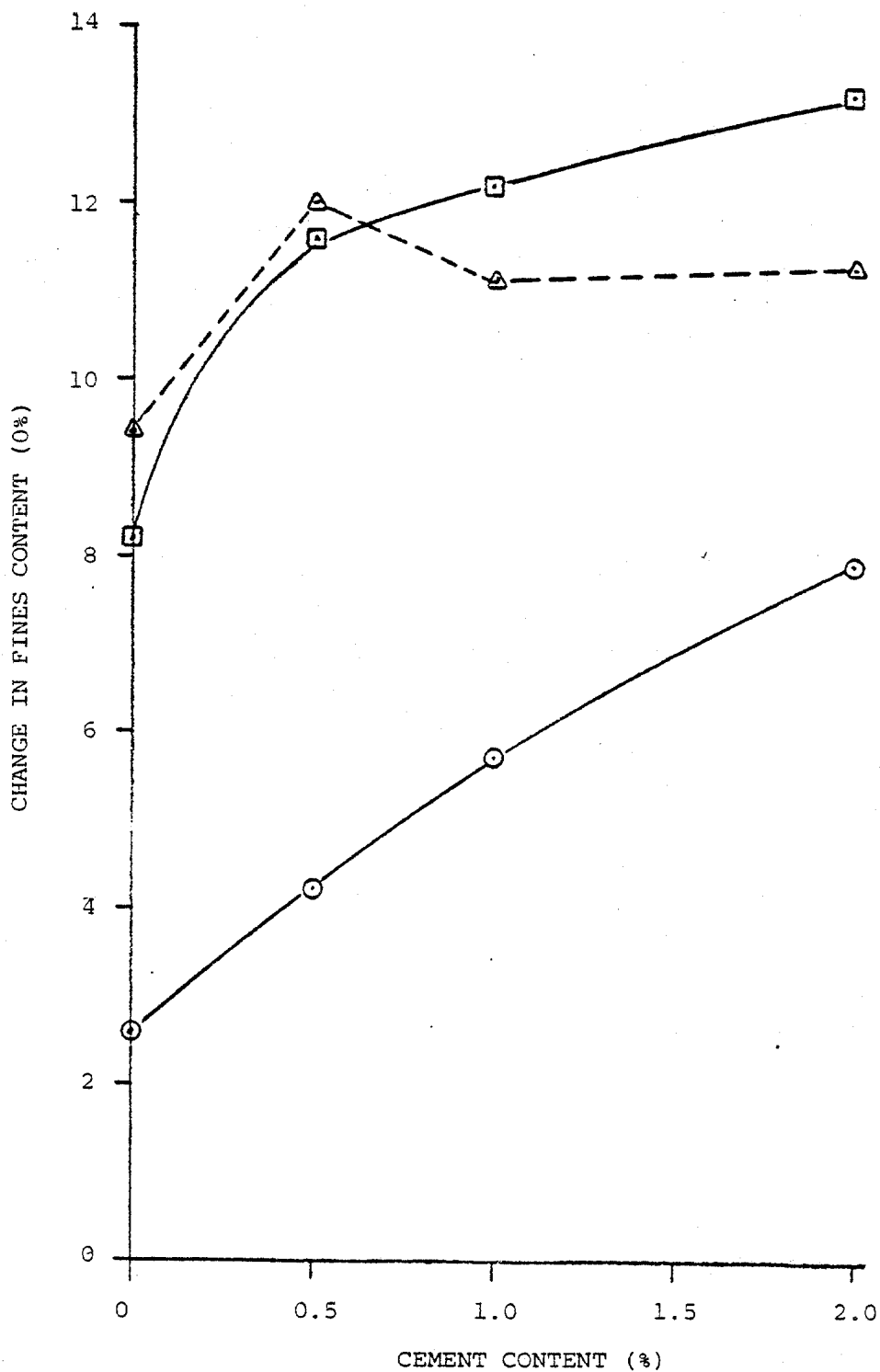
GRAIN SIZE DISTRIBUTION CURVES FOR
 SPECIMENS AT OR NEAR THE PILE WALL -
 LOWER DENSITY CALCAREOUS SAND
 (CEMENT CONTENT = 2%)

Approved by

Checked by

Drawn by

Compiled by



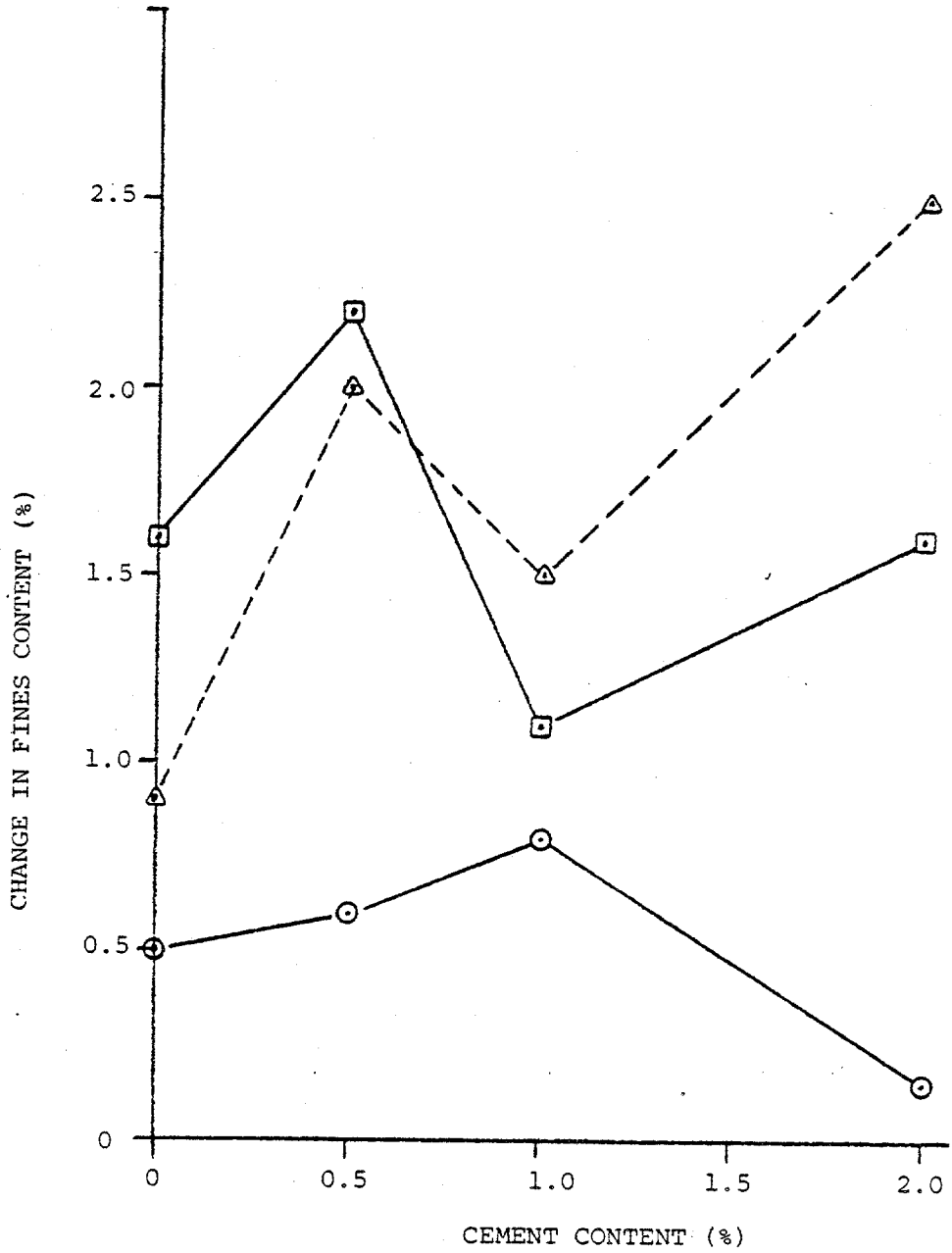
<u>SYMBOL</u>	<u>DEPTH INTERVAL (inches)</u>
○	0 to 4
□	4 to 8
△	8 to 12

