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Subsurface Investigation for Liquefaction Analysis and Piezometer Calibration at Treasure Island Naval Station, California

by

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Introduction

Between January and March, 1994, a drilling program was conducted at the Treasure Island Naval Station to evaluate the liquefaction resistance of soils that did and did not liquefy during the Loma Prieta, California, earthquake of October 17, 1989. A second goal of this drilling program was to test and calibrate a retrievable piezometer system that is designed to monitor dynamic pore-water pressure during liquefaction.

Retrievable Piezometer

A retrievable piezometer can be used to replace failed transducers without redrilling, and the external casing can be installed without the piezometer itself. Many external casings can be installed throughout a region and used only when necessary.

At two sites the USGS retrievable piezometer was placed at depths between 2.3 and 4.6m. The retrievable piezometer involves augering a hole to the testing depth and emplacing a 33-mm outside diameter pvc pipe with a porous stone. The hole is back filled and sealed with bentonite, the top of the boring is capped with a box flush to the ground. Later, a commercial transducer is connected to a 21-mm outside diameter pvc pipe and lowered down the 33 mm casing and screwed into the bottom porous-stone assembly. A calibrating transducer (the same type and model as in the USGS retrievable piezometer) was installed inside a penetrometer with a 60° conical tip and an external sleeve that protects the porous filter, located immediately behind the tip, during advancement through dry soil. After the instrument was advanced to the proper depth the tip with the porous filter was advanced past the protective sleeve. Pore pressure was elevated separately by dynamic impact and blasting.

The first calibration tests were conducted within the U.S. Geotechnical Test Site established at the Treasure Island fire station (building 157) (de Alba and others, 1994). A 590 kg weight (diameter 72 cm) was dropped 0.69 to 1.63 m onto a steel plate (91 cm square, 0.6 cm thick) to elevate pore pressure, each test involved dropping the weight one time. The surficial distance from the energy source to the piezometers ranged from 1 to 3.6 m. At an empty field (bounded by 11th and 13th streets and H and I ave) pore pressure was elevated using the 590 kg weight and no. 8 blasting caps (50 grains, 3 grams) and primer cord. The explosives were placed 2 m from the piezometers at depths of 2.4 to 2.7 m. A USGS explosives expert handled the explosives under the supervision of Navy personnel.

Liquefaction

Gray and brown, fine to medium grained sand was hydraulically dredged from San Francisco Bay to create Treasure Island (fig. 1). During the Loma Prieta earthquake Treasure Island experience a peak ground acceleration of 0.16 g (Shakal and other, 1989) and portions of the soil beneath Treasure Island liquefied and were vented to the ground surface as sand boils. During November, 1989, a survey of Treasure Island was made to document ground effects such as sand boils, settlement, and ground cracking. During this survey samples of more than 30 sand boils were taken for grain size analysis (Bennett, in press).

Although the soil beneath the fire station did not liquefy, surrounding areas did. The surrounding liquefaction may have affected the peak ground acceleration. Fifteen seconds into the acceleration record at the fire station there is a sudden drop in ground acceleration, and 16 seconds into the record there is practically no response (Idriss, 1991). De Alba and others (1994) ascribe the behavior of the acceleration record to the liquefaction of the underlying sand.

Besides the generation of sand boils, Treasure Island experienced significant ground settlement and lateral deformation that damaged lifelines for water and gas (Seed and others, 1990).

The primary objective of this report is to document the subsurface stratigraphy at the liquefaction and non-liquefaction sites (fig. 2), and to explore the relation between sand boils and subsurface sediment. This documentation adds to the geotechnical data base of liquefaction by clarifying which layers actually liquefy during earthquakes. Another objective is to briefly describe the piezometer calibration test in terms of what was done and where it was done, results of the calibration work will be reported later by the primary investigator, Behnam Hushmand of Hushmand Associates.

METHODS

Cone Penetration Test

The cone penetration test (CPT) was used to determine soil stratigraphy and obtain data for liquefaction analysis. The locations of the CPT are shown in figures 3, 4, and 5. The CPT measures the penetration resistance (q_c) at the tip of a 10-cm^2 cone and the side friction (f_s) along a 150-cm^2 sleeve behind the cone. Soil type and density or consistency can be interpreted from the tip resistance and the friction ratio (R_f, in percent) between q_c and f_s. The procedures and equipment are consistent with the requirements of ASTM standard D-3441-79 (ASTM, 1983). Tip and sleeve resistances are digitized and recorded every 10 cm during the advancement of the penetrometer into the soil. Graphs of tip resistance and friction ratio are then used to define the soil profile and guide placement of standard penetration tests (SPT).

Standard Penetration Test

The SPT is a dynamic penetration test that measures penetration resistance and obtains a sample for visual examination and laboratory testing. The locations of the SPT are shown in figures 4 and 5. The test involves hammering a 5-cm Mobile[1] "ADO sampler" (with liners) into the soil and counting the number of hammer blows its takes to advance the sampler 46 cm. The first 15 cm is seating, the sum of the hammer blows in the second and third 15 cm intervals is the field blow count, N. A Mobile B-50 and 25-cm outside-diameter hollow stem augers (10-cm inside diameter) were used to advance the boring. During sampling the sampler was driven using a Mobile "In-hole sampling hammer", the 64 kg hammer was lifted and dropped using a Mobile "Safe-T-Driver" hoist. The combined efficiency of the hammer-hoist setup is approximately 68 percent (Douglas and Strutynsky, 1984). The SPT procedure followed the guidelines outlined in ASTM standard D-1586-67 (ASTM, 1983), modifications for use with hollow-stem augers are described in Youd and Bennett (1983).

Laboratory

Samples collected from the SPT and from cuttings returned from the side of the auger were examined in the field for texture, layering, and color (Munsell, 1975). Water content samples were taken, samples were bagged and returned to the laboratory for index testing. Water content measurements (D2216-80, ASTM, 1983) are done immediately upon return to the laboratory. Grain size characteristics are determined using sieves and hydrometer tests. Grain diameters equal to the tenth (D_{10}), fiftieth (D_{50}), and sixtieth (D_{60}) percentiles are used to determine the coefficient of uniformity ($C_u=D_{60}/D_{10}$) and the median grain size (D_{50}). Liquid limit (D423-66) and plastic limit (D424-59) are measured to determine plasticity. Sediment was classified using the Unified Soil Classification (USC) modified by Howard (1987).

Liquefaction Analysis

The liquefaction resistance of the fill and the natural deposits was determined using the simplified procedure developed by Seed and others, 1985. The procedure is based on the empirical relation between penetration measured by the SPT and the cyclic

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[1]Trade names are used for descriptive purposes only and do not imply endorsement by the USGS.

stress ratio induced in the soil by an earthquake. The blow count is normalized for an overburden pressure of 1 kg/cm^2, and a hammer efficiency of 60 percent. The earthquake-induced cyclic stress ratio (CSR) is a function of peak ground acceleration (a), the acceleration due to gravity (g), total stress of overlying soil and water, initial vertical effective stress, and a stress reduction factor (r_d) that varies from 1 near the ground surface to about 0.9 at a depth of 10 m. The form of the equation follows:

$$CSR=0.65*(\frac{a}{g})*(\frac{total\ stress}{effective\ stress})*r_d \qquad (1)$$

The peak ground acceleration measured at Treasure Island fire station was 0.16 g, where g is the acceleration due to gravity. The water table at the time of drilling was 1.5 to 3 m, and the soil density was estimated to be 1.92 kg/cm^2.

RESULTS

Sand boils

The grain size characteristics of sand boils near soundings 5 and 6 are listed in Table 1. A complete listing of the more than 30 sand boil locations and grain size characteristics is found in Bennett, in press. A histogram showing the frequency distribution of the median grain sizes for the sand boils is shown in figure 6.

Subsurface sediment

Grain size characteristics of subsurface samples are listed in Table 1. Logs of the soundings that include CPT, SPT, grain size data, and soil descriptions are shown in figures 7 through 17. Variation in median size with depth for soundings 1, 5, and 6 are shown in figures 18 through 20. A histogram showing the frequency distribution of the median sizes for the subsurface samples is shown in figure 6.

The stratigraphy at sounding 1 consists of one upward coarsening grain size sequence. The upper 2 m consists of olive to dark-yellowish brown silty sand with very abundant shells and shell fragments. Between 2 and 6 m is a layer of olive to olive gray silty sand to sand with silt with fewer shells than the above layer. Between 6 and 13 m is black sandy silt to sand of varying density. Below 13 m is clayey silt.

At sounding 5 two upward fining grain size sequences occur, the sample between 4.3 and 4.7 m contains parts of both sequences. The bottom part of the sample represents the top of the lower sequence and the top half of the sample represents the bottom part of the upper sequence. This sample also contains a marked color change, the top half is brown, whereas the bottom half is gray.

The stratigraphy at sounding 6 consists of a very dense, fine, olive to dark brown sand from 0-1.5 m, this is an upward fining sequence; between 1.5 and 10 m is a medium dense, olive gray to black at the bottom, fine to medium grained sand, this layer coarsens upward from 10 m to about 5.5 m then fines upward to 1.5 m; below this is a very loose black silty sand; and finally, below 15 m is soft clayey silt.

The histograms in figure 6 show the distribution of the subsurface median grain size and the bimodal distribution of the sand boil median grain size. The difference between the distribution of the median grain size of the sand boils and the subsurface samples is a result of the sampling program, the sand boil sites selected to investigate belonged to the coarse brown/gray class of sand boils. No sampling was done at sites where fine (less than 0.123 mm D_{50}) gray sand boils occurred.

Liquefaction analysis

Data used to determine liquefaction resistance is shown in Table 2. Two methods were used to determine the liquefaction resistance required to liquefy; 1) blow counts from the SPT were normalized for an overburden pressure of 1 kg/cm^2 and a hammer energy of 60 percent, 2) data from the CPT were converted to equivalent blow counts by using the relation between median grain size and the ratio q_c/N ratio (Robertson and others, 1983). Variation in liquefaction resistance with depth is shown in figures 21, 22, and 23. The factor of safety (required stress ratio/induced stress ratio) for all the tests is shown in figure 24.

ANALYSIS

During the Loma Prieta earthquake portions of the soil beneath Treasure Island liquefied, this is evidenced by the abundant sand boils and settlement that occurred throughout the island (Seed and others, 1990; and Bennett, in press).

Two of the sites where sand boils occurred were investigated. Two sites where piezometer calibration tests took place were also investigated. A cross section showing the relation between these 4 sites is shown in figure 25. At sounding 5 the stratigraphic origin of the sand boil (D_{50}=0.245 mm) can be determined by observing where the median size of the sand boil intersects the lines that represent the fining upward sequences (Bennett, 1994). This intersection occurs at about 2.7 m and 5.2

m (fig. 19). Examination of the liquefaction resistance at sounding 5 (fig. 22) indicates that the soil between about 5.2 and 7.6 m has a low resistance to liquefaction, this would seem to indicate the sand boil originated from 5.2 m. But, the sand boil is brown and this indicates that it came from the interval 1.8 to 2.7 m.

At sounding 6 there are also multiple grain size sequences (fig. 20), a short fining upward sequence occurs between 0 and 2 m, a thicker fining upward sequence occurs between 2 and 5 m, between 6 and 11 m a coarsening upward sequence occurs. The sand boils sampled near sounding 6 are olive gray. The color and high liquefaction resistance (fig. 23) of the interval 0 to 3.1 m support the conclusion that the sand boils did not originate in the upper 3.1 m of the soil column. Subsurface soil color similar to the sand boil color occurs between 3.1 and 8.8 m. Within this zone the range of the sand boil median grain size intersects the coarsening upward and fining upward sequences in two places, 3.4 to 4.3 m and 7.6 to 8.8 m (fig. 20). The layer interpreted to have liquefied is 3.4 to 4.3 m based on; a clay layer about 0.3 m-thick overlies the layer postulated to have liquefied, this clay layer would allow pore pressure to build up rather than dissipate, and if the interval 7.6 to 8.8 m would have liquefied the layers above it probably also would have liquefied and therefore a wider range of median size of sand boils would have been found.

No sand boils occurred on the fire station grounds near sounding 1. The closest sand boil occurred on the school playground approximately 150 m north of sounding 1. Liquefaction resistance (fig. 21) as determined from the CPT and SPT only agree in the upper 2.7 m. Below this depth the CPT indicates a high resistance to liquefaction, whereas the SPT indicates a low resistance. This is the only boring in which a high water level in the augers was not maintained during penetration testing. A large volume of natural ground water from the boring was requested by a civil engineer for testing, to prevent contamination, no water was added to the boring. I attribute the discrepancy in the liquefaction resistance to a low water level in the augers during testing. Low water level in the augers reduces the effective stress on the soil being tested and allows sand to flow into the augers because of the pressure differential. The high liquefaction resistance determined by the CPT agrees with the field evidence on the grounds of the fire station, that is, no liquefaction.

Near borings 5 and 6 the sand boils originated from layers 2.5 to 4 m below the ground surface. But, this zone doesn't have the lowest overall factor of safety, the layer between 6 and 8 m has the lowest factor of safety, determined by CPT and SPT methods (fig. 24). Possible explanations for this conflict are:

1. Sand boils don't necessarily originate from the zone with the lowest factor of safety, they originate from the highest stratigraphic interval with a factor of safety less than 1.
2. Sediment between 6 and 8 m did liquefy but was not vented to the surface.
3. Similar to 2, but sand from 6 to 8 m was vented to the surface, but not near sounding 5. The coarsest sand boil that was sampled has a median size of 0.378 mm, this sand boil was located 335 m north of sounding 5. Sand at sounding 5 that is similar in color and grain size (D_{50} = 0.361 mm) to the sand boil occurs at 7.9 m.

Figure 26 shows all (from Bennett, in press) of the sand boil median sizes at the top of the figure (depth = 0). All of the subsurface median sizes are plotted at their respective depths. All of the sand boil samples can be related to subsurface samples except the 10 finest samples (D_{50} = 0.062 to 0.123 mm). This is evidence that not all of the subsurface layers that liquefied were sampled.

CONCLUSIONS

1. Sand boils can be used to identify what layers liquefied during an earthquake.
2. Not all of the layers that liquefied on Treasure Island were sampled in this investigation.
3. Although the test results were not shown the retrievable piezometer recorded pore pressure changes induced by dropping a large weight and by detonating blasting caps. During one of the tests a piezometer failed to respond properly, it was unscrewed and replaced with another piezometer.

ACKNOWLEDGEMENTS

I would like to thank all the people who assisted this project: Captain Thomas Berns, Commander, Naval Station Treasure Island, gave permission for the drilling; Michael White, Fire Chief, Naval Station Treasure Island, for his cooperation and assistance with our drilling program at the fire station; Thomas Cuckler, Head of the Planning Division, Civil Engineering Department, Naval Station Treasure Island, cleared all of the testing sites; Richard Faris, Western Division Naval Engineering Command, Geotechnical Engineering Branch, acted as liaison with the navy; Dr. Behnam Hushmand, Hushmand Associates, conducted the piezometer calibration, Dr. Ronald Scott, CalTech; Brian Rague, Jet Propulsion Laboratory, Pasadena, set up equipment for the piezometer calibration; Richard Warrick, USGS, for his assistance with running and setting up the General Earthquake Observation System (GEOS); John Vanschacck, for handling the explosives; Thomas Chase, for transporting the blasting material via boat to Treasure Island; and Coyn Criley, for running the GEOS recording system, assisting with field testing and laboratory testing of the samples. I also thank Raymond Wilson for his helpful review comments.

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CAPTIONS

1. Location of borrow areas for Treasure Island in San Francisco Bay. Different borrow areas account for the range in grain size of the fill and therefore the range in grain size of the sand boils. Map modified from Seed and others, 1990.
2. Location of major sounding areas on Treasure Island. Sounding sites 1-2 (fire station) and 3-4, 7-11 (empty field) were chosen for the calibration experiment. Sounding sites 5 (baseball field) and 6 (playground) were chosen because of their proximity to sand boils.
3. Location of soundings at fire station (building 157). Piezometers (P2-P10) are reported in de Alba, and others, 1994, and are included on this map for reference purposes only.
4. Local map of soundings, piezometers, and weight drops at fire station. SPT = standard penetration test, CPT = cone penetration test, W1-4 = weight drops, PC = USGS piezocone, RW = Richard Warrick piezometer test, CT1 and CT2 = CalTech calibrating piezometer. Side and back fence refer to chain link fence that surrounds the fire station property.
5. Map of soundings and piezometers at blast site. CPT = cone penetration test, SPT = standard penetration test, blast boring = location of boring that contained explosive material, weight drop = location of weight drop, piez1 and piez2 = USGS retrievable piezometers, piez CalTech = calibrating piezometer from CalTech. The CalTech piezometer is 38.4 m (126 ft) from the western edge of the side walk on the east side of the vacant lot and 31.7 m (104 ft) north of the tree at the south end of the vacant lot. The vacant lot is bounded on the north by 13th St., on the south by 9th St., on the west by Ave. H, and on the east by Ave. I. Locations are based on California coordinate system, zone 3.
6. Histograms of frequency of median grain size for subsurface (a) and sand boil (b) samples. Note that the finest sand boil samples (represented by the 3 samples on the far left side of figure 6b) are not represented in the subsurface samples.
7. Log of sounding 1 at the Fire Station. Coordinates are based on California coordinate system, zone 3.
8. Log of sounding 2 at the Fire Station. Coordinates are based on California coordinate system, zone 3.
9. Log of sounding 3 at the blast site. Coordinates are based on California coordinate system, zone 3.

10. Log of sounding 4 at the blast site. Coordinates are based on California coordinate system, zone 3
11. Log of sounding 5 near the sand boil at the baseball field. Coordinates are based on California coordinate system, zone 3
12. Log of sounding 6 near the pump station in the playground. Coordinates are based on California coordinate system, zone 3
13. Log of sounding 7 at the blast site. Coordinates are based on California coordinate system zone 3.
14. Log of sounding 8 at the blast site. Coordinates are based on California coordinate system zone 3.
15. Log of sounding 9 at the blast site. Coordinates are based on California coordinate system zone 3.
16. Log of sounding 10 at the blast site. Coordinates are based on California coordinate system zone 3.
17. Log of sounding 11 at the blast site. Coordinates are based on California coordinate system zone 3.
18. Median grain size vs. depth at sounding 1, fire station. Shells are abundant in the upper 2 meters. No sand boils occurred on the fire station property.
19. Median grain size vs. depth at sounding 5, baseball field. The sample at about 4.5 m is very important because it contains parts of both the upper brown unit and the lower gray unit. The sand boil median size intersects both fining upward sequences. The sand boil is brown and probably originated near 2.5 m.
20. Median grain size vs. depth at sounding 6, playground.
21. Liquefaction resistance vs. depth at sounding 1. The stress ratio induced by the earthquake (equation 1) is the same for both the SPT and CPT evaluation of liquefaction resistance. When the induced stress ratio is greater than that needed to liquefy the factor of safety is less than 1 and indicates a low resistance to liquefaction. There is poor agreement between the two types of tests because a low water level was maintained in the SPT boring to obtain natural water samples.
22. Liquefaction resistance vs. depth at sounding 5.
23. Liquefaction resistance vs. depth at sounding 6.
24. Factor of safety vs. depth at soundings with SPT and CPT.
25. Cross section. Soundings 1, 4, 5, and 6 are projected onto cross section line A-B (fig. 2). Cone resistance is shown alongside lithology column as a reference, maximum resistance is 18 MN/m^2. Liqefaction zones at soundings 5 and 6 are marked with open circles. Water table marked by triangles.
26. Relation between sand boil and subsurface median grain size. More than 30 sand boil samples (Bennett, in press) are compared to subsurface samples. All of the sand boil samples can be related to subsurface samples except the finest 10 samples. This indicates that not all of the soil that liquefied was sampled.

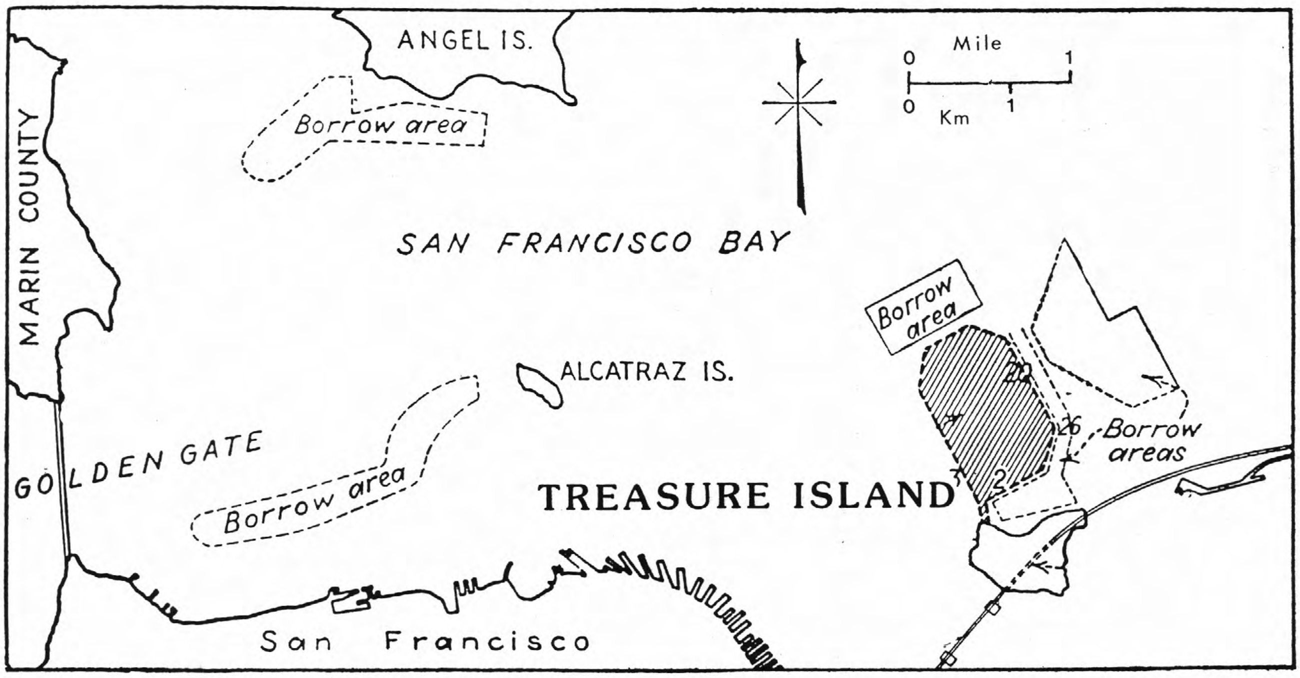
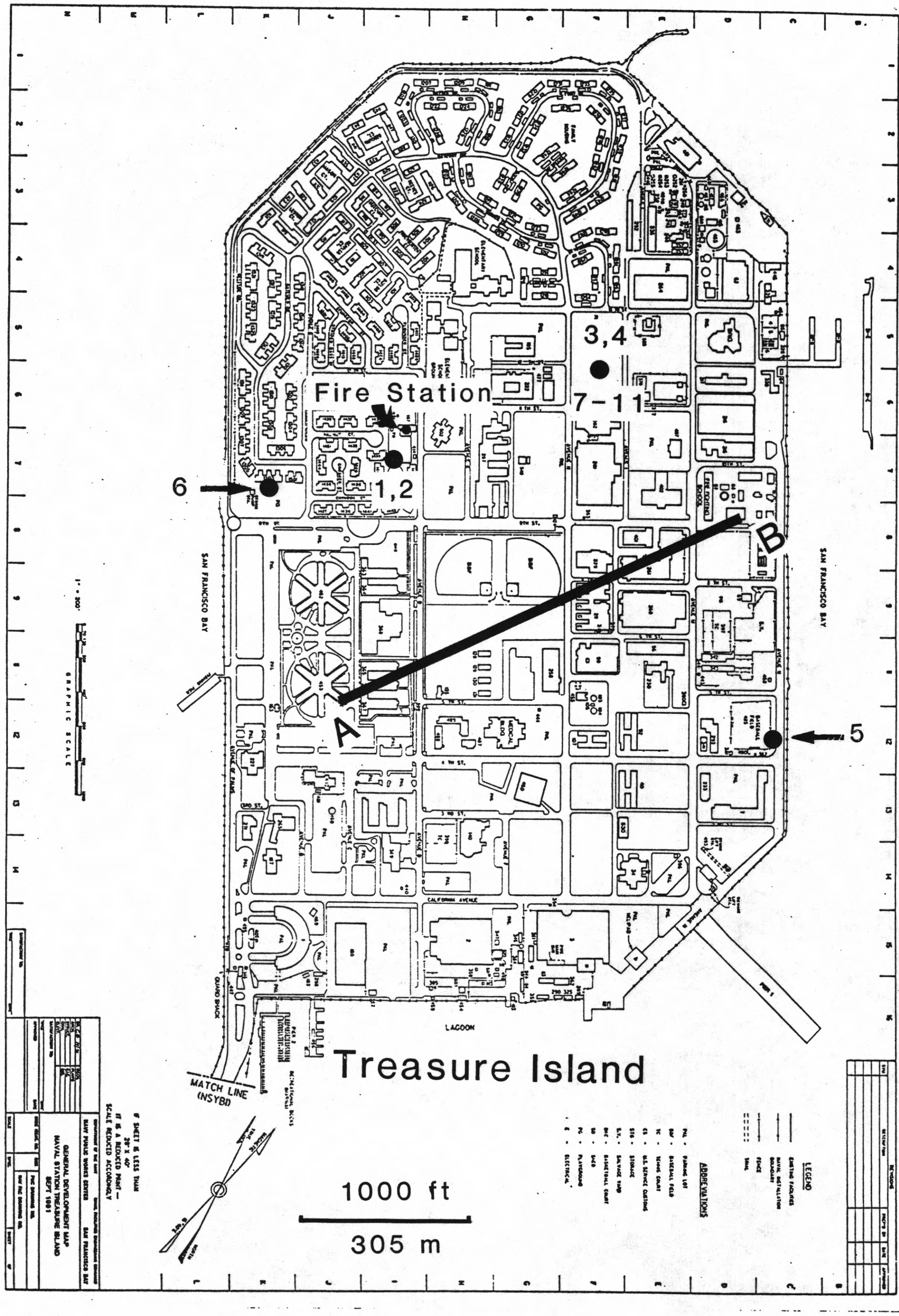

ANGEL IS.
Borrow area
MARIN COUNTY
Mile
0
1
0
Km
1
SAN FRANCISCO BAY
Borrow area
ALCATRAZ IS.
GOLDEN GATE
Borrow area
TREASURE ISLAND
Borrow areas
San Francisco

Figure 1


Treasure Island



Fire Station
3,4
7-11
1,2
6
5
A
B
Treasure Island
1000 ft
305 m
SAN FRANCISCO BAY
LAGOON
MATCH LINE (NSYBI)

Figure 2

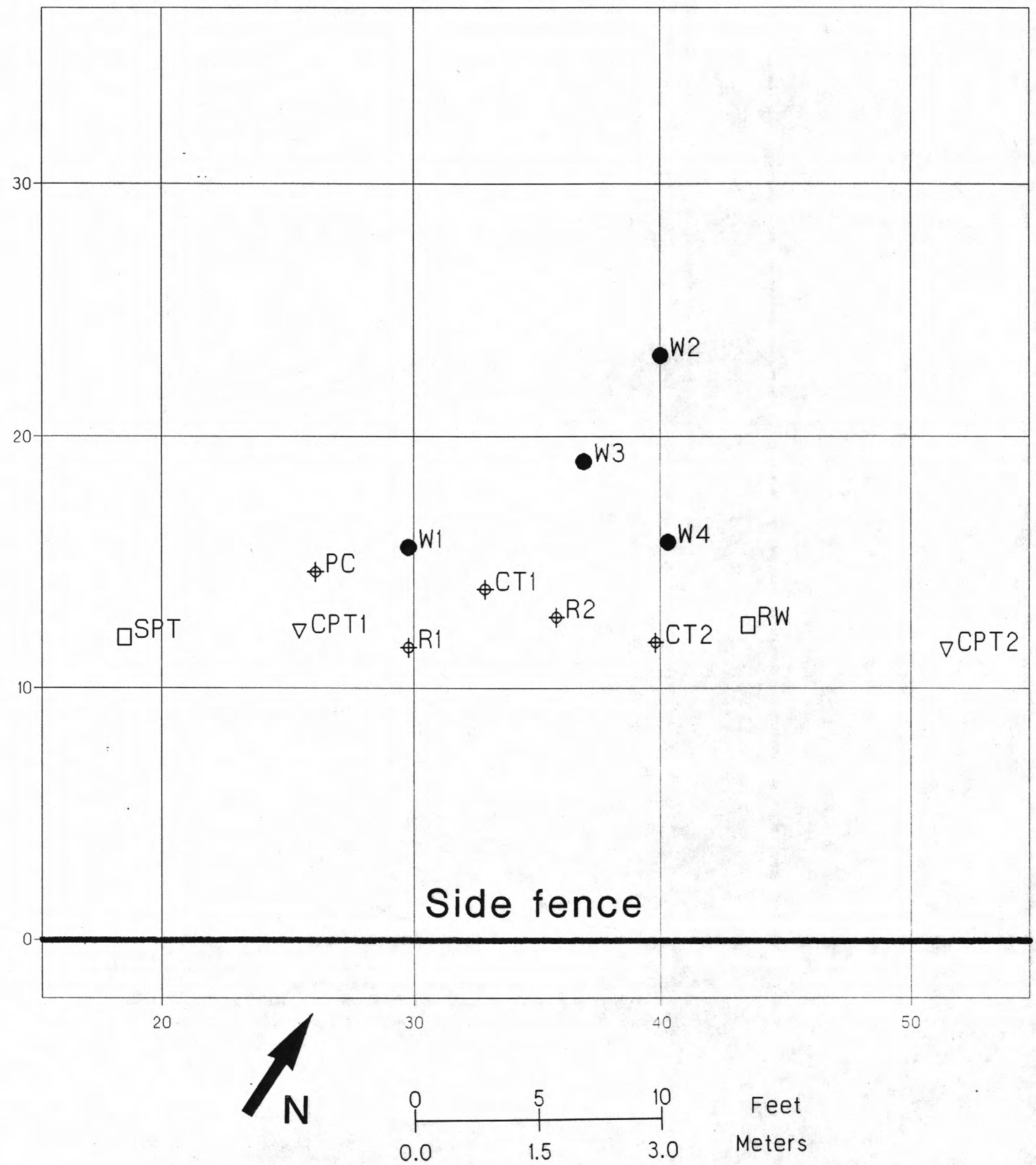
County: SAN FRANCISCO, 7.5 min Quad: OAKLAND WEST