- NOTES: 1. Pile penetration is 12 inches
2. Dry Density - 1.17 gm/cc

Ertec
The Earth Technology Corporation

FIGURE 4 - 18

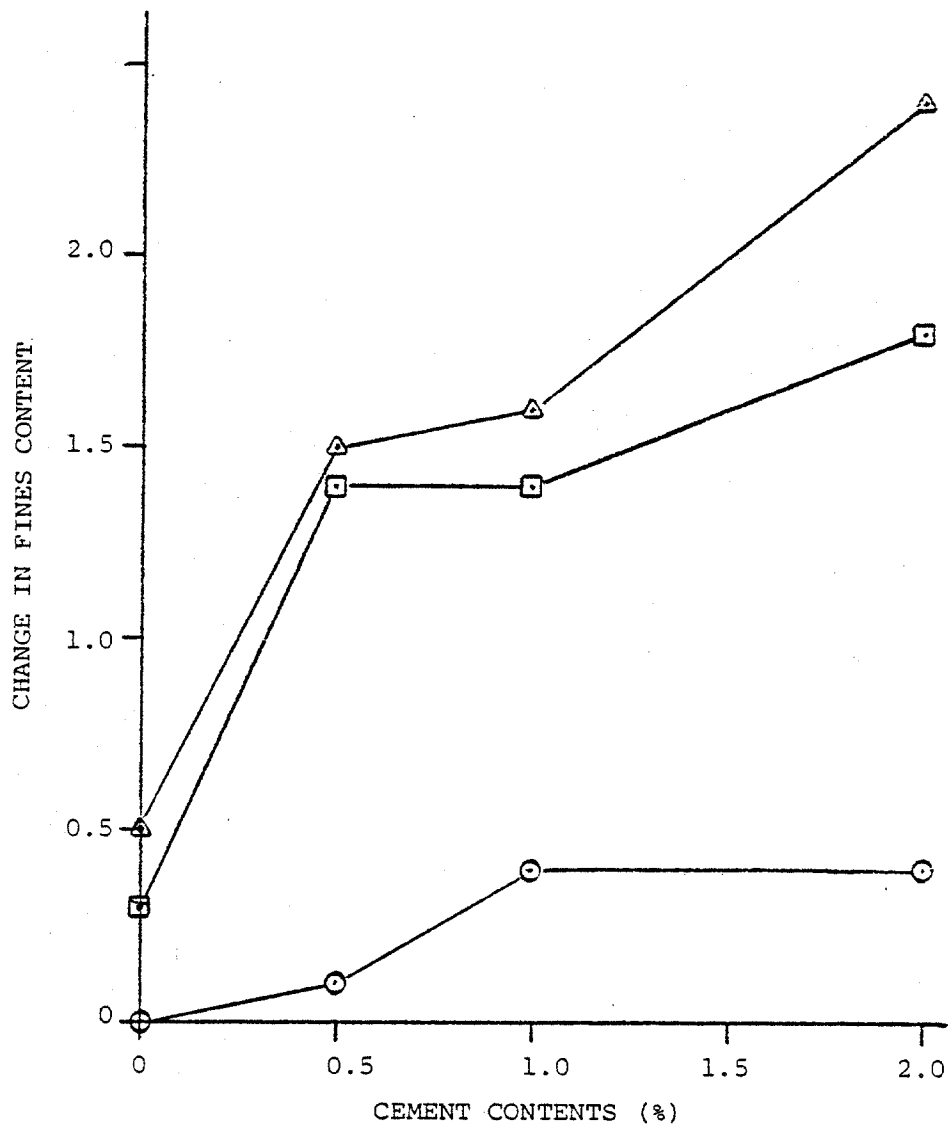
CHANGE IN FINES CONTENT AT OR NEAR
THE PILE WALL VERSUS CEMENT CONTENT
- HIGHER DENSITY CALCAREOUS SAND



<u>SYMBOL</u>	<u>DEPTH INTERVAL (inches)</u>
○	0 to 4
□	4 to 8
△	8 to 12

- NOTES: 1. Pile Penetration is 12 inches
 2. Dry Density = 0.94 gm/cc

	FIGURE 4 - 19
CHANGE IN FINES CONTENT AT OR NEAR THE PILE WALL VERSUS CEMENT CONTENT - LOWER DENSITY CALCAREOUS SAND	



SYMBOL DEPTH INTERVALS (inches)

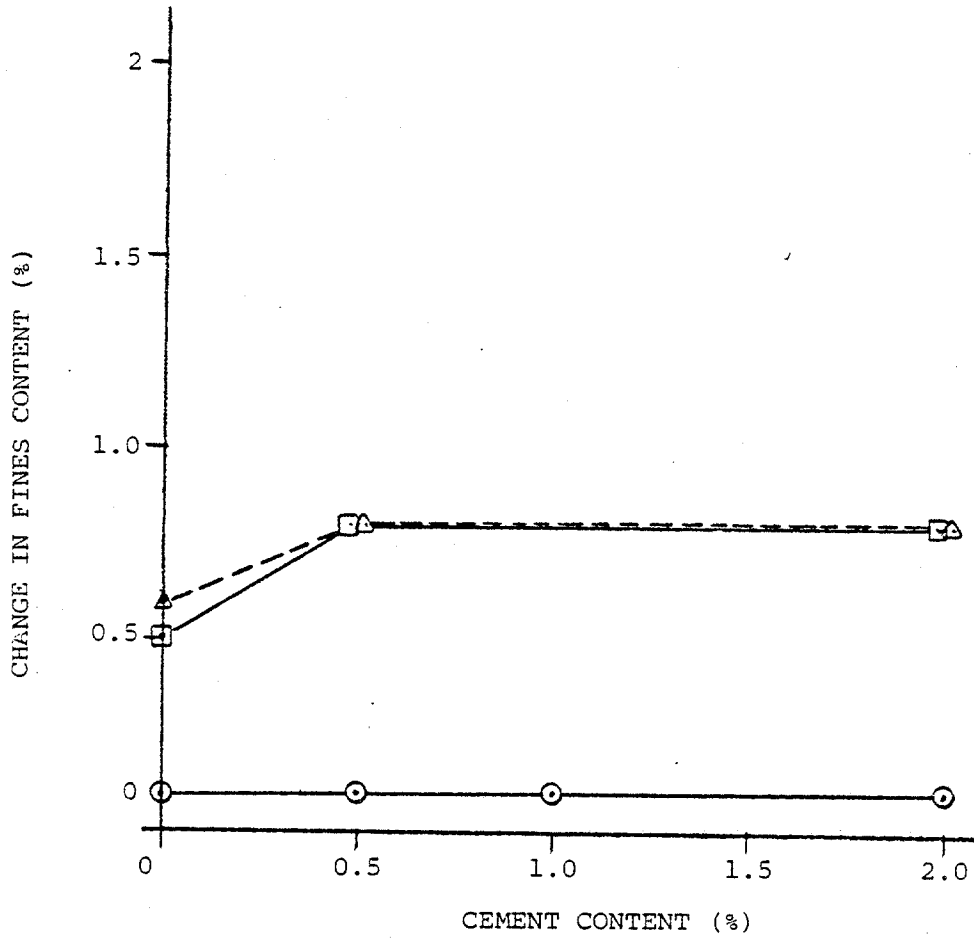
- 0 to 4
 □ 4 to 8
 △ 8 to 12

NOTES: 1. Pile penetration is 12 inches
 2. Dry Density = 1.61 gm/cc



FIGURE 4 - 20

CHANGE IN FINES CONTENT AT OR NEAR
 THE PILE WALL VERSUS CEMENT CONTENT
 - HIGHER DENSITY SILICA SAND



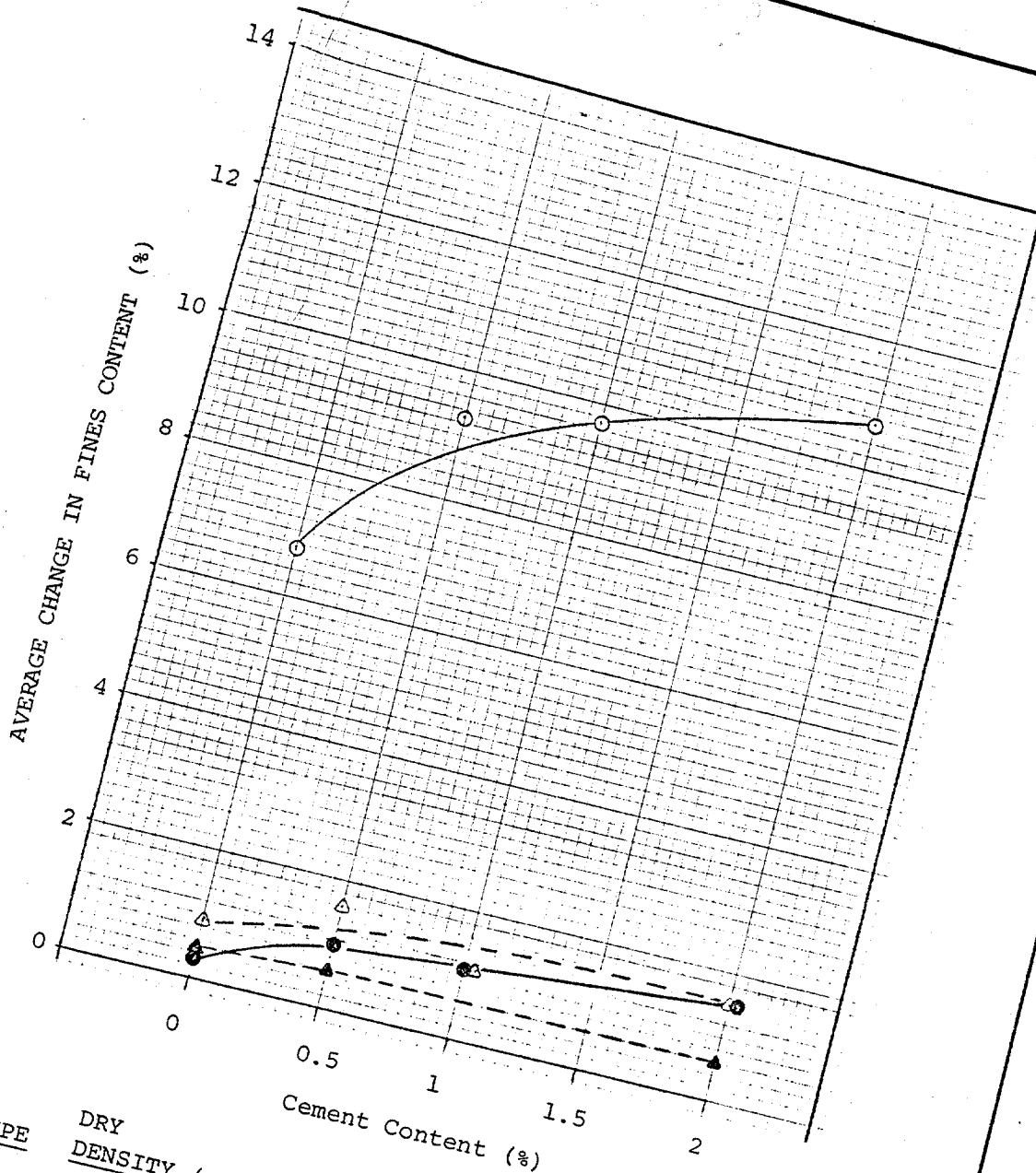
<u>SYMBOL</u>	<u>DEPTH INTERVALS (inches)</u>
○	0 to 4
□	4 to 8
△	8 to 12