LOCATION: Fire Station, Treasure Island

Figure 3

▽=CPT □=SPT ⌖=PIEZOMETER

County: SAN FRANCISCO, 7.5 min Quad: OAKLAND WEST

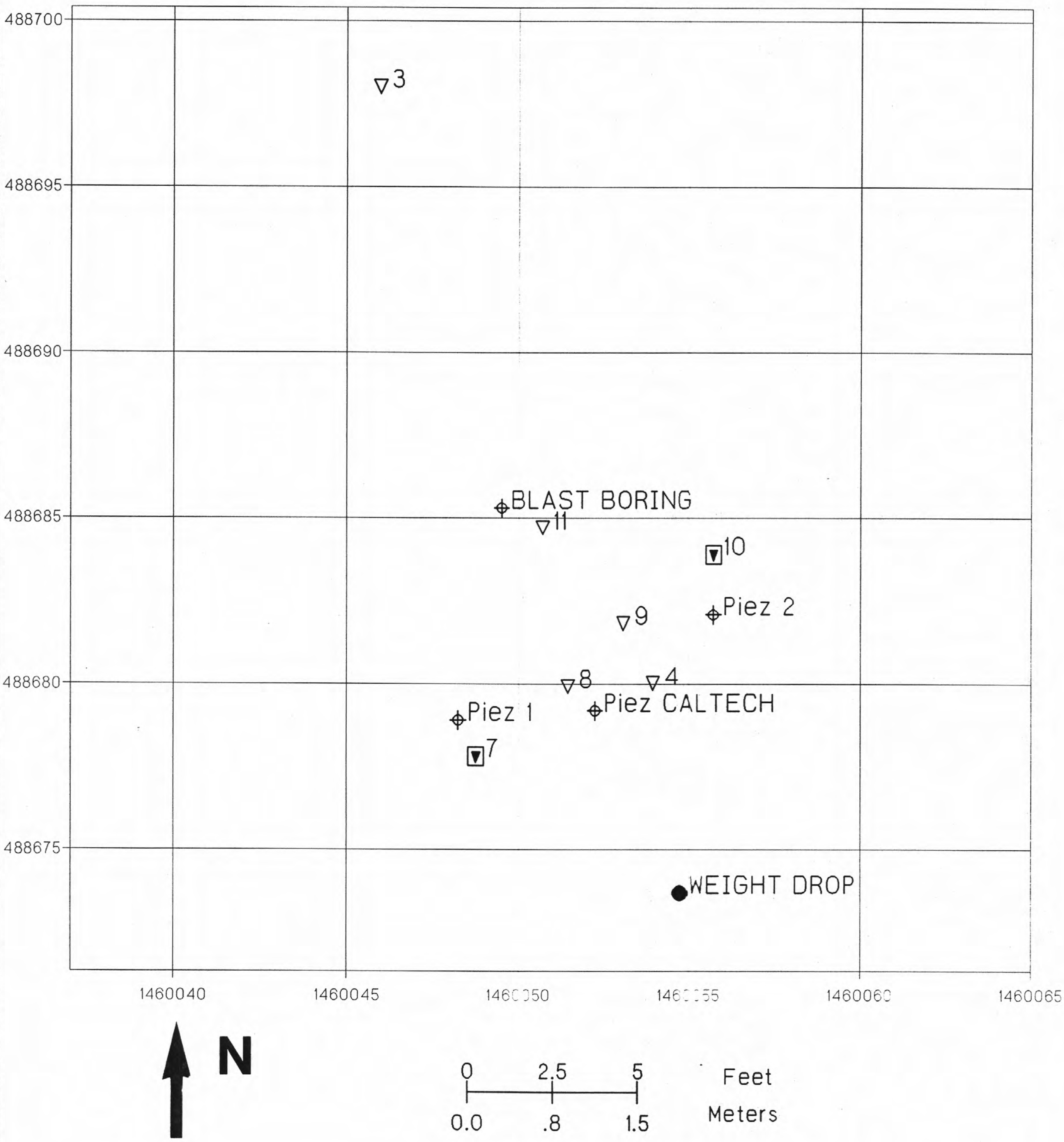


LOCATION: Calibration array at fire station

Figure 4

▽=CPT □=SPT ●=WEIGHT ⌖=PIEZOMETER

County: SAN FRANCISCO, 7.5 min Quad: OAKLAND WEST



LOCATION: Blast Site

Figure 5

▽=CPT ▼=CPT and SPT ●=WEIGHT ⌖=PIEZOMETER

Median size and frequency

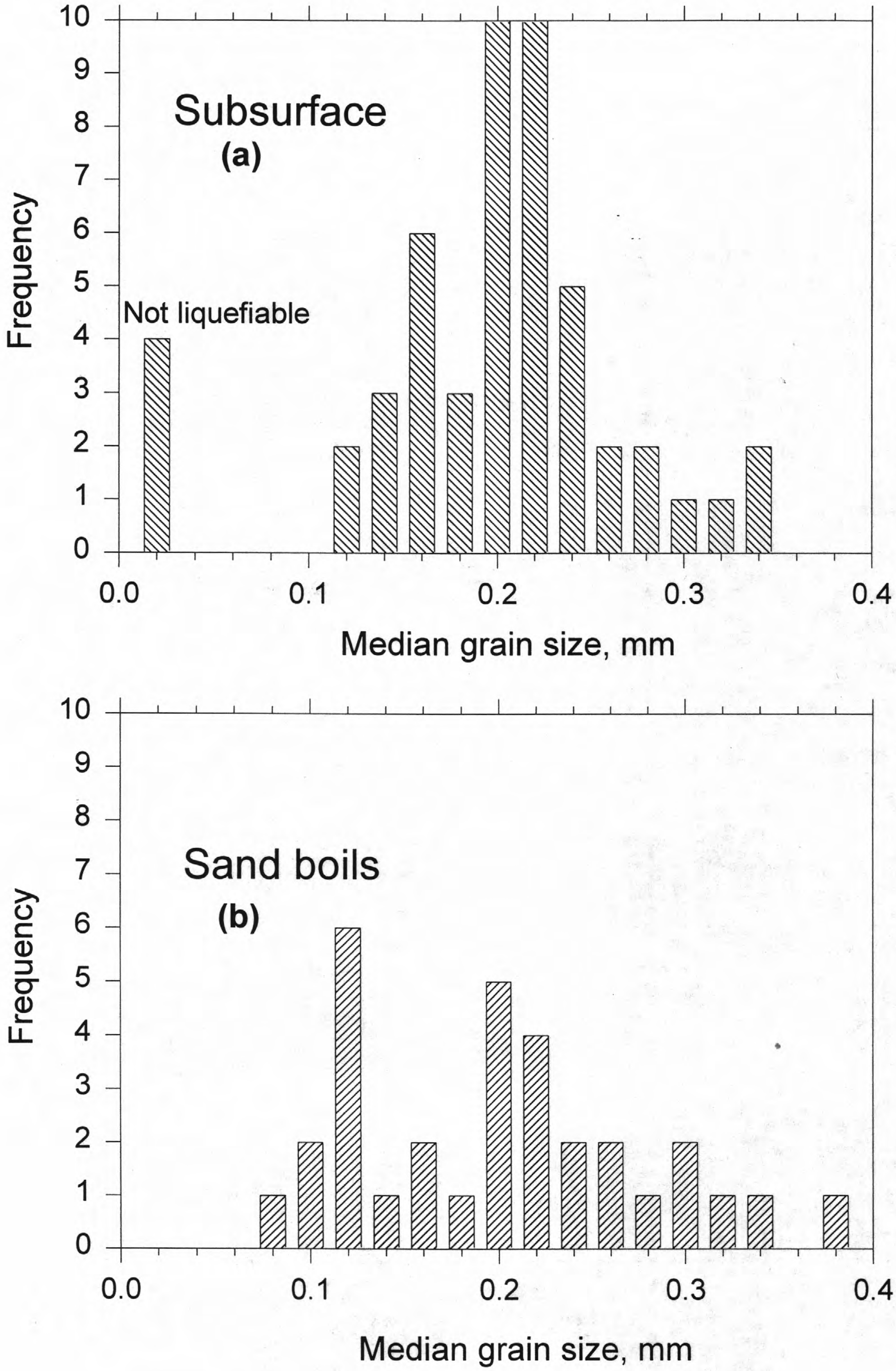


Figure 6

USGS GEOTECHNICAL LOG

HOLE NUMBER 1

LOCATION TREASURE ISLAND (TI)

DATE DRILLED CPT: 1/20/94; SPT: 1/28/94

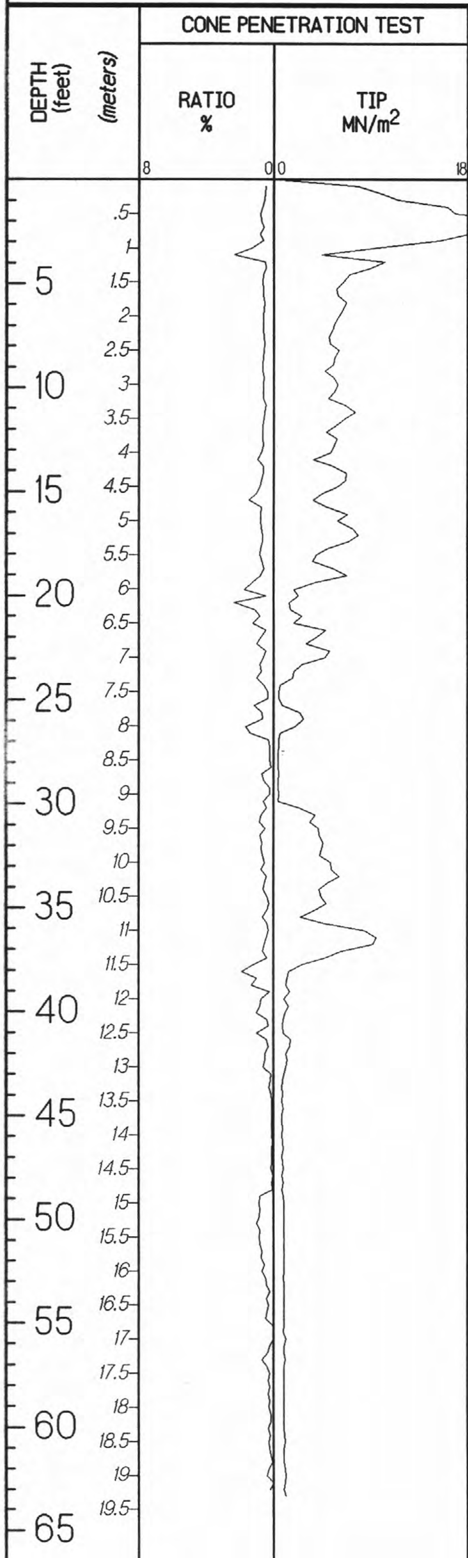
PERSONNEL L: Bennett; D: Bennett/Criley

PROJECT CALIBRATE PIEZOMETER/INVESTIGATE SAND BOILS

COORDINATES X: 1459146, Y: 487746

GROUNDWATER 5 ft.; 1.5 m

ELEVATION 11 ft.; 3.4 m MSL



SPT - N	D50 (mm)	FINES (%)	CLASS	LIQ-RESIS
31	0.199	32	SM	D
16	0.198	15	SM	H
10	0.189	10	SP-SM	H
3	0.190	13	SM	H*
3	0.139	24	SM	H*
5	0.170	11	SP-SM	H*
5	0.175 0.110	12 26		H*
1	0.157	20	SM	H*

SOIL DESCRIPTION (MAP CLASSIFICATION)

Fill:
- Silty sand, olive, 5Y4/3, uniform, dry: ... and, silty sand, dark yellowish brown, 10YR4/4 to olive brown, 2.5YR4/4, shells very abundant
- Silty sand, olive, 5Y4/3, dry, some 5 cm thick layers where shell concentration is 90%
- Silty sand, olive, 5Y4/4, very few shells, uniform texture, no gravel
- Silty sand, greener than olive, 5Y4/4, no bedding, shells common
- Silty sand, olive gray, 5Y4/2, fewer shells, uniform bedding, 2.5 cm thick clay layer 25 cm from bottom
- Silty sand, olive gray, 5Y4/2, no bedding, few shells
- Silty sand, olive, 5Y4/3, and....
- Sandy silt, black, 5Y2.5/1, very soft
- Silty sand, olive gray, 5Y4/2, very loose

Natural (?):
- Sand

Bay Mud:
- Bay Mud, lean clay

End of sounding, 63.3 ft., 19.3 m

Figure 7

REMARKS: Fire station, closest to fence corner

Magnitude= 7.1

Acceleration= 0.16 g

USGS GEOTECHNICAL LOG

HOLE NUMBER 2

LOCATION TREASURE ISLAND (TI)

DATE DRILLED CPT: 1/20/94

PERSONNEL D: Bennett/Criley

PROJECT CALIBRATE PIEZOMETER/INVESTIGATE SAND BOILS

COORDINATES X: 1459170, Y: 487757

GROUNDWATER 5 ft.; 1.5 m

ELEVATION 11 ft.; 3.4 m MSL

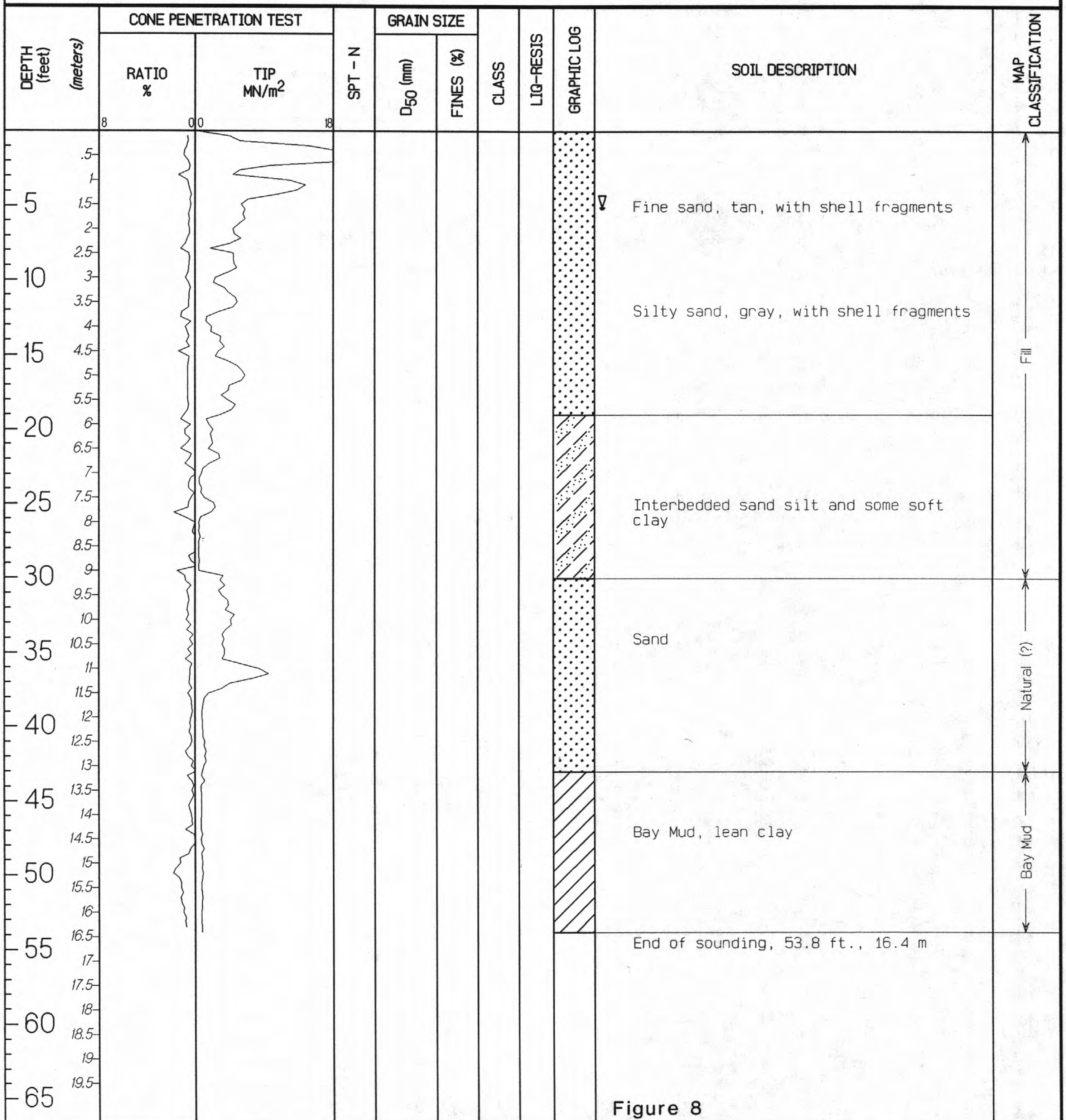


Figure 8

REMARKS: Fire Station

Magnitude= 7.1

Acceleration= 0.16 g

USGS GEOTECHNICAL LOG

HOLE NUMBER **3**

PROJECT CALIBRATE PIEZOMETER/INVESTIGATE SAND BOILS

LOCATION TREASURE ISLAND (TI)