- NOTES: 1. Pile penetration is 12 inches
 2. Dry Density = 1.51 gm/cc



FIGURE 4 - 21

CHANGE IN FINES CONTENT AT OR NEAR THE PILE WALL VERSUS CEMENT CONTENT - LOWER DENSITY SILICA SAND



SAND TYPE	DRY DENSITY (gm/cc)
Calcareous	1.17
Calcareous Silica	0.94
Silica	1.61
Silica	1.51



FIGURE 4 - 22

AVERAGE CHANGE IN FINES CONTENT
VERSUS CEMENT CONTENT
FOR THE PILE

350

300

250

200

NUMBER OF BLOWS REQUIRED FOR PILE TO PENETRATE 12 INCHES

150

100

50

0

0

2

4

6

8

AVERAGE CHANGE IN FINES CONTENT (%) AT 0'

SYMBOL

SAND TYPE

DRY DENSITY (gm/cc)

MOISTURE CONTENT (%)

○
△
●
▲

Calcareous 1.17
Calcareous 0.94
Silica 1.61
Silica 1.51

19
19
10
10

15-pound dead weight hammer
1 foot

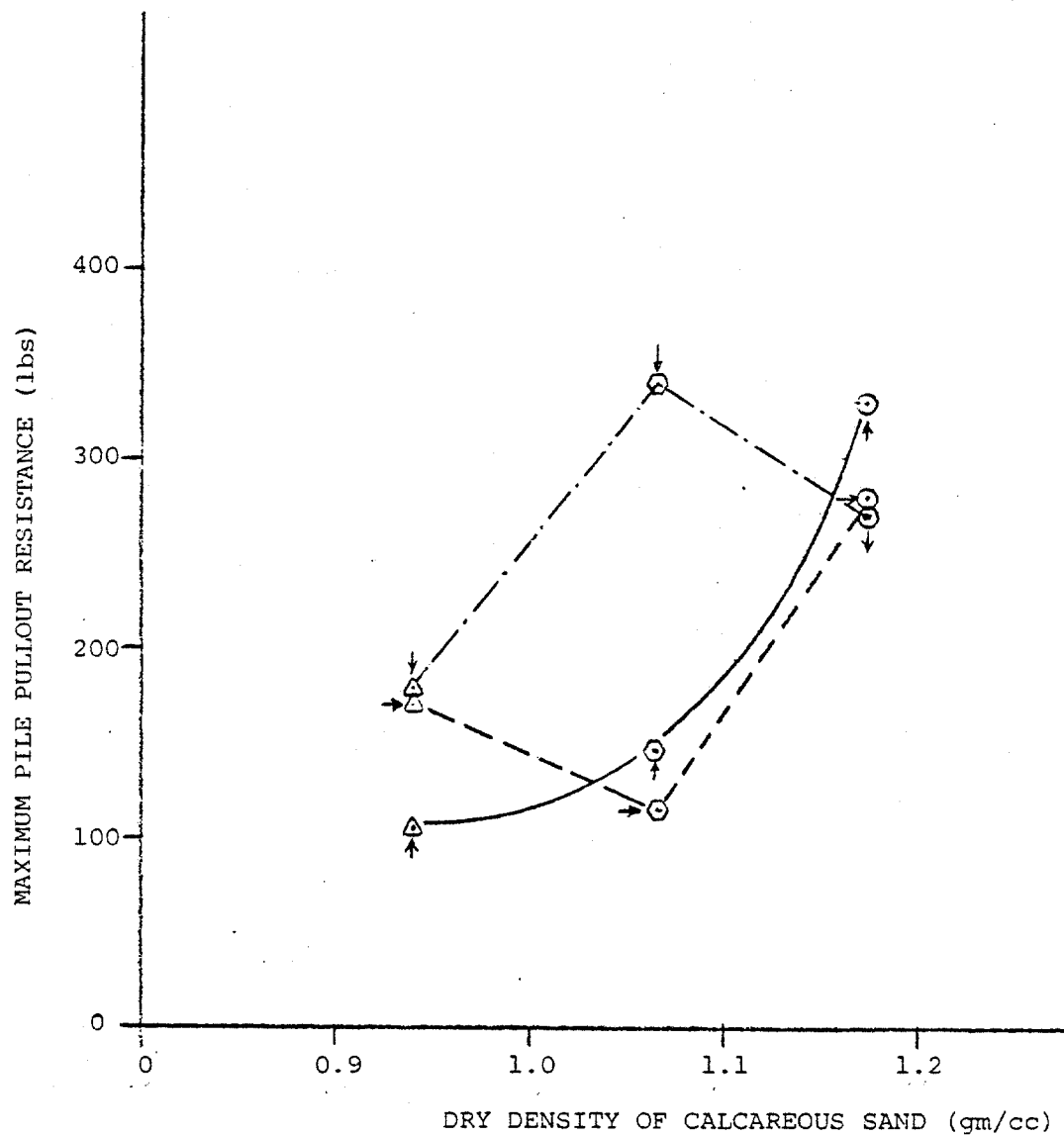
ARROW DIRECTI
INDICATE CEM

↑ = 0%
↓ = 1%

Compiled by

Drawn by

AV
OR NE



- ⊙ Higher density calcareous samples (Test No. C-1, C-2, C-3)
- ⊠ Medium density calcareous samples (Test No. SC-1, SC-2 and SC-3)
- △ Lower density calcareous samples (Test No. C-5, C-6, and C-7)

- NOTES: 1. Arrow direction indicates cement content: ↑=0%, →=0.5% and ↓=1%
2. Pile diameter = 1.5 inches



FIGURE 4-26

PILE PULLOUT RESISTANCE VERSUS DRY DENSITY OF CALCAREOUS SAND

5.0 SUMMARY, REMARKS AND CONCLUSIONS

5.1 Summary

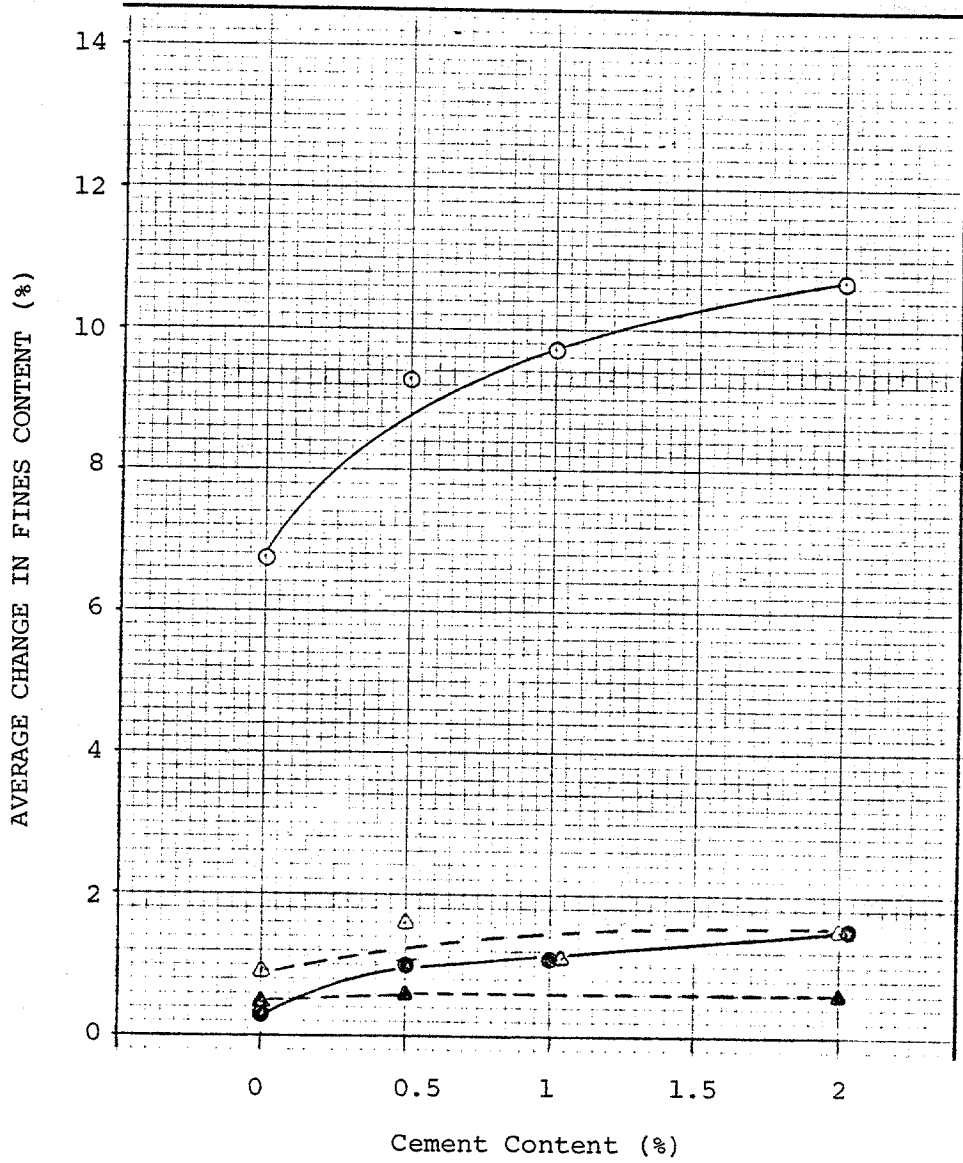
The following summarized comments can be made with respect to crushability, cement content, pile driving resistance and pullout resistance:

1. Pile Driving Resistance

- o induces grain crushing proportional to the amount of driving energy;
- o increases with an increase in cement content in higher density silica sand and calcareous sand;
- o increases with an increase in soil density;
- o does not have a definitive relation with the cement content in lower density silica and calcareous sand samples; and
- o is not a rational parameter in assessing pullout capacity for piles in calcareous sands.

2. Pile Pullout Resistance

- o increases with the density in non-cemented calcareous sand samples;
- o increases with increasing cement content, soil density and driving resistance for piles in silica sand;
- o increases slightly with increasing pile driving resistance for piles in lower density calcareous sand;



<u>SYMBOL</u>	<u>SAND TYPE</u>	<u>DRY DENSITY (gm/cc)</u>
○	Calcareous	1.17
△	Calcareous	0.94
●	Silica	1.61
▲	Silica	1.51



FIGURE 4 - 22

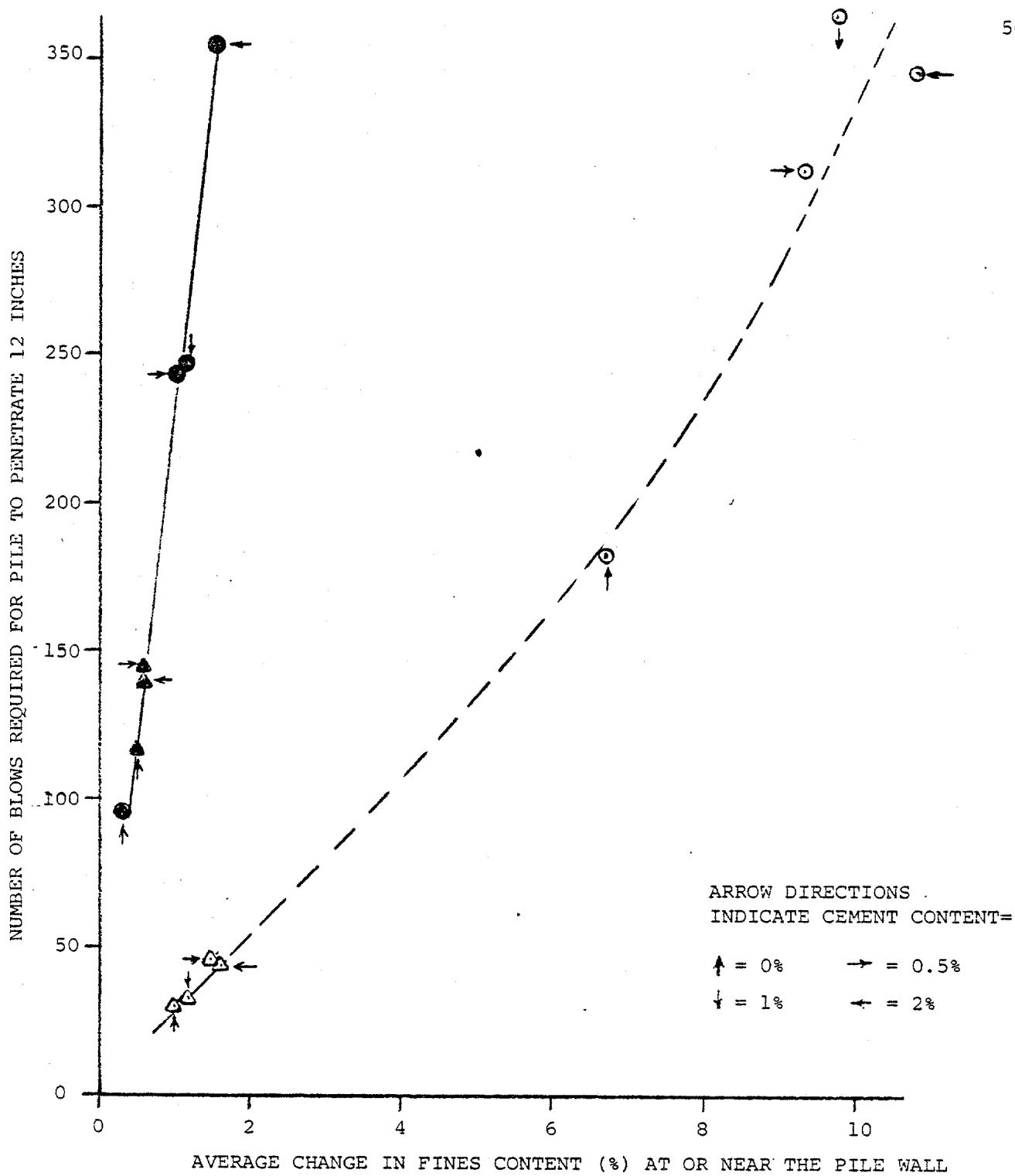
AVERAGE CHANGE IN FINES CONTENT
 VERSUS CEMENT CONTENT - AT OR NEAR
 THE PILE WALL

Approved by

Checked by

Drawn by

Compiled by



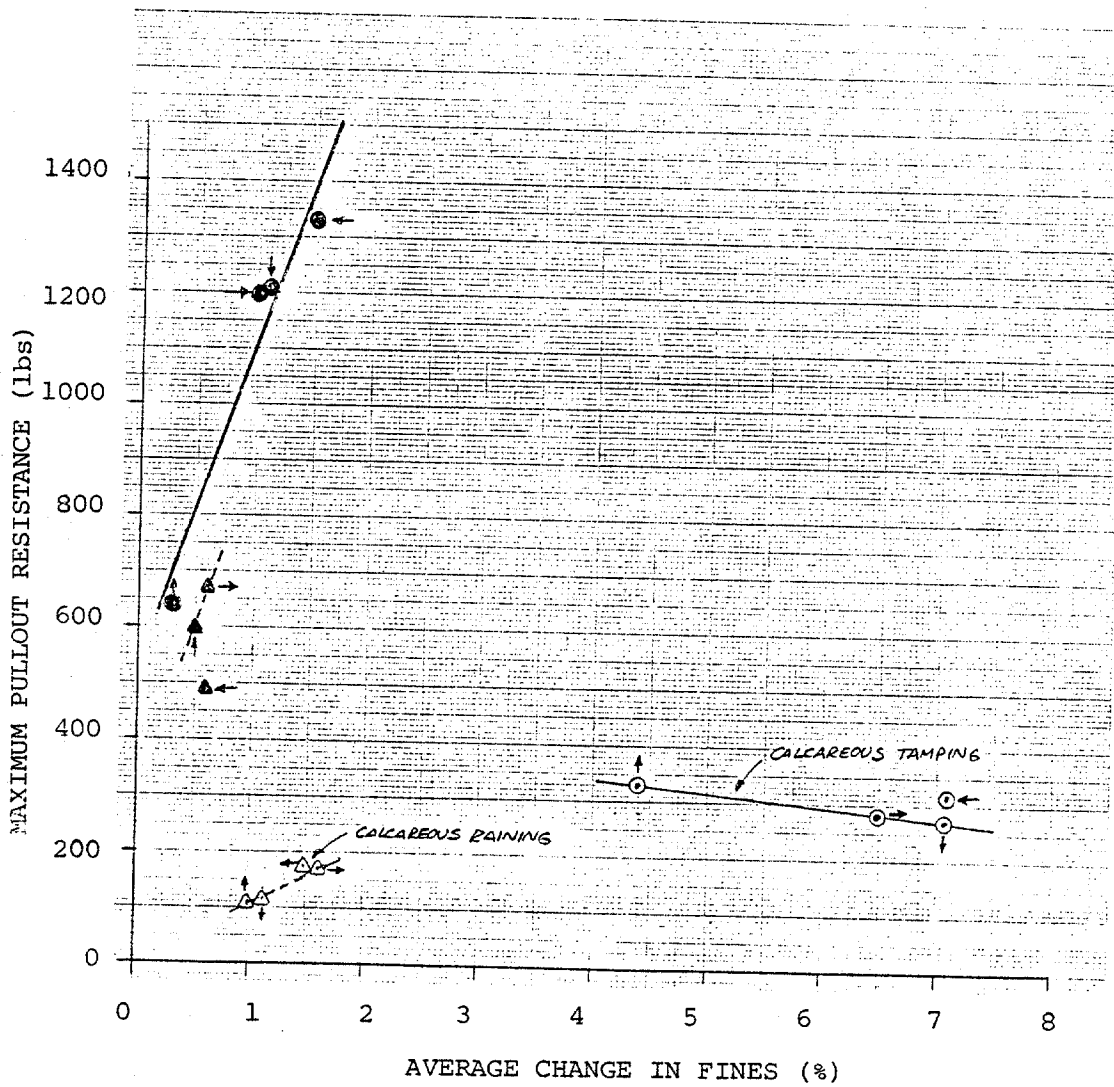
SYMBOL	SAND TYPE	DRY DENSITY (gm/cc)	MOISTURE CONTENT (%)
○	Calcareous	1.17	19
△	Calcareous	0.94	19
●	Silica	1.61	10
▲	Silica	1.51	10