COORDINATES X: 1460046, Y: 488698

DATE DRILLED CPT: 1/20/94

GROUNDWATER 5.2 ft.; 1.6 m

PERSONNEL D: Bennett/Criley

ELEVATION 11 ft.; 3.4 m MSL

DEPTH (feet) / (meters)	CONE PENETRATION TEST: RATIO % (8–0) / TIP MN/m^2 (0–18)	SPT - N	GRAIN SIZE: D_{50} (mm)	GRAIN SIZE: FINES (%)	CLASS	LIQ-RESIS	GRAPHIC LOG	SOIL DESCRIPTION	MAP CLASSIFICATION
								Sand with silt, dry and dense crust	
								Sand with silt	
								Interbedded sand and clay	
								Bay Mud, lean clay to sandy silt	
								End of sounding, 63.3 ft., 19.3 m	

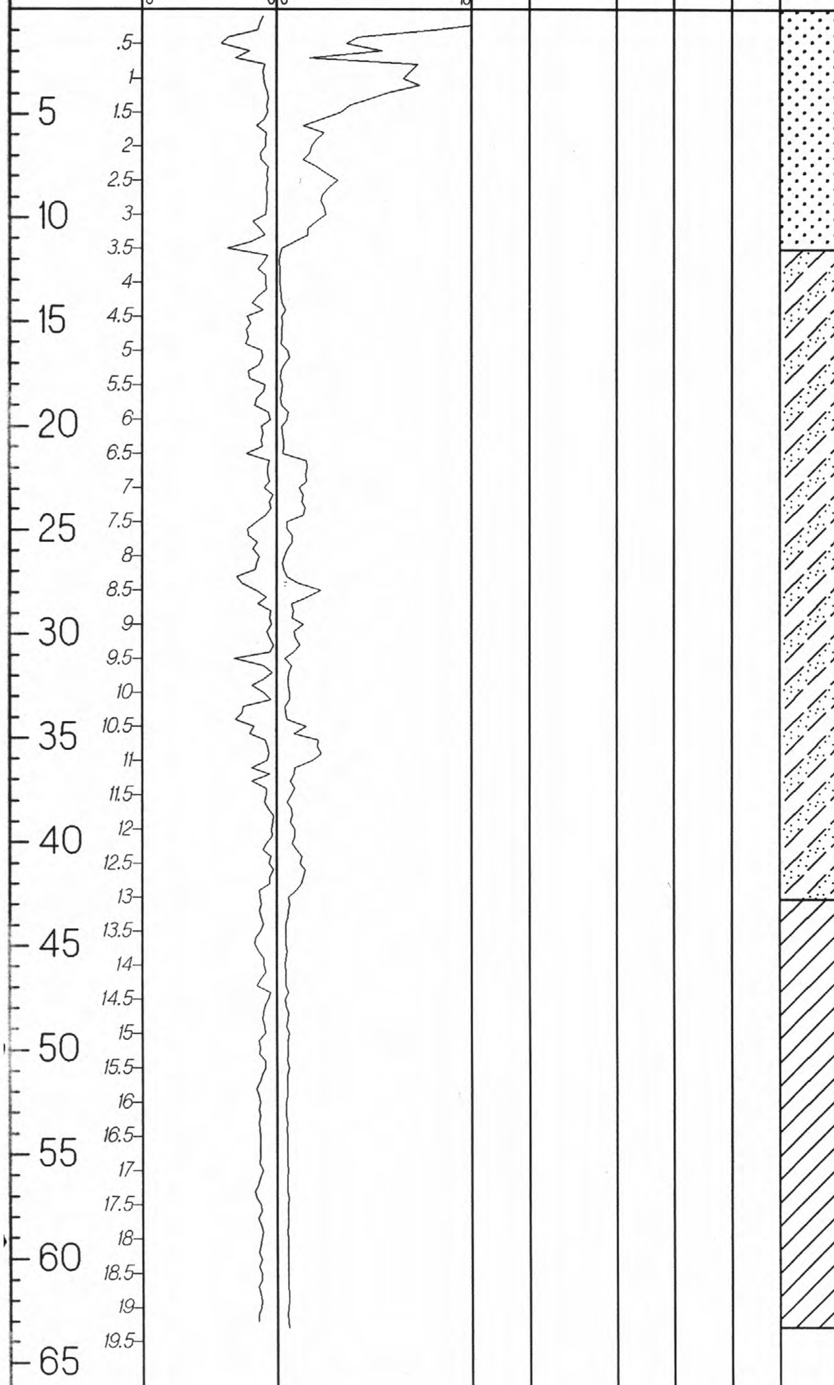


Figure 9

REMARKS: Blast site, at north end of site

Magnitude= 7.1

Acceleration= 0.16 g

USGS GEOTECHNICAL LOG

HOLE NUMBER 4

PROJECT CALIBRATE PIEZOMETER/INVESTIGATE SAND BOILS

LOCATION TREASURE ISLAND (TI)

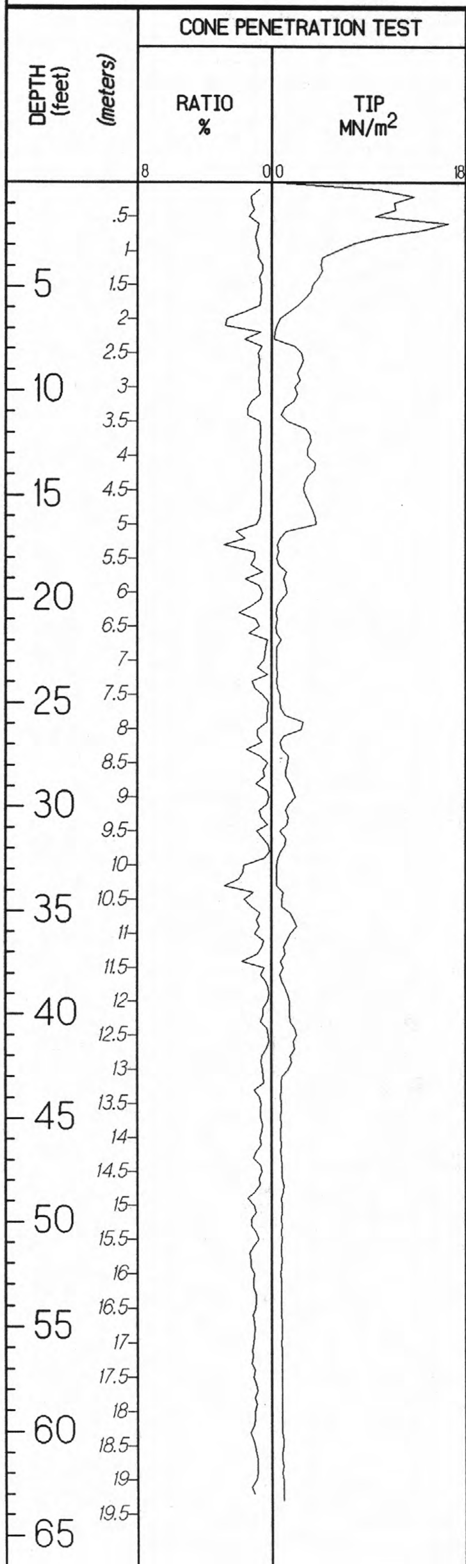
COORDINATES X: 1460054, Y: 488680

DATE DRILLED CPT: 1/21/94

GROUNDWATER 5 ft.; 1.5 m

PERSONNEL D: Bennett/Criley

ELEVATION 11 ft.; 3.4 m MSL



SPT - N	GRAIN SIZE: D_{50} (mm)	GRAIN SIZE: FINES (%)	CLASS	LIQ-RESIS	GRAPHIC LOG	SOIL DESCRIPTION	MAP CLASSIFICATION
						Sand with silt, dry, dense, crust Very loose zone, 2.3 m Sand with silt	Fill
						Interbedded sand and clay	Fill
						Bay Mud, lean clay to sandy silt	Bay Mud
						End of sounding, 63.3 ft., 19.3 m	

Figure 10

REMARKS: Blast site, near CALTECH piezometer

Magnitude= 7.1

Acceleration= 0.16 g

USGS GEOTECHNICAL LOG

HOLE NUMBER 5

LOCATION TREASURE ISLAND (TI)

DATE DRILLED CPT: 1/21/94; SPT 3/8/94

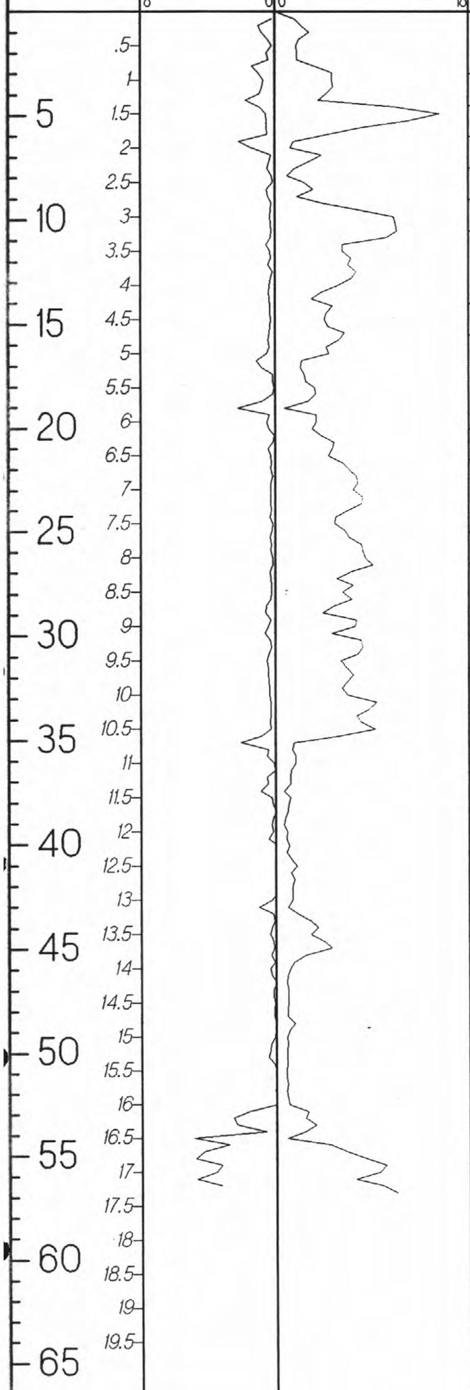
PERSONNEL D: Bennett/Criley; L: Bennett

PROJECT CALIBRATE PIEZOMETER/INVESTIGATE SAND BOILS

COORDINATES X: 1461857, Y: 487288

GROUNDWATER 5 ft.; 1.5 m

ELEVATION 11 ft.; 3.4 m MSL



SPT - N	D50 (mm)	FINES (%)	CLASS	LIQ-RESIS
12	0.199	12	SP-SM	D
5	0.221	17	SM	L*
22	0.252	6	SP-SM	H
9	0.302 0.218	4 7		L
4	0.291	3	SP	L
10	0.361 0.360	2 4	SP	L
12	0.208	12	SP-SM	L*
3	0.185	18	SM	L

SOIL DESCRIPTION

Silty sand, olive brown, 2.5Y4/4, dry, loose, very poor to no stratification, some shells

Sandy shelly mush, clayey silt, and shelly silty sand, dark grayish brown, 2.5Y4/2, wet, loose, well bedded

Pebbley sand, very dark grayish brown, 2.5Y3/2, medium dense, small shell fragments common in lower half, maximum pebble size 5 mm, no true bedding, hint of stratification from shells

Sand, pebbley and shelly, very dark gray, 5Y3/1, sharp contact with; fine silty sand, black, 5Y2.5/1, no gravel, no shells, uniform bedding

Sand, pebbley, shelly, black, 5Y2.5/1, no bedding

Coarse sand, no shells, browner than lower half, may be slough, and; .. silty sand, some pebbles and shells, black, 5Y2.5/1

Very fine sand, black, 5Y2.5/1, black, no bedding, medium dense

Sandy silt, 5Y2.5/1, black, no bedding, (natural?)

Lean clay to sandy silt (CL-ML)

Sandy silt, dense

End of sounding, 56.8 ft., 17.3 m

MAP CLASSIFICATION

Fill, grayish brown

Fill, gray to black

Natural material, black

Figure 11

REMARKS: Baseball field, sandboil #5. 7 ft. east of fence. 32 ft northwest of southern-most telephone pole on block.

Magnitude= 7.1

Acceleration= 0.16 g

USGS GEOTECHNICAL LOG

HOLE NUMBER 6

PROJECT CALIBRATE PIEZOMETER/INVESTIGATE SAND BOILS

LOCATION TREASURE ISLAND (TI)

COORDINATES X: 1458584, Y: 487296

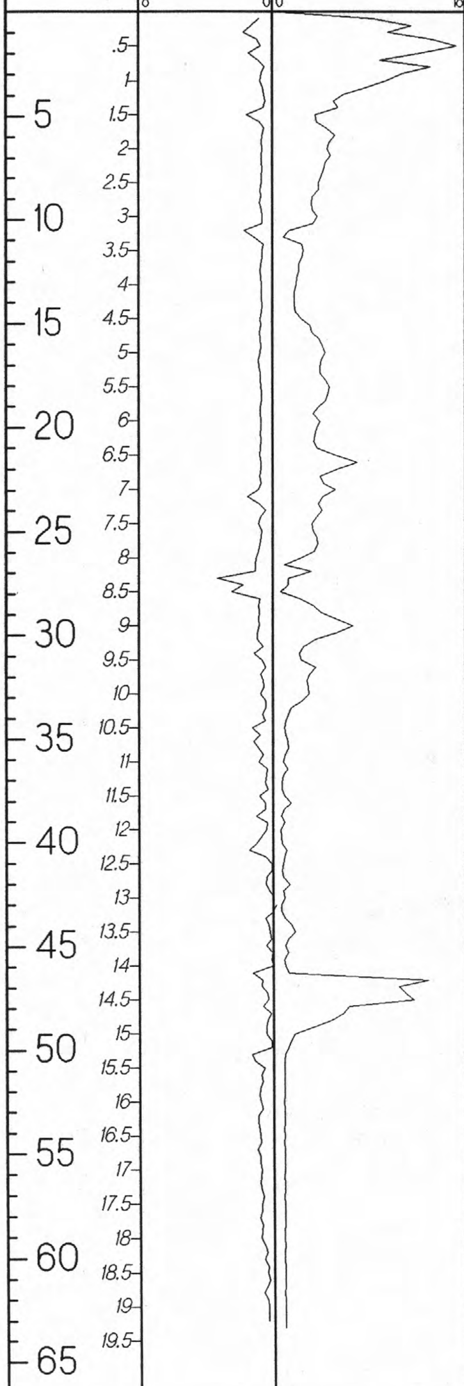
DATE DRILLED CPT: 1/21/94; SPT: 3/15/94

GROUNDWATER 5 ft.; 1.5 m

PERSONNEL L: Bennett; D: Bennett/Criley

ELEVATION 11 ft.; 3.4 m MSL

CONE PENETRATION TEST: RATIO % (scale 8–0); TIP MN/m² (scale 0–18)



SPT - N	D_{50} (mm)	FINES (%)	CLASS	LIQ-RESIS
9	0.219	5	SP-SM	H
11	0.239	6	SP-SM	H
6	0.152	12	SM	H*
9	0.203	5	SP-SM	L
9	0.262	5	SP-SM	L
6	0.267	3	SP	L
4	0.228	5	SP-SM	L
15	0.208	9	SP-SM	L*
2	0.146	29	SM	L

SOIL DESCRIPTION (MAP CLASSIFICATION)

Fill, brown:
- Fine sand to silty sand, 5Y4/3, olive, no bedding
- Fine sand, 10YR3/3, dark brown, well sorted, some shells, no bedding
- Fine sand to silty sand, 2.5Y4/4, olive brown, very loose, no bedding

Fill, gray:
- Fine silty sand, loose, with shell fragments parallel to bedding
- Fine sand, 5Y4/2, olive gray, some shells
- Fine sand, 5Y3/2, dark olive gray, shells common
- Silty sand, 5Y3/2, dark olive gray, shells present, no bedding
- Sand, 2.5Y4/2, dark grayish brown, no shells, and; ...fine sand, 5Y2.5/1, black, no shells, uniform

Natural/fill, black:
- Sand, silt, 5Y2.5/1, black, some shells throughout, slightly plastic, firm
- Sand

Bay Mud:
- Bay Mud, lean clay with sand

End of sounding, 63.3 ft., 19.3 m

Figure 12

REMARKS: Playground, pump station. Sand boils 12, 13 and 16 near here. 25 ft south of fence, 8 ft north of path, 96 ft NE of palm tree.

Magnitude= 7.1

Acceleration= 0.16 g

USGS GEOTECHNICAL LOG

HOLE NUMBER 7

LOCATION TREASURE ISLAND (TI)

DATE DRILLED CPT: 3/7/94; SPT: 2/22/94

PERSONNEL L: Bennett; D: Bennett/Criley

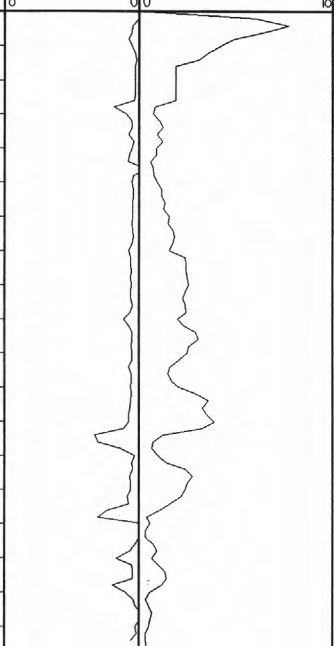
PROJECT CALIBRATE PIEZOMETER/INVESTIGATE SAND BOILS

COORDINATES X: 1460048.8, Y: 488677.8

GROUNDWATER 5.2 ft.; 1.6 m

ELEVATION 11 ft.; 3.4 m MSL

CONE PENETRATION TEST: RATIO % (8–0); TIP MN/m^2 (0–18)



DEPTH (meters)	SPT - N	D_{50} (mm)	FINES (%)	CLASS
.5	16	0.207	6	SP-SM
1.5	5	0.189	11	SP-SM
2.5	1			
3	4	0.198	7	SP-SM

SOIL DESCRIPTION

Silty sand to fine sand, olive brown, 2.5Y4/4, well sorted, uniform, no bedding; and, fine sandy silt, bottom 5 cm, sharp contact, no shells

Silty sand, dark olive gray, 5Y3/2, well sorted, no bedding, no shells

Lost sample

Sand, dark olive gray, 5Y3/2, no bedding, uniform sample

Lean clay

Silty sand, loose

Sandy silt

End of sounding, 30.5 ft., 9.3 m

MAP CLASSIFICATION: Fill

Figure 13

REMARKS: Blast site, closest to piez-1, SPT done first, CPT second

Magnitude= 7.1

Acceleration= 0.16 g

USGS GEOTECHNICAL LOG

HOLE NUMBER 8

LOCATION TREASURE ISLAND (TI)

DATE DRILLED CPT: 3/7/94

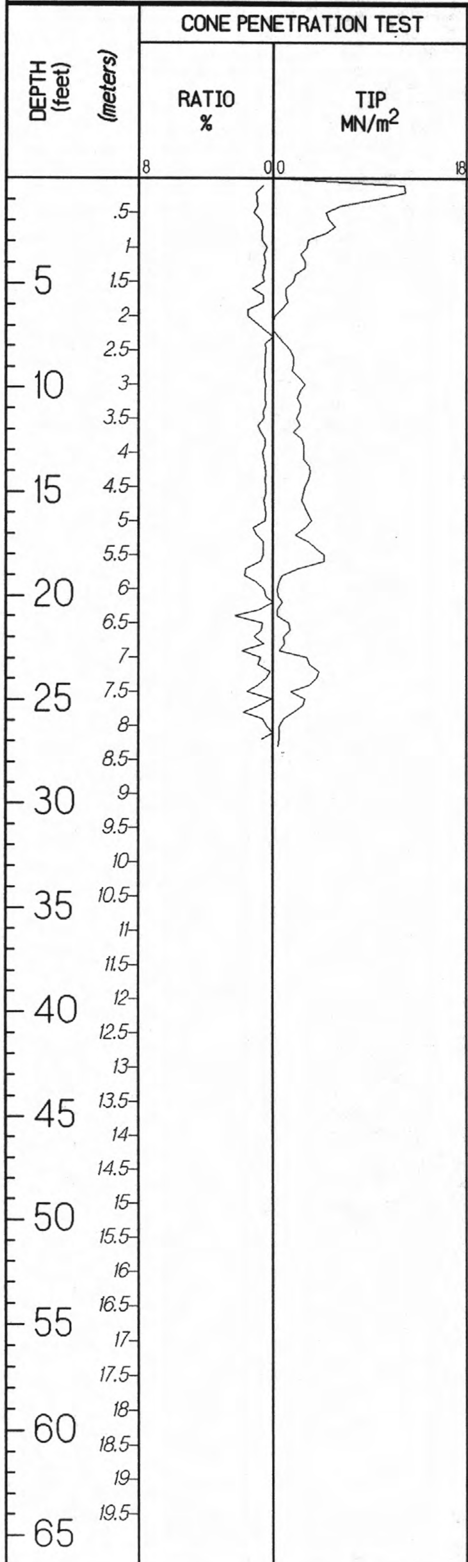
PERSONNEL D: Bennett/Criley

PROJECT CALIBRATE PIEZOMETER/INVESTIGATE SAND BOILS

COORDINATES X: 1460051.5, Y: 488679.9

GROUNDWATER 5 ft.; 1.5 m

ELEVATION 11 ft.; 3.4 m MSL



SPT - N	GRAIN SIZE D_{50} (mm)	GRAIN SIZE FINES (%)	CLASS	LIQ-RESIS	GRAPHIC LOG	SOIL DESCRIPTION	MAP CLASSIFICATION
						Sand, dense, dry crust	Fill
						Very loose or soft sediment	
						Sand with silt	
						Sandy silt, very loose	
						Silty sand	
						End of sounding, 27.3 ft., 8.3 m	

Figure 14

REMARKS: Blast site, after the blast

Magnitude= 7.1

Acceleration= 0.16 g

USGS GEOTECHNICAL LOG

HOLE NUMBER 9

LOCATION TREASURE ISLAND (TI)

DATE DRILLED CPT: 3/7/94

PERSONNEL D: Bennett/Criley

PROJECT CALIBRATE PIEZOMETER/INVESTIGATE SAND BOILS

COORDINATES X: 1460053.1, Y: 488681.8

GROUNDWATER 5 ft.; 1.5 m

ELEVATION 11 ft.; 3.4 m MSL

DEPTH (feet)	(meters)	CONE PENETRATION TEST: RATIO % (8–0)	CONE PENETRATION TEST: TIP MN/m² (0–18)	SPT - N	GRAIN SIZE: D50 (mm)	GRAIN SIZE: FINES (%)	CLASS	LIQ-RESIS	GRAPHIC LOG	SOIL DESCRIPTION	MAP CLASSIFICATION
0–18	0–5.5									Sand with silt, dense, dry crust Very loose or soft sediment Sand with silt, loose, thin interbedds of lean clay present	Fill
18–21	5.5–6.5									Sandy silt, loose	Fill
21–29.9	6.5–9.1									Silty sand, loose	Fill
29.9	9.1									End of sounding, 29.9 ft., 9.1 m	

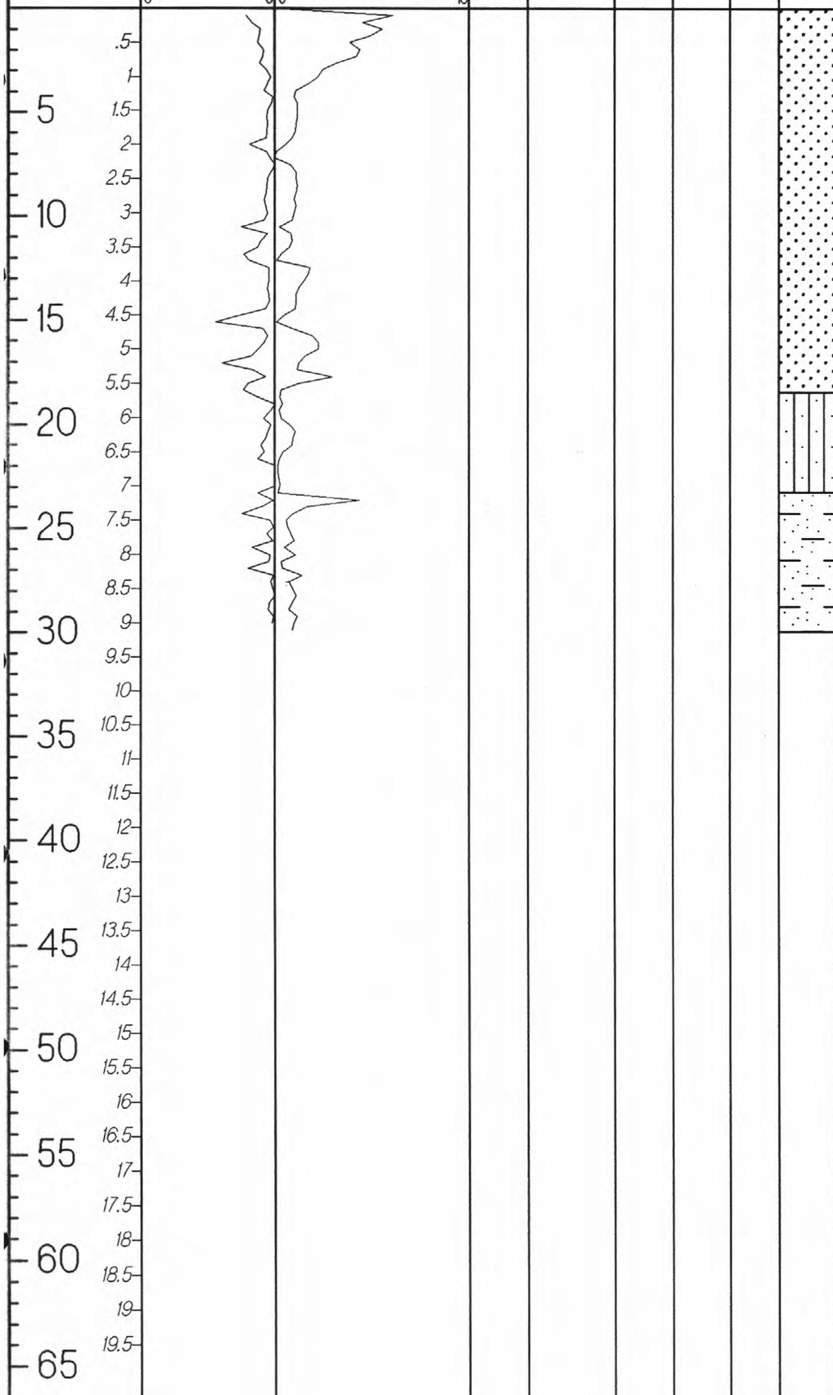


Figure 15

REMARKS: Blast site, after the blast

Magnitude= 7.1

Acceleration= 0.16 g

USGS GEOTECHNICAL LOG

HOLE NUMBER **10**

PROJECT CALIBRATE PIEZOMETER/INVESTIGATE SAND BOILS

LOCATION TREASURE ISLAND (TI)

COORDINATES X: 1460055.7, Y: 488683.9

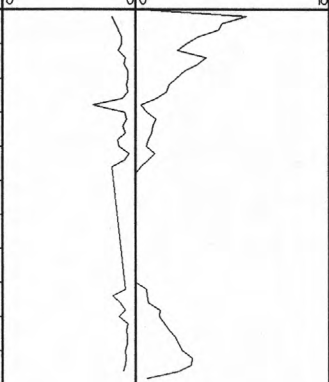
DATE DRILLED SPT:2/22/94; CPT: 3/7/94

GROUNDWATER 5.2 ft.; 1.6 m

PERSONNEL L: Bennett; D: Bennett/Criley

ELEVATION 11 ft.; 3.4 m MSL

CONE PENETRATION TEST: RATIO % (scale 8–0); TIP MN/m2 (scale 0–18)



DEPTH (feet)	(meters)	SPT - N	D_{50} (mm)	FINES (%)	CLASS	LIQ-RESIS
	1	11	0.175 0.137	12 21		
5	1.5–2	3	0.155	11	SP-SM	
10	3	1	0.005	95	CH	
			0.015	81	CL	

Depth scale: 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65 ft; .5–19.5 m

SOIL DESCRIPTION

Sand grades downward to sandy silt, olive brown, 2.5Y4/4, sharp contact with underlying sand, olive, 5Y4/4

Fine sand to silty sand, olive gray, 5Y4/2, no bedding, no shells, uniform sample

Fat CLAY to lean clay with sand, dark gray 5Y4/1, uniform, no bedding, no shells, very sticky and plastic, water content ranges from 77 to 69 percent, very soft, pushed entire sample distance by hand, ucs=0.1 ksc

USGS piezometer 2 located at 2.7 m

Sand with silt

End of sounding 17.7 ft., 5.4 m

Depth interval 8-9.5 ft

Water content	69-77 percent
Liquid limit	76
Plasticity index	46
Liquidity index	1.0
Activity	1.6

Depth interval 9.5-10.5 ft

Liquid limit	47
Plasticity index	23
Activity	1.2

MAP CLASSIFICATION: Fill

Figure 16

REMARKS: Blast site, SPT first, before blast; CPT second, after blast, weak zone between 2.3 and 4.0 m could not read tip resistance; closest to piez-2

Magnitude= 7.1

Acceleration= 0.16 g

USGS GEOTECHNICAL LOG

HOLE NUMBER **11**

PROJECT CALIBRATE PIEZOMETER/INVESTIGATE SAND BOILS

LOCATION TREASURE ISLAND (TI)

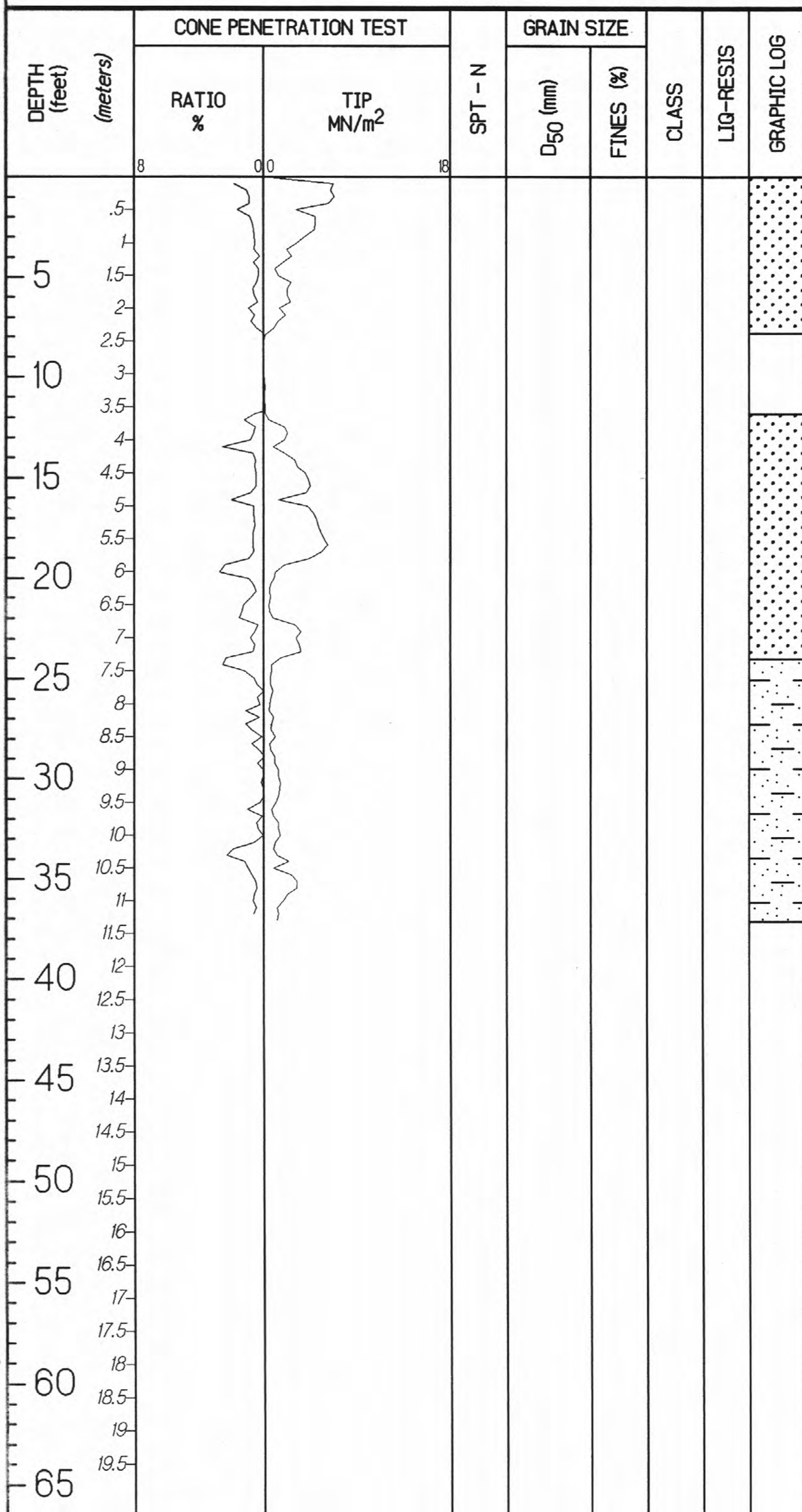
COORDINATES X: 1460050.7, Y: 488684.7

DATE DRILLED CPT: 3/10/94

GROUNDWATER 5 ft.; 1.5 m

PERSONNEL D: Bennett/Criley

ELEVATION 11 ft.; 3.4 m MSL



SOIL DESCRIPTION	MAP CLASSIFICATION
Sand with silt, dry, dense, crust	Fill
Caps and prima-cord set between 2.4 to 2.7 m	Fill
Sand with silt, frequent thin layers of lean clay to sandy silt	Fill
Silty sand, loose to very loose	Fill
End of sounding, 37.1 ft., 11.3 m	