NOTE: 1. 15-Pound dead weight hammer
 2. Drop Height = 1 foot



FIGURE 4 - 23

PILE DRIVING RESISTANCE VERSUS AVERAGE CHANGE IN FINES CONTENT AT OR NEAR THE PILE WALL



SYMBOL	SAND TYPE	DRY DENSITY (gm/cc)	PREPARATION METHOD
⊙	Calcareous	1.17	Tamping
△	Calcareous	0.94	Raining
●	Silica	1.61	Tamping
▲	Silica	1.51	Raining

NOTE: Arrow directions indicate cement contents:

- ↑ = 0%
- = 1.0%
- ↓ = 0.5%
- ← = 2%

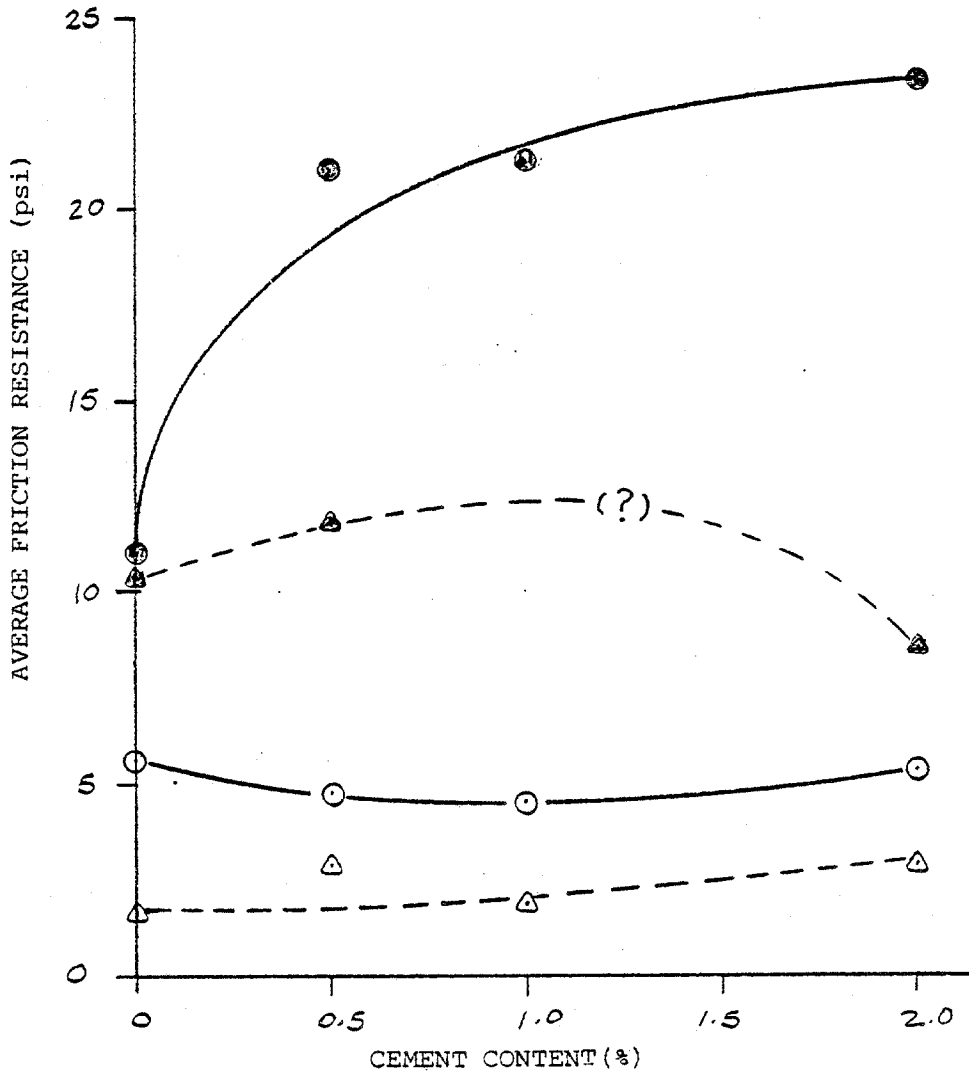


FIGURE 4 - 24

MAXIMUM PULLOUT RESISTANCE VERSUS AVERAGE CHANGE IN FINES AT OR NEAR PILE WALL

Approved by _____
 Checked by _____
 Drawn by _____
 Compiled by _____

Approved by /
Checked by /
Drawn by /
Compiled by /

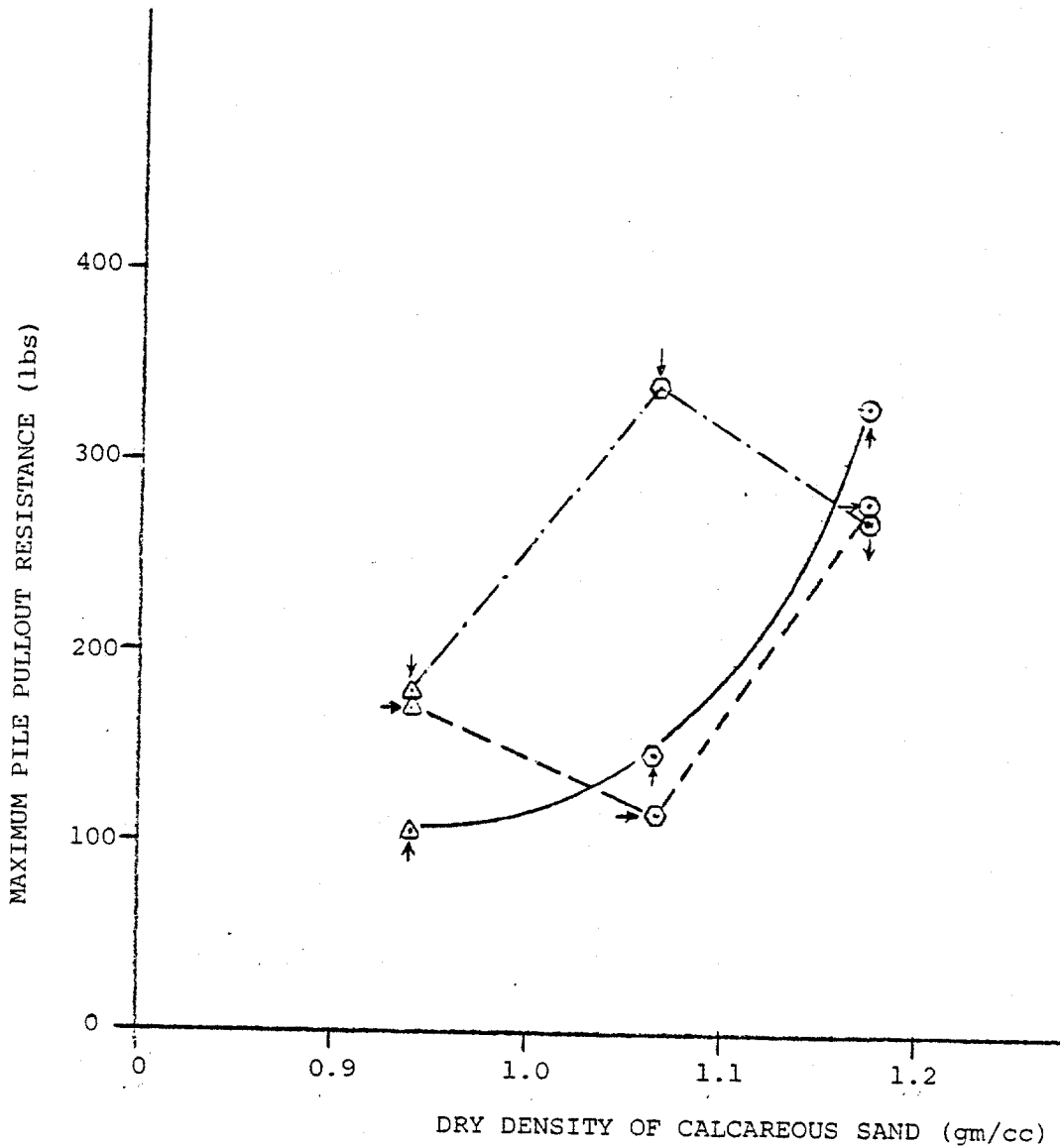


SYMBOL	TYPE OF SOIL	PREPARATION	DRY DENSITY (gm/cc)
○	Calcareous	Tamping	1.17
△	Calcareous	Raining	0.94
●	Silica	Tamping	1.61
▲	Silica	Raining	1.51



FIGURE 4 - 25

AVERAGE FRICTION RESISTANCE
VERSUS CEMENT CONTENT



- ⊙ Higher density calcareous samples (Test No. C-1, C-2, C-3)
- ⊠ Medium density calcareous samples (Test No. SC-1, SC-2 and SC-3)
- △ Lower density calcareous samples (Test No. C-5, C-6, and C-7)

NOTES: 1. Arrow direction indicates cement content: ↑=0%, →=0.5% and ↓=1%
 2. Pile diameter = 1.5 inches



FIGURE 4-26

PILE PULLOUT RESISTANCE VERSUS DRY DENSITY OF CALCAREOUS SAND

5.0 SUMMARY, REMARKS AND CONCLUSIONS

5.1 Summary

The following summarized comments can be made with respect to crushability, cement content, pile driving resistance and pullout resistance:

1. Pile Driving Resistance

- o induces grain crushing proportional to the amount of driving energy;
- o increases with an increase in cement content in higher density silica sand and calcareous sand;
- o increases with an increase in soil density;
- o does not have a definitive relation with the cement content in lower density silica and calcareous sand samples; and
- o is not a rational parameter in assessing pullout capacity for piles in calcareous sands.