Figure 17

REMARKS: Blast site, 0.4 m from blast boring, made after the blast

Magnitude= 7.1

Acceleration= 0.16 g

Median grain size vs. depth

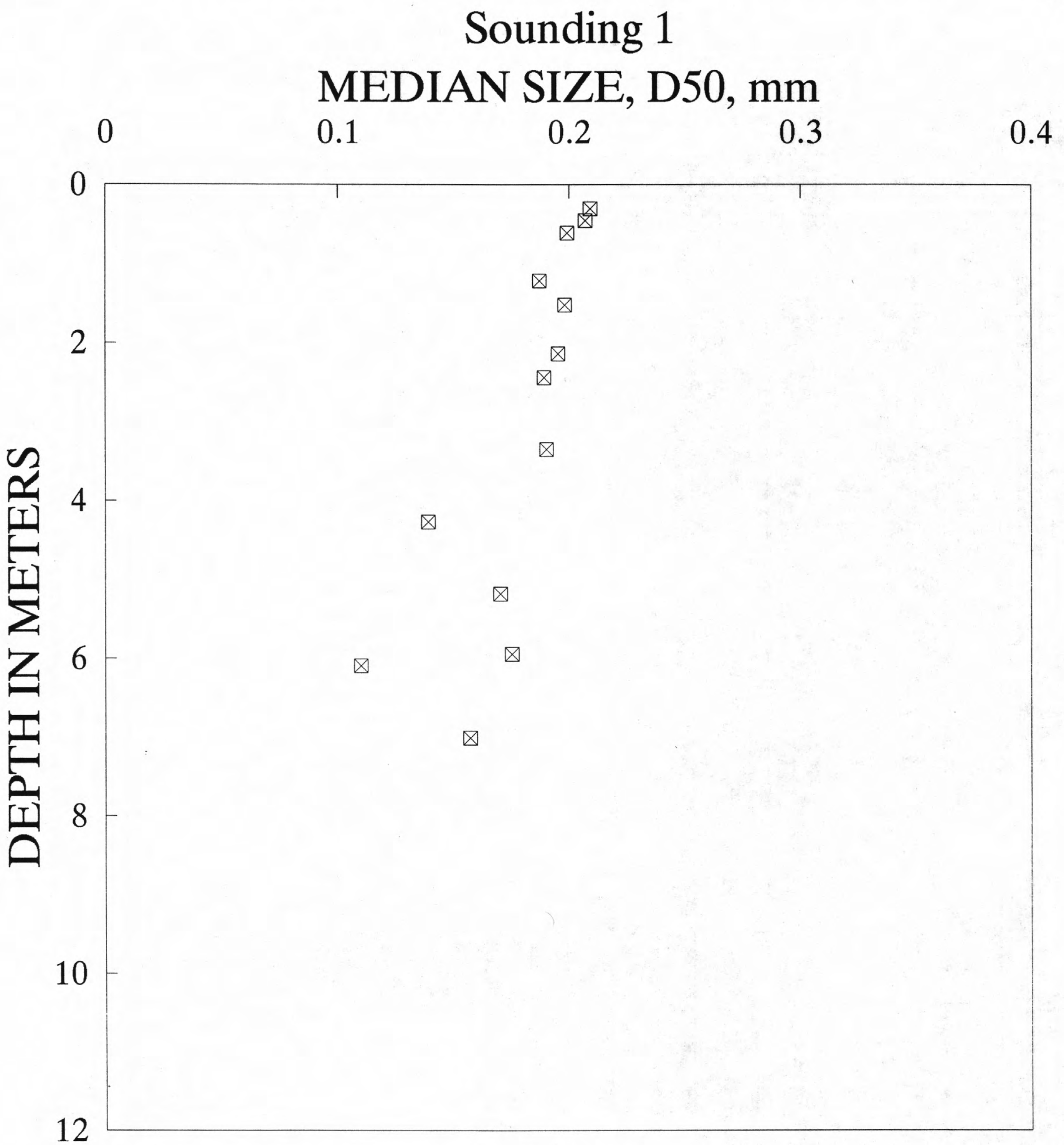


Figure 18

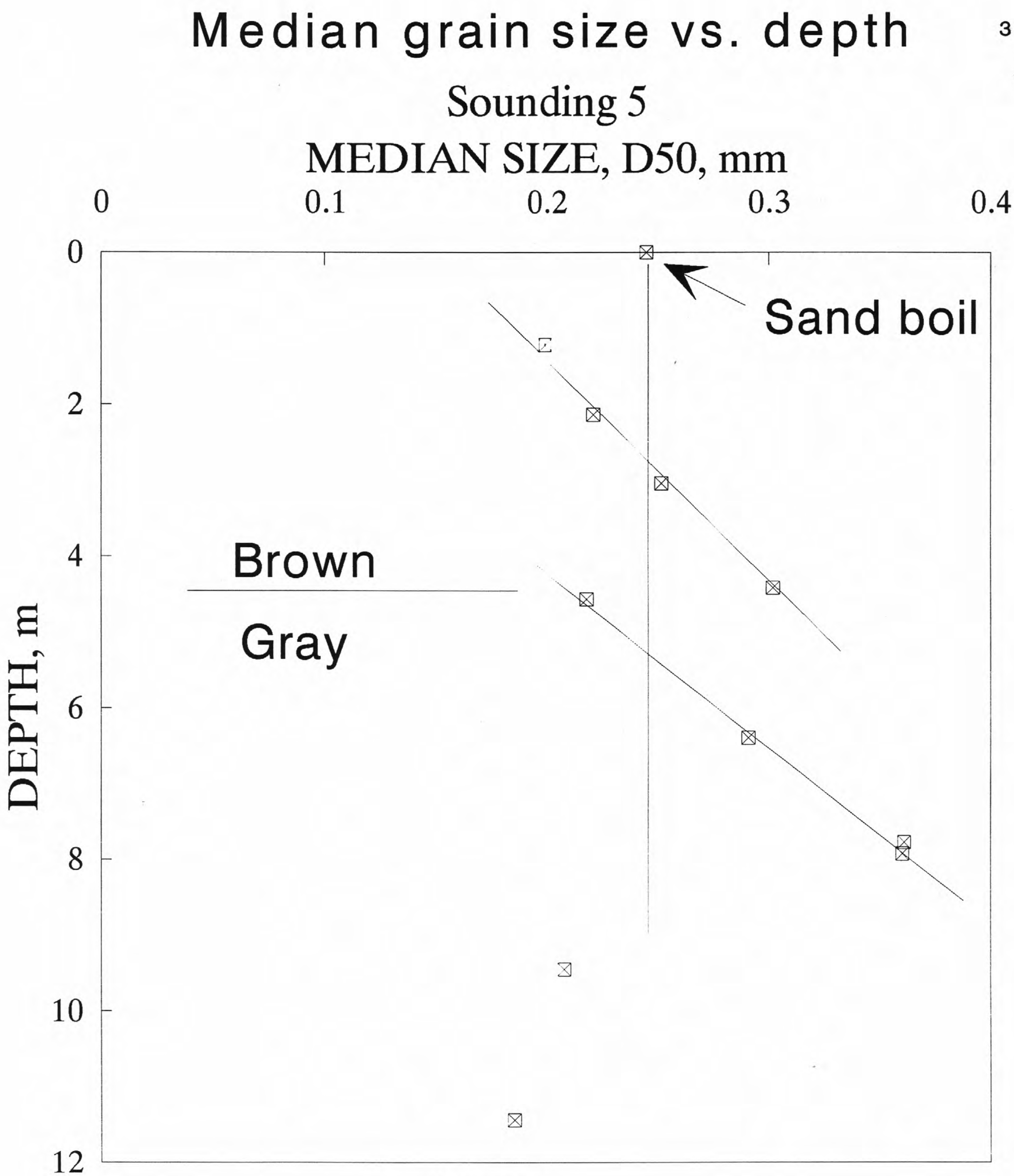

Median grain size vs. depth
Sounding 5
MEDIAN SIZE, D50, mm
0
0.1
0.2
0.3
0.4
Sand boil
Brown
Gray
DEPTH, m
0
2
4
6
8
10
12

Figure 19

Median grain size vs. depth

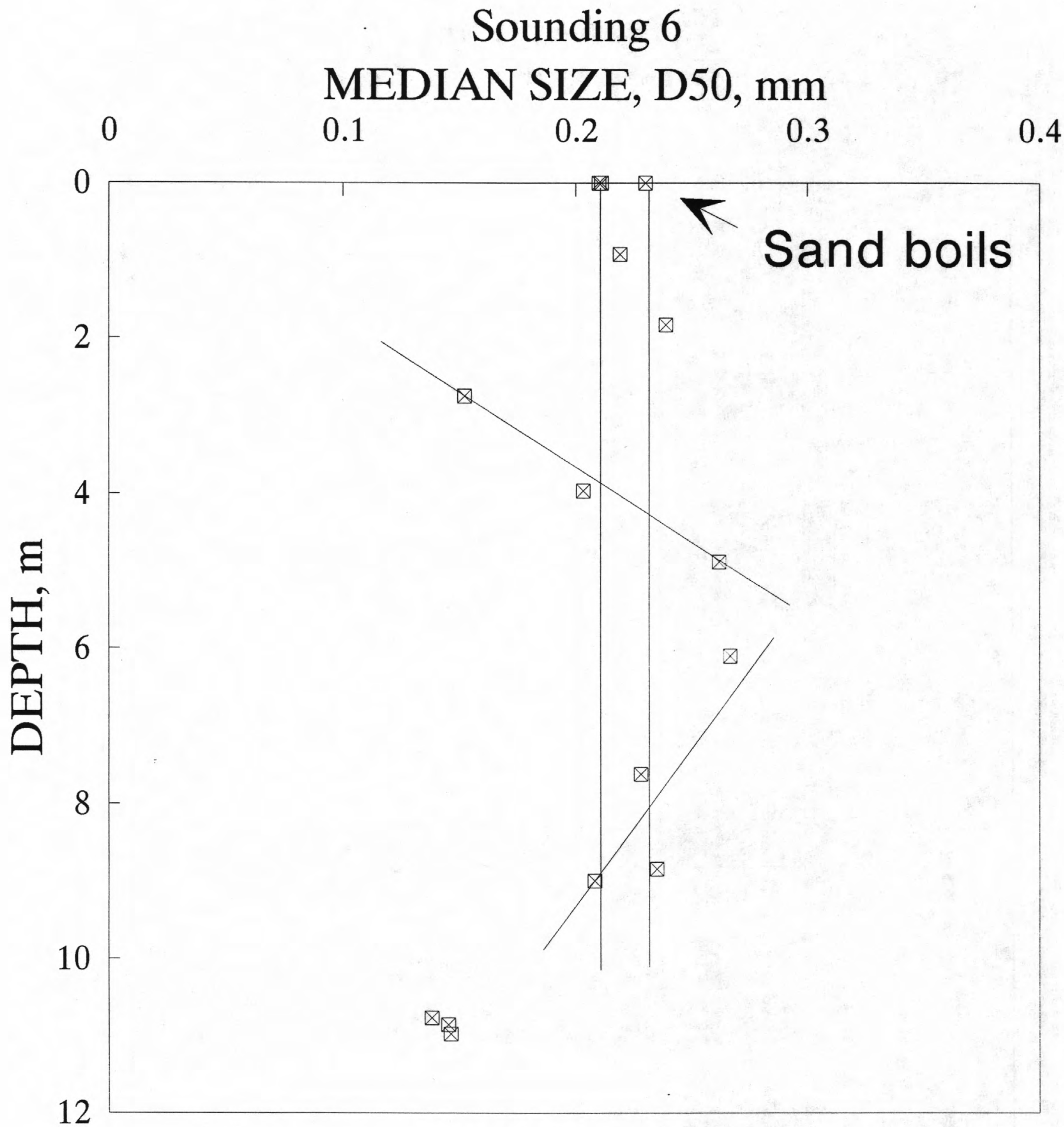


Figure 20

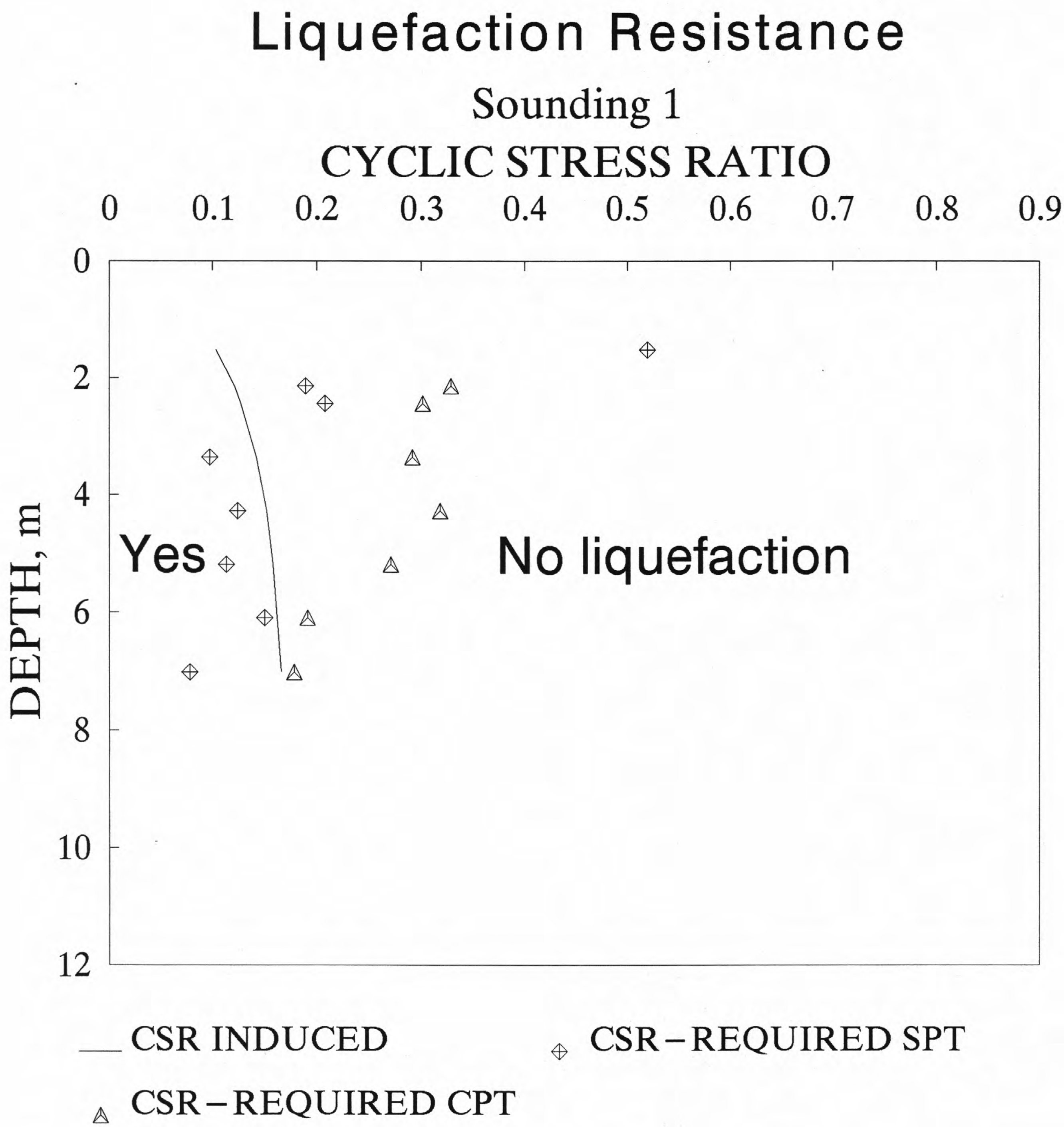

Liquefaction Resistance
Sounding 1
CYCLIC STRESS RATIO
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
2
4
6
8
10
12
DEPTH, m
Yes
No liquefaction
CSR INDUCED
CSR-REQUIRED SPT
CSR-REQUIRED CPT

Figure 21

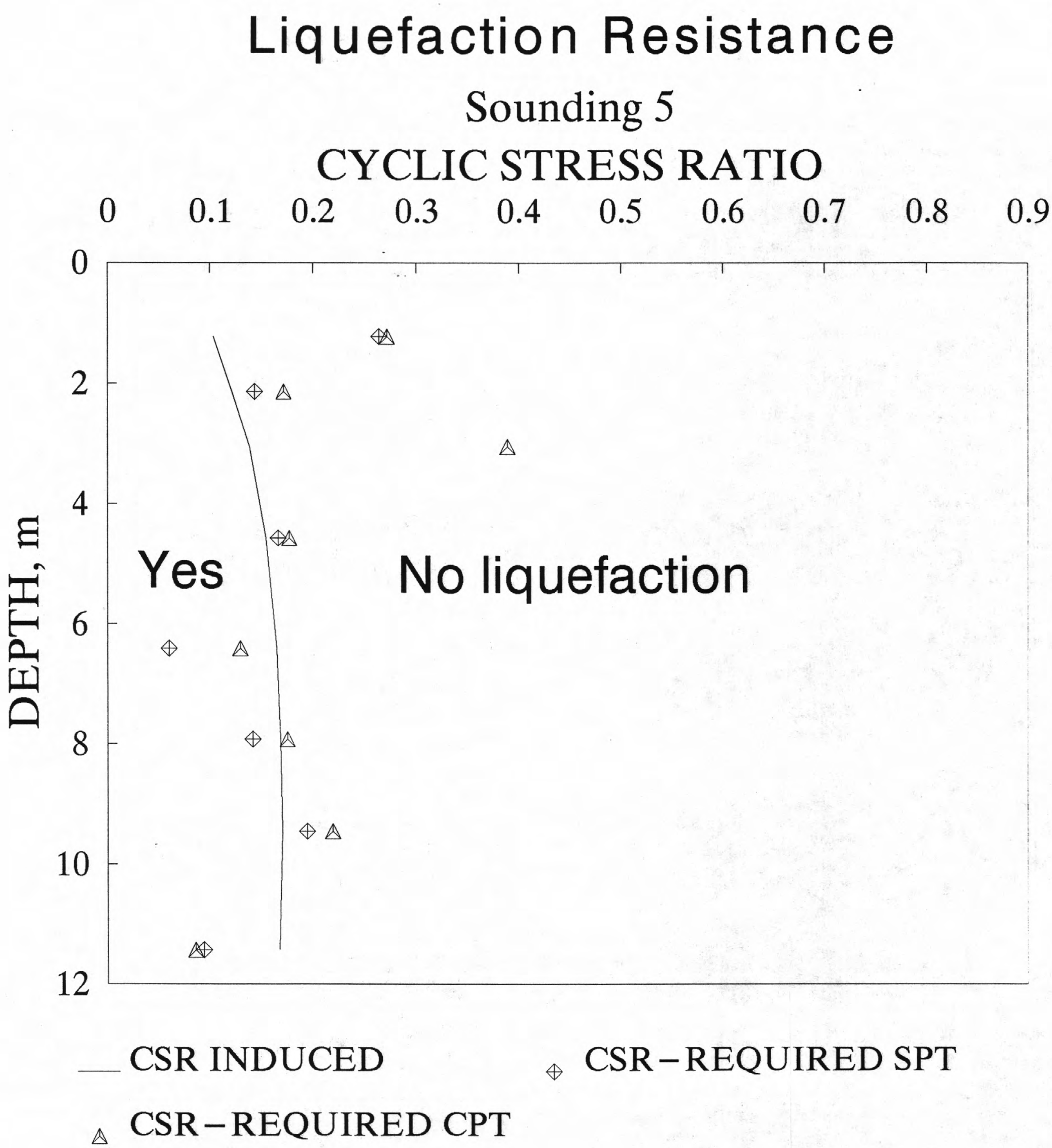

Liquefaction Resistance
Sounding 5
CYCLIC STRESS RATIO
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
DEPTH, m
0
2
4
6
8
10
12
Yes
No liquefaction
CSR INDUCED
CSR−REQUIRED SPT
CSR−REQUIRED CPT

Figure 22

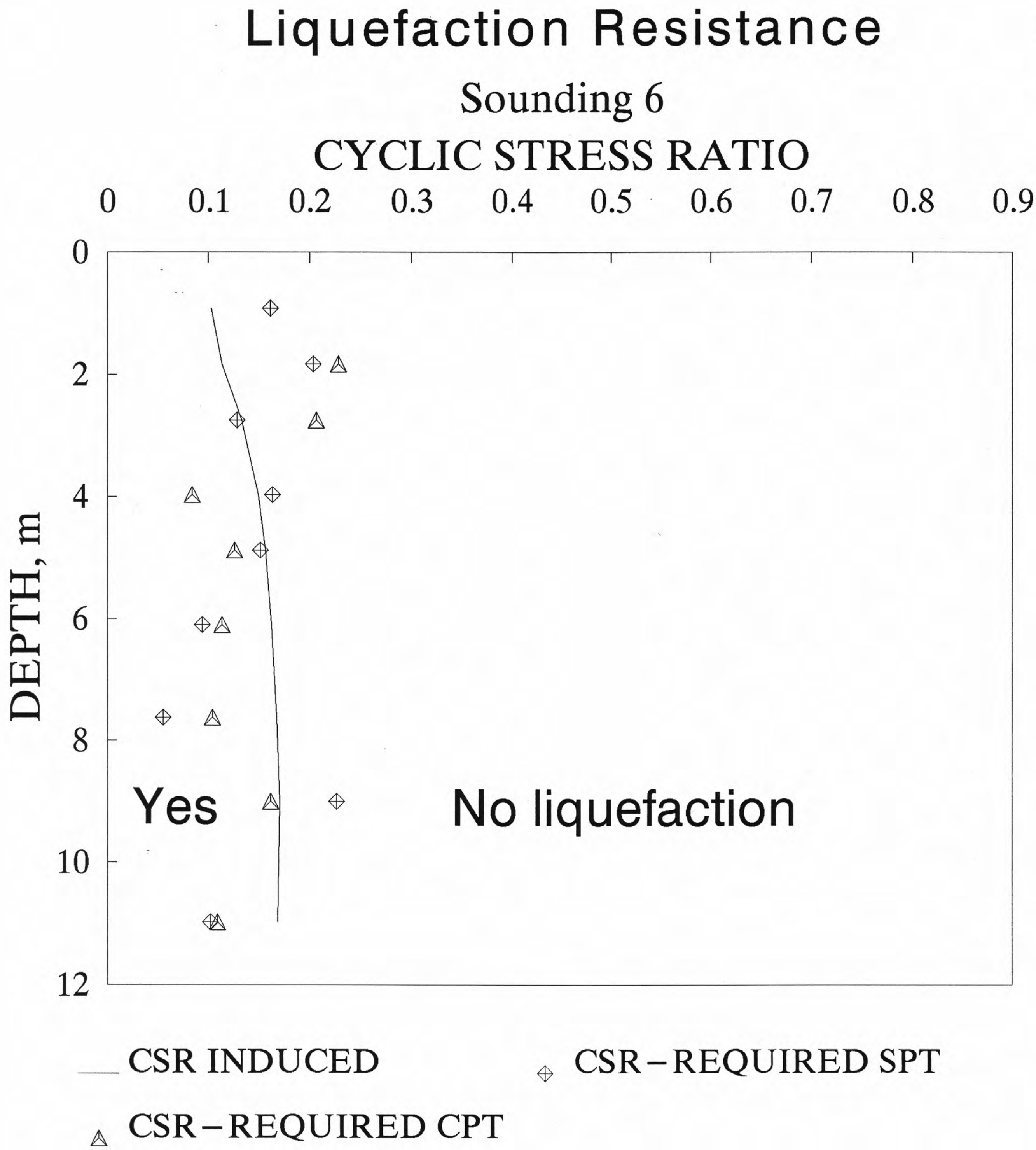
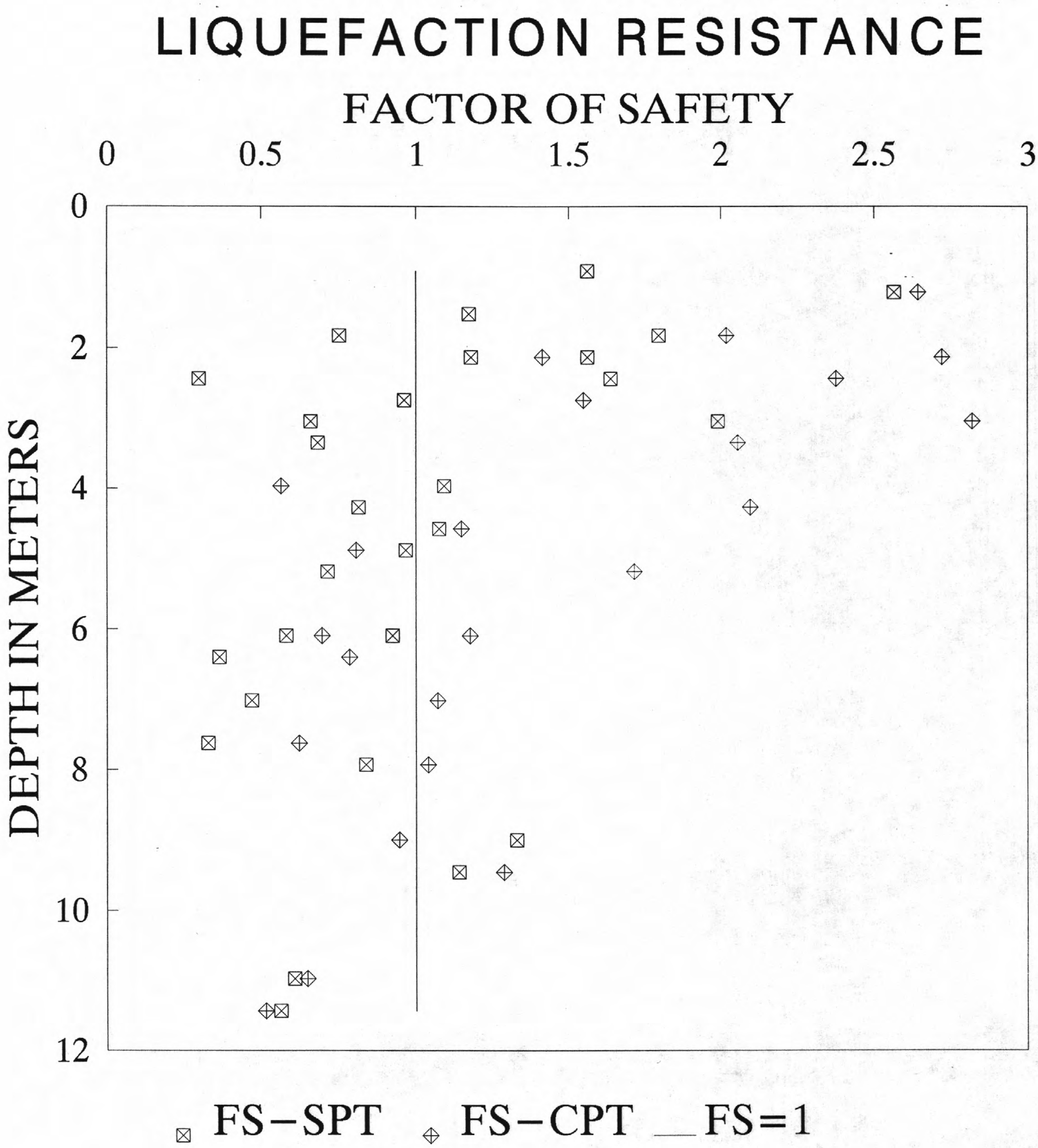

Liquefaction Resistance
Sounding 6
CYCLIC STRESS RATIO
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
DEPTH, m
0
2
4
6
8
10
12
Yes
No liquefaction
CSR INDUCED
CSR−REQUIRED SPT
CSR−REQUIRED CPT