2. Pile Pullout Resistance

- o increases with the density in non-cemented calcareous sand samples;
- o increases with increasing cement content, soil density and driving resistance for piles in silica sand;
- o increases slightly with increasing pile driving resistance for piles in lower density calcareous sand;

- o is significantly reduced due to grain crushing for piles in higher density calcareous sand; and
- o cannot be determined solely by pile driving resistance for piles in calcareous sand due to grain crushing effect.

3. Crushability:

- o depends on interrelated effects of grain hardness, pile penetration resistance to driving, cement content, and soil density;
- o is proportional to pile driving resistance;
- o takes place predominantly at or near the pile wall and decreases significantly as the distance away from the pile wall increases;
- o increases with an increase in cement content for both higher density calcareous sand and silica sand;
- o has a significantly adverse effect in the pullout resistance of piles in higher density calcareous sands; and
- o is negligible in silica sands and lower density calcareous sand.

5.2 Remarks

The behavior of piles in calcareous sand is complex. The results of this investigation established certain definitive behavioral patterns with respect to crushability, cement content, density, driving resistance and pullout resistance. It is clear that the frictional characteristics of a pile in

calcareous soil depend on the interrelated effects of these items and none of these items alone can adequately explain the observed behavior.

It should be noted that the frictional characteristics of a pile in calcareous sands are a function of the friction parameter between the pile and soil, and the lateral soil stress on the pile. Grain crushing might slightly reduce the coefficient of friction between the soil and pile (Noorany, 1982a). But this reduction alone cannot fully explain the extremely low pile pullout resistance values of piles in calcareous sand. It is reasonable to postulate that grain crushing also significantly reduces the lateral soil stress on the piles. No reasonable design methodology can be established without well-documented, realistic pile-load test data (in laboratory and in the field). These data should include measurements of axial shear transfer and lateral stress at or near the pile wall. It is important that load tests should be performed on piles of various sizes to account for potential scale (size) effects. Measurements at all stages of pile loading (installation, set-up, static and cyclic loadings) can then be analyzed with the objective of developing an improved design procedure for piles in calcareous sand.

Other areas of further research and development may include the investigations of the following:

1. Effect of other installation techniques such as drilling and grouting, jacking, and vibratory methods
2. Fundamental research towards further understanding the engineering behavior of various calcareous sediment types.

5.3 Conclusions

A series of laboratory experiments were successfully performed using a model pile driven into calcareous sand and silica sand samples, prepared at two different densities and four different cement contents. The results of this investigation demonstrated the effects of

1. pile driving on soil grain crushability,
2. crushability on pile pullout resistance, and
3. cement content on pile pullout resistance and soil grain crushability.

The summary described in Section 5.1, indicates that the behavior of piles in calcareous sand depends on a number of interrelated key parameters. These parameters include, but are not limited to, crushability, pile penetration resistance, soil density, pile pullout resistance and cement content.

The behavior of piles in calcareous sand is complex. None of the above items alone can fully explain the pile behavior observed in this investigation. While this investigation represents one of the initial steps toward establishing a better understanding of soil-pile interaction mechanism for piles in calcareous soils, further research and development work are necessary to establish a rational design methodology for piles in calcareous sediments.

One of the most urgent needs is the establishment of well-documented, realistic pile load test data in the laboratory and in the field for piles of various sizes in various calcareous sediments. Together with analytical studies, these data can be evaluated to better understand pile behavior in

calcareous sediments with a view towards establishing an improved pile design methodology. Any well-documented pile load test data should include a detailed characterization of the calcareous sediments as well as measurements of shear transfer and lateral soil stress at or near the pile wall under all stages of pile loading conditions (installation, setup, static and cyclic loadings).

6.0 REFERENCES

- Agarwal, S. L., A. K. Malhotra, R. Banerjee (1977), Engineering Properties of Calcareous Soils Affecting the Design of Deep Penetration Piles for Offshore Structures, OTC 2792, Offshore Technology Conference, 1977.
- Angemeer, J., E. Carlson, and J. H. Klick (1973), Techniques and Results of Offshore Pile Load Testing in Calcareous Soil, OTC 1894, Offshore Technology Conference, 1973.
- Angemeer, J., E. Carlson, S. Stroad, and M. Kurzene (1975), Pile Load Tests in Calcareous Soils Conducted in 400 Feet of Water from a Semi-Submersible Exploratory Rig, OTC 2311, Offshore Technology Conference, 1975.
- Datta, M., S. K. Gulbati, G. V. Rao (1979), Crushing of Calcareous Sand During Shear, OTC 3525, Offshore Technology Conference, 1979.
- Datta, M., S. K. Gulbati, G. V. Rao (1980), An Appraisal of the Existing Practice of Determining the Axial Load Capacity of Deep Penetrating Piles in Calcareous Sand, OTC 3867, Offshore Technology Conference, 1980.
- Datta, M., G. V. Rao, and S. K. Gulbati (1981), The Nature and Engineering Behavior of Carbonate Soils at Bombay High, India, Marine Geotechnology, Volume 4, No. 4, pp. 307 to 341.
- Demars, K. R., V. A. Nacci, W. E. Kelly, and M. C. Wang (1976), Carbonate Content: An Index Property for Ocean Sediments, OTC 2627, Offshore Technology Conference, 1976.
- King, R. W., W. R. Van Hooydonk, H. F. Kolk, and D. Windle (1980), Geotechnical Investigation of Calcareous Soils on the Northwest Shelf, Australia, OTC 3772, Offshore Technology Conference, 1980.
- McClelland Engineers, Inc. (1980), Geotechnical Considerations for Nearshore Foundation Design in Calcareous Material, Civil Engineering Laboratory, PO No. N62583/80 M R028, 1980.
- Noorany, I. (1982a), Friction of Calcareous Sands, Civil Engineering Laboratory, PO No. N62583/81 M R647, March, 1982.
- Noorany, I. (1982b), Classification of Marine Sediments, Preprints, 1982 ASCE Convention and Exhibit, New Orleans, LA., October, 1982.

Appendix A

APPENDIX A

TEST EQUIPMENT AND PROCEDURES

A.1 Equipment

Most equipment used in this testing program was custom-built in accordance with project requirements and applications. Apparatus are listed as follows:

- a. Miniature Pile - A 1.5-inch diameter and 18-inch long, solid steel rod with a flat tip.
- b. Pile Driver - A driving assembly consisting of a 0.5-inch diameter, 4-foot long steel rod and hammers.
- c. Red Barrel - A 30-inch diameter, 30-inch high test drum capable of applying confining pressure.
- d. Pile Guiding Assembly - a setup consisting of three steel posts mounted onto the cover of the red barrel, and a bearing plate having a 0.5-inch diameter hole aligned with a 1.5-inch diameter hole on the cover of the red barrel for the pile to go through.
- e. Split Mold - A 9.0-inch diameter, 18-inch long split tube for preparing test samples.
- f. Membrane - A rubber membrane having a 9-inch diameter and a 0.025-inch thickness.
- g. Instrumentation - A strain-gaged load cell attached to the top of the pile to monitor pile pullout resistance, and a displacement transducer to monitor pile head displacement.

- h. Tamper - A tamper having a contact surface area equal to approximately one-half of the soil surface being compacted and a rod which could be adjusted to the thickness of the soil being compacted.
- i. Recorder - A high frequency chart record with a three channel X-Y-Y output.
- j. Signal Conditioner - A Daytonic signal conditioner connected to a load cell and a displacement transducer, and having digital output.
- k. Actuator - A hydraulic actuator having a 40,000 pound pulling capacity.
- l. Hydraulic System - A system consisting of a hydraulic pump with a needle valve for adjusting rate of loading.
- m. Other accessories - air compressor, vacuum pump, pressure gages, water tank, rubber tubes, bolts and nuts, and etc.

A.2 Sample Preparation

The following sample preparation methods were developed during the progress of this testing program. These methods were developed to achieve uniform, homogeneous samples. The step-by-step sample preparation procedures are described as follows:

A.2.1 Air-dry the material (silica and calcareous sands)

A.2.2 Prepare each test sample in 18 one-inch high, layers. For each layer, the amount of dry sand required to achieve the prescribed void ratio was calculated as follows:

<u>Type of Sand</u>	<u>Void Ratio</u>	<u>Dry Sand Required (gm)</u>	<u>Sample Preparation Methods</u>
Calcareous	1.4	1226	Tamping
Calcareous	2.0	981	Raining
Silica	0.65	1675	Tamping
Silica	0.75	1579	Raining

- A.2.3 Add the required amount of Portland cement Type I (0, 0.5, 1, or 2 percent by weight) to the dry sand and mix them thoroughly.
- A.2.4 Add water (19 percent for calcareous sand, or 10 percent for silica sand) to the sand-cement mixture, and blend thoroughly.
- A.2.5 Setup a split mold with a membrane stretched inside by applying vacuum.
- A.2.6 For the tamping method, adjust the tamping rod so that 1-inch layer of compacted sample can be achieved. Pour the moist sand-cement sample from the bag into the mold. Tamp the sample until the surface of compacted sample is smooth. Repeat this step until an 18-inch high sample is achieved.
- A.2.7 For the raining method, screen the moist sand-cement sample from each bag through a No. 10 sieve. Soil particles are then dropped freely to form a loose density. Smooth the surface of the sample for each layer of screening. Repeat this step until the height of sample is 18 inches.
- A.2.8 Release the vacuum and disconnect vacuum lines.
- A.2.9 Bring the compacted sample with the mold into the humidity room and cure it for at least 3 days.