Figure23



LIQUEFACTION RESISTANCE
FACTOR OF SAFETY
0
0.5
1
1.5
2
2.5
3
0
2
4
6
8
10
12
DEPTH IN METERS
FS−SPT
FS−CPT
FS=1

Figure24

TREASURE ISLAND

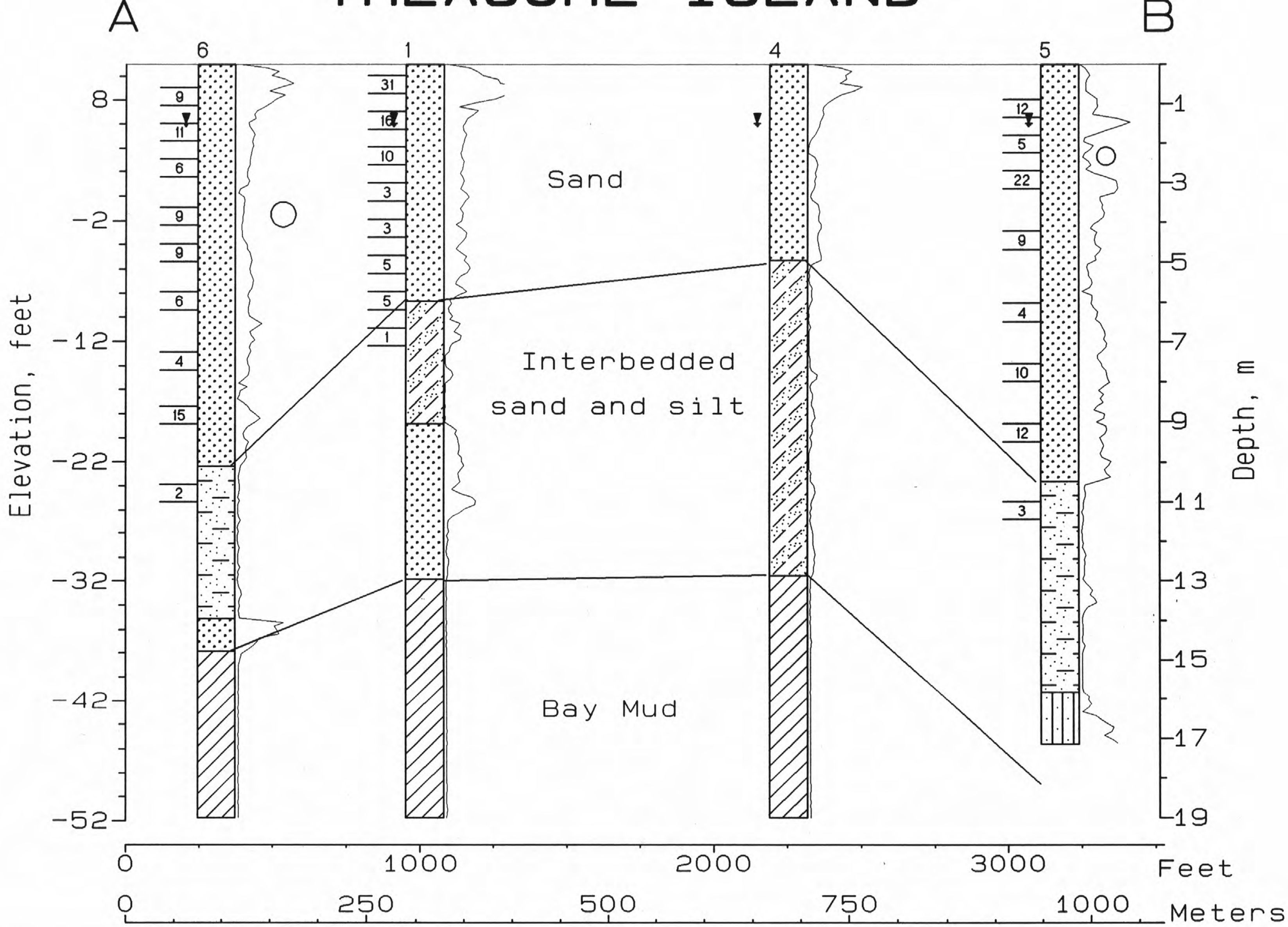


Figure 25

U.S. GEOLOGICAL SURVEY CROSS SECTION

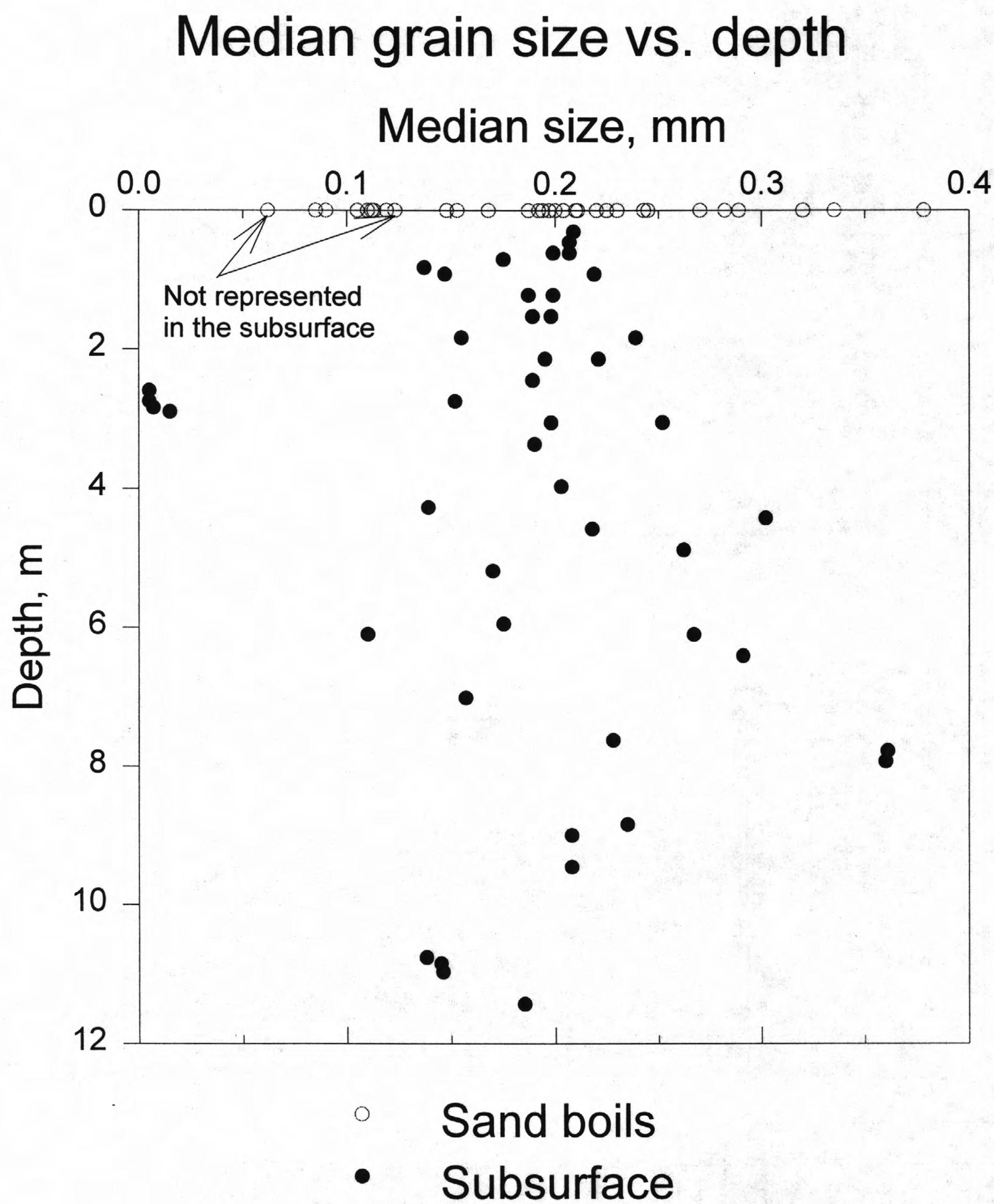

Median grain size vs. depth
Median size, mm
0.0
0.1
0.2
0.3
0.4
0
2
4
6
8
10
12
Depth, m
Not represented
in the subsurface
Sand boils
Subsurface

Figure 26

Table 1. Grain size characteristics of samples

SAMPLE	DEPTH (ft)	SPT N	DEPTH RANGE	G	S	M	C	D50	Cu	UNIFIED SOIL CLASSIFICATION	
January 28, 1994 Fire station											
Tic1−1b	1.5		1−2.5	0	81	5	14	0.207	80	SM	Silty SAND
Tic1−1a	2	31	1−2.5	0	68	12	20	0.199		SM	Silty SAND
Tic1−2	5	16	4−5.5	0	85	9	6	0.198	5.0	SM	Silty SAND
Tic1−3	8	10	7−8.5	0	90	10		0.189	2.8	SP−SM	SAND with silt
Tic1−4	11	3	10−11.5	0	87			0.190		SM	Silty SAND
Tic1−5	14	3	13−14.5	0	76	19	5	0.139	7.7	SM	Silty SAND
Tic1−6	17	5	16−17.5	0	89			0.170	3.2	SP−SM	SAND with silt
Tic1−7b	19.5		19−20.5	0	88			0.175		SP−SM	SAND with silt
Tic1−7a	20.0	5	19−20.5	0	74	21	5	0.110	11	SM	Silty SAND
Tic1−8	23.0	1	22−23.5	0	80	15	5	0.157	4.1	SM	Silty SAND
Piezometer hole for usgs retrievable at fire station (R1)											
Tic1b−1	1		0.5−1.5	2	83	9	6	0.209	9.2	SM	Silty SAND
Tic1b−2	4	16	3−4.5	0	90	10		0.187	3	SP−SM	SAND with silt
Tic1b−3	7	9	6−7.5	0	90	10		0.195	2.7	SP−SM	SAND with silt
24 February, 1994 Blast site											
Tic7 was called Tic3a											
Tic10 was called Tic3b											
Tic7−1	2.0	16	1−2.5	0	94	6	0	0.207	2	SP−SM	SAND with silt
Tic7−2	5.0	5	4−5.5	0	89	5	6	0.189	3.4	SP−SM	SAND with silt
Tic7−3	8.0	NA	7−8.8								
Tic7−4	10.0	4	9−10.5	0	93	7	0	0.198	2.4	SP−SM	SAND with silt
Tic10−1c	2.3			0	88	12		0.175	3.2	SP−SM	SAND with silt
Tic10−1b	2.7			0	79	21	0	0.137	3.6	SM	Silty SAND
Tic10−1a	3.0	11	2−3.5	0	89	11		0.147	2.4	SP−SM	SAND with silt
Tic10−2	6.0	3	5−6.5	0	89	11		0.155	2.5	SP−SM	SAND with silt
Tic10−3b	8.5		8−9.5	0	5	43	52	0.005		CH	Fat CLAY
Tic10−3a	9.0	1	8−9.5	0	6	45	49	0.005		ch	Fat clay
Tic10−4	9.3		8−10	0	13	44	43	0.007		cl	Lean clay
Tic10−5	9.5		9.5−10.5	0	19	46	35	0.015		CL	Lean CLAY with sand
March 8, 1994 Baseball field											
Ti−5 SB	0	sb	surface	0	94	6		0.245	2.8	SP−SM	SAND with silt
Ti5−1	4.0	12	3−4.5	0	88	12		0.199	4.3	SP−SM	SAND with silt
Ti5−2	7.0	5	6−7.5	0	83	14	3	0.221	10	SM	Silty SAND
Ti5−3	10.0	22	9−10.5	0	94	6	0	0.252	2.3	SP−SM	SAND with silt
Ti5−4b	14.5	9	14−15.5	1	95	4	0	0.302	2.9	SP	SAND
Ti5−4a	15.0	9	14−15.5	0	93	7	0	0.218	2.5	SP−SM	SAND with silt
Ti5−5	21.0	4	20−21.5	0	97	3	0	0.291	2.5	SP	SAND
Ti5−6b	25.5		25−26.5	1	97	3	0	0.361	2.7	SP	SAND
Ti5−6a	26.0	10	25−26.5	2	94	4	0	0.360	2.6	SP	SAND
Ti5−7	31.0	12	30−31.5	0	88	12		0.208	4	SP−SM	SAND with silt
Ti5−8	37.5	3	36.5−38	0	82	9	9	0.185	34	SM	Silty SAND

SAMPLE	DEPTH (ft)	SPT N	DEPTH RANGE	G	S	M	C	D50	Cu	UNIFIED SOIL CLASSIFICATION	
March 15, 1994	Playground/pump station										
Ti−12 SB	0	sb	surface	0	97	3	0	0.210	2	SP	SAND
Ti−13 SB	0	sb	surface	0	98	2	0	0.230	2	SP	SAND
Ti−16 SB	0	sb	surface	0	98	2	0	0.211	2	SP	SAND
Ti6−1	3.0	9	2−3.5	0	95	5	0	0.219	2	SP−SM	SAND with silt
Ti6−2	6.0	11	5−6.5	0	94	6	0	0.239	2.4	SP−SM	SAND with silt
Ti6−3	9.0	6	8−9.5	0	88	12		0.152	2.6	SM	Silty SAND
Ti6−4	13.0	9	12−13.5	0	95	5	0	0.203	1.9	SP−SM	SAND with silt
Ti6−5	16.0	9	15−16.5	0	95	5	0	0.262	2	SP−SM	SAND with silt
Ti6−6	20.0	6	19−20.5	0	97	3	0	0.267	1.9	SP	SAND
Ti6−7	25.0	4	24−25.5	0	95	5	0	0.228	2.0	SP−SM	SAND with silt
Ti6−8b	29.0		28.5−30	0	95	5	0	0.235	2.2	SP−SM	SAND with silt
Ti6−8a	29.5	15	28.5−30	0	91	9		0.208	2.8	SP−SM	SAND with silt
Ti6−9c	35.3		35−36.5	0	72	17	11	0.138	41	SM	Silty SAND
Ti6−9b	35.6		35−36.5	0	72	17	11	0.145	46	SM	Silty SAND
Ti6−9a	36.0	2	35−36.5	0	71	18	11	0.146	45	SM	Silty SAND

G = Gravel, >4.75 mm
S = Sand, 4.75>S>0.075 mm
M = Silt, 0.075>M>0.005 mm
C = Clay, <0.005 mm
D50 = Median grain size
Cu = Coefficient of uniformity (D60/D10)

Table 2. Liquefaction resistance

SITE	ACCEL-ERATION g	WATER TABLE ft.	DEPTH ft.	SPT N	(N1)60	FINES %	D50 mm	CYCLIC STRESS RATIO IND	CYCLIC STRESS RATIO REQ	Fs N	Qc MN/M^2	Qc KG/CM^2	N Qc	STRESS RATIO REQ-Qc	Fs Qc
TIC-1	0.16	5	5	16	24.5	15	0.198	0.103	0.519	5.0	7.05	71.9	27.4	1.99	4.9
7' test from 1b			7	9	13.8	10	0.195	0.121	0.189	1.6	5.89	60.1	22.9	0.329	2.7
			8	10	15.3	10	0.189	0.127	0.208	1.6	5.45	55.6	21.6	0.302	2.4
			11	3	4.9	13	0.190	0.142	0.097	0.7	6.29	64.2	19.5	0.292	2.1
			14	3	4.5	24	0.139	0.152	0.124	0.8	5.55	56.6	17.7	0.319	2.1
			17	5	7	11	0.170	0.158	0.113	0.7	6.97	71.1	19.2	0.271	1.7
			20	5	6.6	11	0.110	0.162	0.150	0.9	3.25	33.2	9.7	0.191	1.2
			23	1	1.3	20	0.157	0.166	0.078	0.5	3.87	39.5	9.7	0.178	1.1
TIC-7	0.16	5	5	5	7.6	11	0.189	0.103	0.121	1.2					
CPT after blast			8	1	1.5	NA		0.127	0.038	0.3					
			10	4	6.7	7	0.198	0.138	0.091	0.7	3.92	40.0			
TIC-10	0.16	5	6	3	4.6	11	0.155	0.113	0.085	0.8	3.65	37.2			
CPT after blast			9	1											
Ti-5	0.16	5	4	12	18.4	12	0.199	0.103	0.264	2.56	4.87	49.7	18.8	0.272	2.64
baseball field			7	5	7.6	17	0.221	0.121	0.143	1.18	2.65	27.0	10	0.171	1.41
			10	22	37	6	0.252	0.138	1.990	1.99	9.14	93.2	27.4	0.389	2.82
			15	9	13.2	7	0.218	0.154	0.166	1.08	5.19	52.9	14.1	0.177	1.15
			21	4	5.2	3	0.291	0.164	0.060	0.37	4.96	50.6	11	0.129	0.79
			26	10	12	4	0.360	0.168	0.141	0.84	7.89	80.5	15	0.175	1.04
			31	12	13.4	12	0.208	0.170	0.194	1.14	7.31	74.6	15.3	0.219	1.29
			37.5	3	3.1	18	0.185	0.167	0.094	0.56	1.21	12.3	2.4	0.086	0.51
Ti-6	0.16	5	3	9	13.8	5	0.219	0.103	0.161	1.56	12.08	123.2	45.5	1.99	19.32
playground			6	11	16.8	6	0.239	0.113	0.203	1.80	5.11	52.1	18.8	0.228	2.02
			9	6	7.9	12	0.152	0.133	0.128	0.96	4	40.8	14.4	0.206	1.55
			13	9	13.9	5	0.203	0.149	0.163	1.09	2.5	25.5	7.1	0.084	0.56
			16	9	12.9	5	0.262	0.156	0.151	0.97	4.22	43.0	10.6	0.126	0.81
			20	6	7.9	3	0.267	0.162	0.094	0.58	4.12	42.0	9.5	0.113	0.70
			25	4	4.9	5	0.228	0.167	0.055	0.33	3.9	39.8	8.7	0.104	0.62
			29.5	15	17.1	9	0.208	0.170	0.226	1.33	5.56	56.7	11.9	0.161	0.95
			36	2	2.1	29	0.146	0.168	0.102	0.61	1.24	12.6	2.8	0.109	0.65

SPT, N = Blows per foot
(N1)60 = Modified N, normalized for overburden and corrected for hammer energy
Fines = Size fraction less than 0.075 mm
D50 = Median grain size
Cyclic stress ratio
  IND = Earthquake induced stress ratio, see equation 1.
  REQ = Cyclic stress ratio required to liquefy.
Fs, N = Factor of safety from SPT (REQ/IND)
Qc = CPT tip resistance
N, Qc = N derived from CPT tip resistance.
Stress ratio REQ-Qc = Cyclic stress ratio required to liquefy using CPT
Fs, Qc = Factor of safety from CPT (REQ-QC/IND)

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