- A.2.10 Prepare the red barrel by compacting moist silica sand at the bottom of the red barrel until a 10-inch layer of compacted sand is achieved.
- A.2.11 Smooth and level the surface of the compacted sand and place the round plywood sheet with a 10-inch diameter hole at the center onto the compacted sand. This round plywood is used to center the test sample while placing it in the red barrel.
- A.2.12 Bring the test sample with the mold from the humidity room and place it on the center of the plywood.
- A.2.13 Remove the round plywood and then dismantle the mold carefully.
- A.2.14 Pour the silica sand around the test sample and compact in layers, each layer being about 6 inches, until reaching the top of the red barrel.
- A.2.15 Smooth the top surface of the sand, and place the bearing plate on top of the tested sample. Cover the bearing plate with a rubber tube.
- A.2.16 Connect pressure lines to the rubber tubes.
- A.2.17 Close the cover of the red barrel.
- A.2.18 Apply 20 psi to the rubber tubes through an air-water interface tank. Wait until the water level in the tank becomes stable, which indicates the equilibrium of the pressure inside the red barrel.

A.3 Pile Testing

This section covers the procedures for driving and pulling the pile. The driving system was designed and built to achieve a vertical penetration of the

pile. The pulling system was designed and built to pull the pile at a slow speed of pulling. The procedures are described as follows:

- A.3.1 Mount the pile guiding unit onto the cover of the red barrel.
- A.3.2 Connect one end of the 0.5-inch diameter rod to the top of the pile. Insert the other end of the rod through the guiding hole, and rest the tip of the pile on the top of the test sample.
- A.3.3 Drive the pile using a 15-pound hammer and 12-inch drop height. Record the penetration versus blowcount until a penetration of 12-inches is reached.
- A.3.4 Install pullout test assembly by connecting the top of the pile to the bottom of the load cell and the other end of load cell mounted to the pulling actuator.
- A.3.5 Install the displacement transducer.
- A.3.6 Pull the pile at a speed of 0.04 inch per second and continuously monitor pullout load and pile displacement with an X-Y-Y recorder.

A.4 Subsampling for Grain Size Analyses

- A.4.1 Dismantle the pile pulling test assembly including tension rods, bearing plate, load cell, and displacement transducer.
- A.4.2 Release confining pressure.
- A.4.3 Remove the pile with extremely care to prevent collapsing of the hole. The hole should stand up for either cemented or non-cemented sand samples.

A.4.4 Using a sampling cup, scrape the sand wall outward in three 4-inch layers. For each layer, three specimens should be taken at three zones: 0 to 0.25 inch, 1 to 2 inches and 2 to 3 inches from the pile wall.

A.5 Grain Size Analysis

A.5.1 Oven-dry the collected specimens.

A.5.2 Separate the cement agent and soil grains by lightly rubbing the cemented lumps with fingers. Extreme care should be taken to prevent breakage or crushing of the soil grains.

A.5.3 Weigh the dry specimen and then soak it with distilled water for at least 24 hours.

A.5.4 Wash the soil specimen using tap water through a No. 200 sieve.

A.5.5 Oven-dry the retained soil materials.

A.5.6 Weigh the soil materials and perform sieve analysis using ASTM D-422.

A.6 Pictorial Documentation

A pictorial illustration of the above step-by-step procedures is attached.

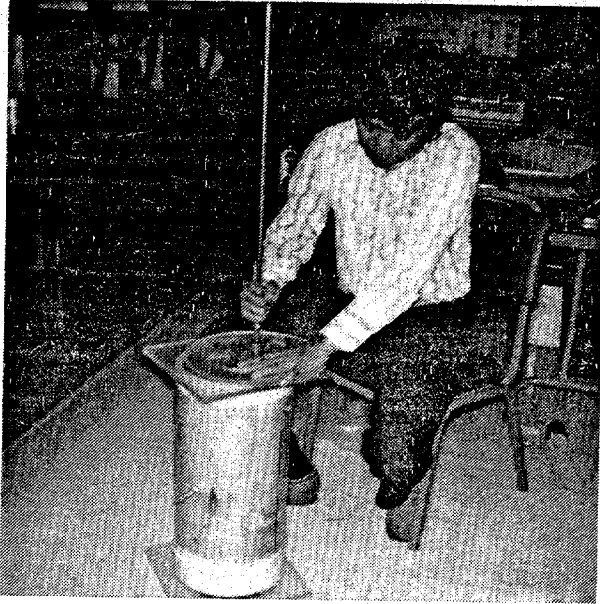


Figure A-1. Compacting sample.

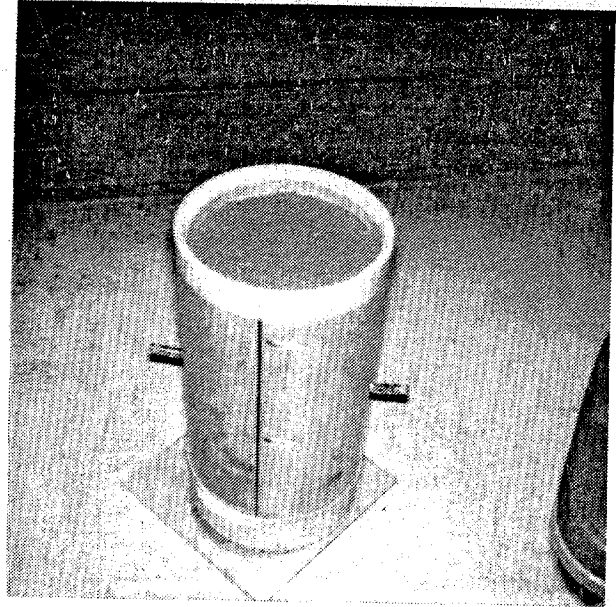


Figure A-2. Sample after compaction.

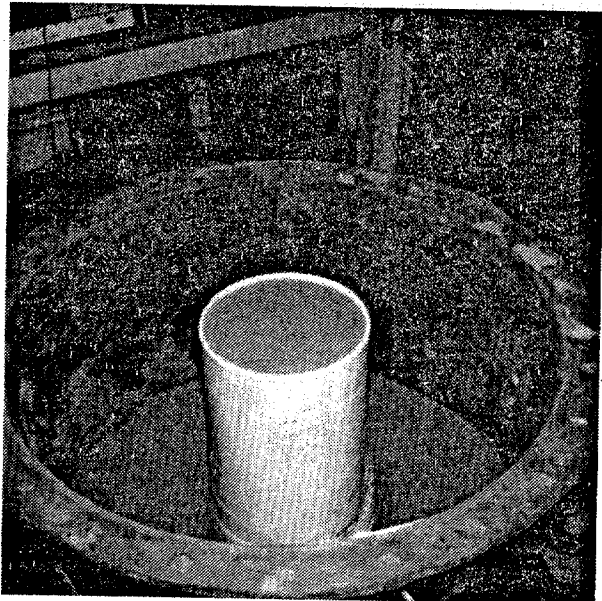


Figure A-3. Sample placed on precompacted sand.

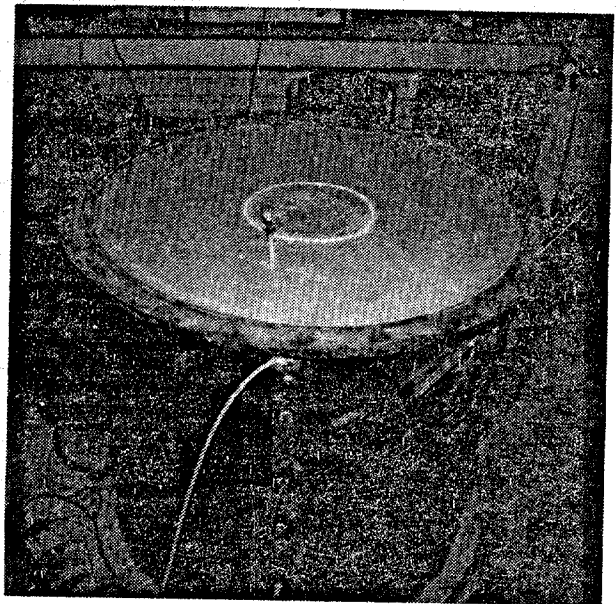


Figure A-4. Sample surrounded by compacted sand.



Figure A-5. Rubber tubes placed on top of sand.

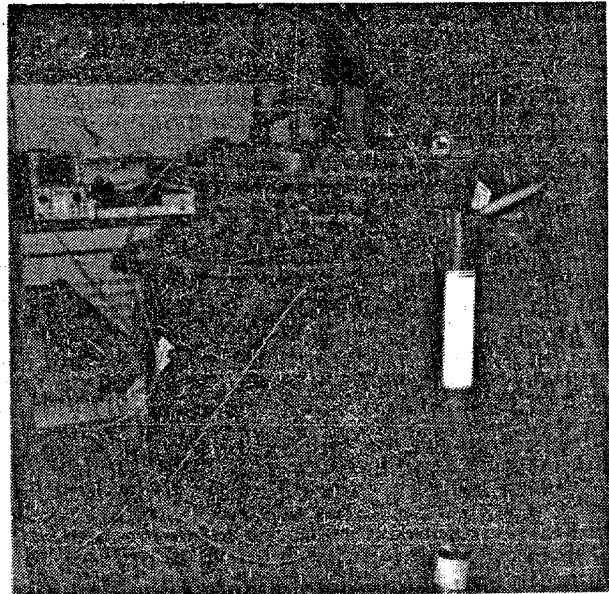


Figure A-6. Assemble the cover.

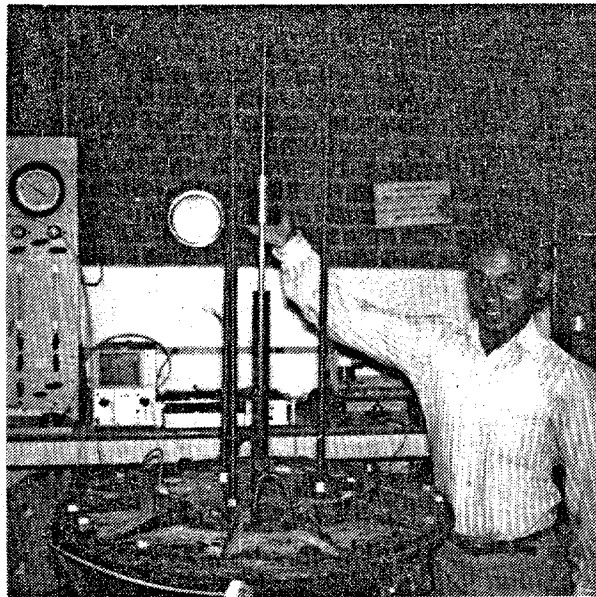


Figure A-7. Install pile driving system.

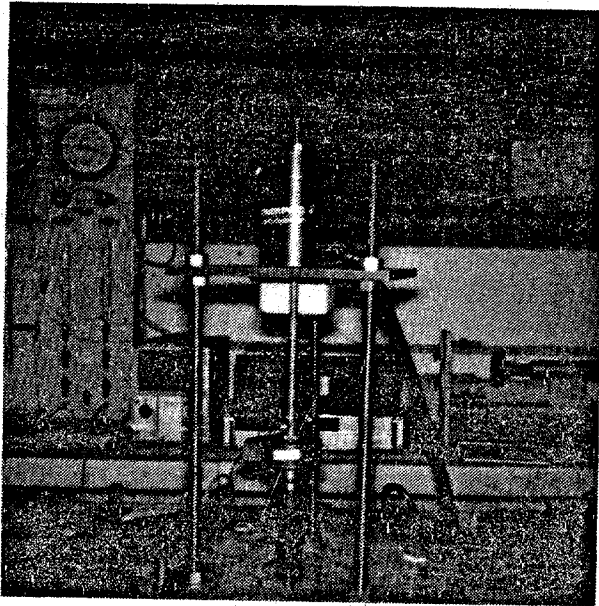


Figure A-8. Pullout setup.

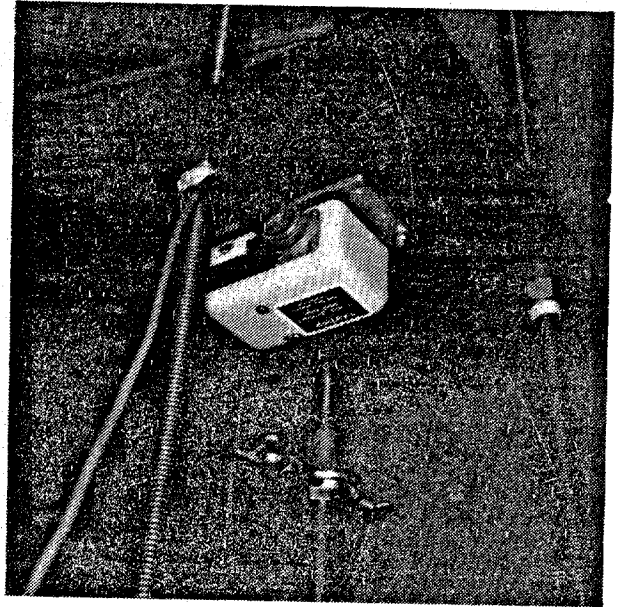


Figure A-9. LVDT measuring displacement.

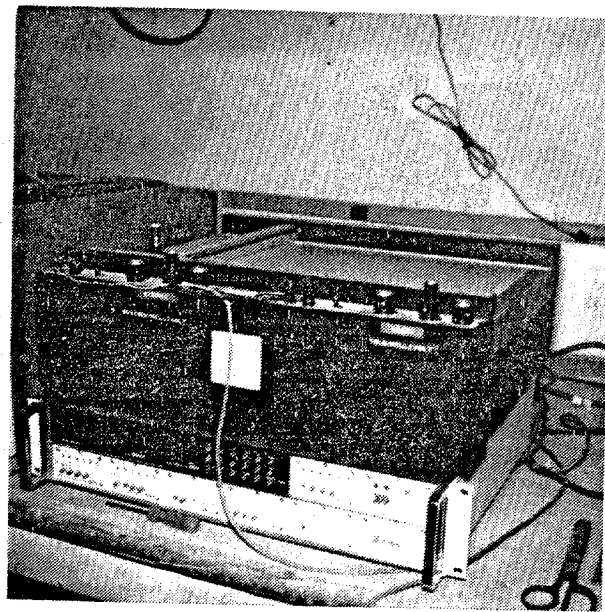


Figure A-10. X-Y-Y' recorder plotting load versus displacement.

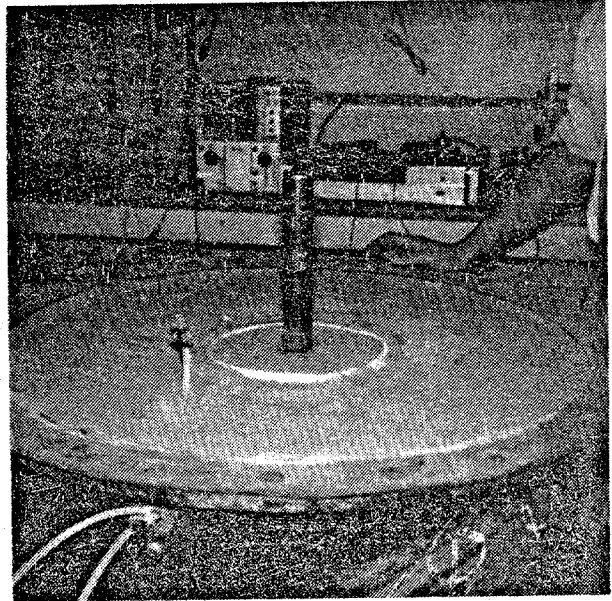
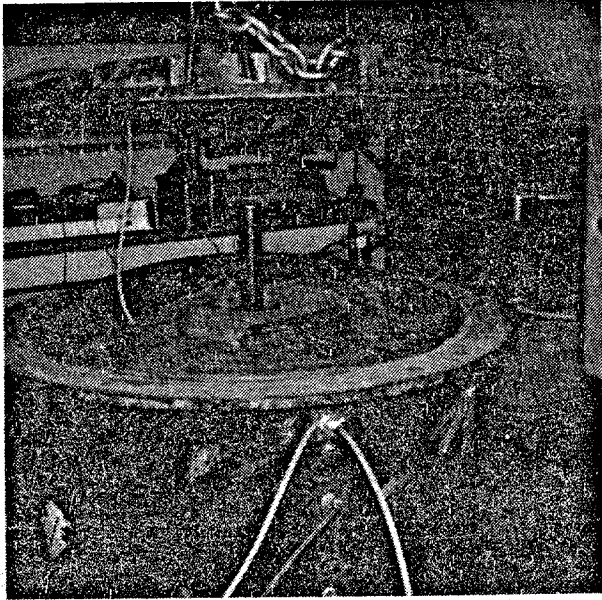


Figure A-11. Removing cover plate.

Figure A-12. After removing rubber tubes.

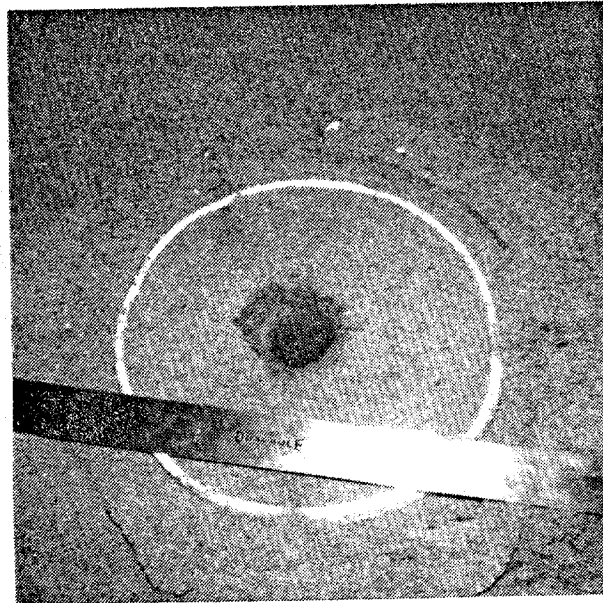


Figure A-13. After pile removal.