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IN SITU DYNAMIC TESTING OF PORE PRESSURE TRANSDUCERS AT TREASURE ISLAND, CALIFORNIA USING "CALTECH PIEZOMETER"

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ABSTRACT

Liquefaction in saturated sandy deposits is one of the most dramatic causes of damage to structures during earthquakes. The onset of liquefaction has been observed through the occurrence of sand boils, building settlements, lateral spreading, and other phenomena during numerous earthquakes. The most recent reminders of liquefaction and its destructive effects were observed in Kobe, Japan during the 17 January 1995 Hanshin earthquake. A thorough understanding of liquefaction phenomena, and formulation and calibration of analytical techniques to predict liquefaction occurrence and its effects, require data from instrumented sites where in-place soil properties have been appropriately established, and where ground motions have been measured for an earthquake strong enough to have generated significant increases in the pore pressures.

So far, among few potentially liquefiable sites around the world that have been permanently instrumented with pore-pressure transducers and accelerometers, only the Wildlife Site in Imperial Valley, California has liquefied during an event. Acceleration and pore-pressure data were recorded at the Wildlife Site during the magnitude 6.6 Imperial Valley earthquake of 24 November 1987 which resulted in liquefaction of the site. However, some unusual aspects were observed in the data, including long rise times of the pore pressures and a time lag between the strong ground shaking and maximum pore pressure development. Conditions associated with installation of the pore-pressure transducers might have been the cause of the anomalies observed in the data. In a comprehensive experimental study under a grant from the U.S. Geological Survey (USGS), the authors performed in-situ dynamic inspection and calibration of the USGS piezometers installed at the Wildlife Site versus a reference pore-pressure transducer carefully installed close to the existing transducers. The field and the laboratory tests performed as part of this research provided valuable information on overall response of the USGS transducers and on the techniques to improve the installation and subsequent in-situ inspection of piezometers at any future site.

Following the Wildlife field study a prototype unit of a new pore-pressure measuring probe, designed at the California Institute of Technology (Caltech), was fabricated and used in a field testing program at Treasure Island, San Francisco, at the National Science Foundation (NSF) U.S. Geotechnical Test Site to develop standard field techniques for installation and in-situ calibration of pore-pressure transducers. A large number of tests was performed using the "Caltech Piezometer" and several types of USGS pore-pressure transducers at the Treasure Island site in February 1994. The piezometers were all installed at similar depths, and pore pressures were generated either by dropping a 1300 lb. (590 kg) weight on the ground surface or by detonating explosives at some depth below ground surface at equal horizontal distances from the piezometers. The new Caltech probe performed well in all the tests conducted, and provided a ready means of introducing a deaired saturated probe into the ground to any required depth in the field. On the other hand, the performance of the USGS piezometers deployed was quite variable. The ease of on-site preparation, calibration, and installation of the "Caltech Piezometer" suggests a number of possible uses for it such as a) long-term installation and monitoring of pore pressures during earthquakes,

b) testing piezometers at existing instrumented sites, c) rapid deployment and measurement of pore pressures during aftershocks, d) monitoring dynamic compaction of hydraulic or liquefiable natural fills, and e) in-situ field measurement of liquefaction potential of granular soils.

KEYWORDS

Liquefaction, earthquakes, new piezometer design, instrumented sites, installation techniques, in-situ calibration

INTRODUCTION

The liquefaction of soils during earthquakes has been extensively studied by engineers since the 1964 Niigata, Japan earthquake, which caused classical liquefaction-induced foundation failures. As a result of this research, simple procedures (e.g. Seed and Idriss, 1971; Seed and de Alba, 1986) and more complex models (e.g., Martin *et al.*, 1975; Prevost, 1981; Siddharthan and Finn, 1982; Zienkiewicz *et al.*, 1990), were developed to predict the liquefaction potential at particular sites under given postulated earthquakes. Validation of these advanced methods requires a comprehensive data set from one-g laboratory cyclic simple shear or triaxial loading tests which model the behavior of a single soil element, one-g shake table tests or centrifuge experiments at elevated g's on soil specimens modeling prototype boundary value problems. It is, of course preferable to calibrate numerical models by comparison with the performance of soil sites that have been instrumented with accelerometers and piezometers, and that have liquefied during strong shaking in earthquakes. A major research study, entitled "Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems (VELACS)", funded by the U.S. National Science Foundation (NSF), included a large number of researchers from universities and private industry who independently conducted various laboratory and centrifuge model tests and predicted results of the experiments prior to, and after completion of the testing program (Arulanandan and Scott, 1993). Different numerical techniques incorporating constitutive relations capable of modeling pore pressure rise and liquefaction phenomena were used. This study was very useful in advancement of our understanding of liquefaction phenomenon and identifying strengths and benefits as well as shortcomings of centrifuge model testing and the use of numerical models for prediction of liquefaction and its consequences. One-g shake table testing of soils and soil-structure systems, particularly to study liquefaction has also received attention by researchers (Iai *et al.*, 1987; Scott, 1989; Gibson and Scott, 1995). However, it is well recognized that instrumented sites subjected to earthquake loading conditions provide the most desirable data set for studying the cause and consequences of liquefaction and the mechanism of soil behavior during and after liquefaction.

Potentially liquefiable sites in Japan, Taiwan, and the United States have been permanently instrumented with pore pressure transducers and accelerometers. So far, among these sites, only the Wildlife Site in Imperial Valley, California, instrumented by the U.S. Geological Survey (USGS) in 1983, has liquefied during an event (Bennett *et al.*, 1984; Holzer *et al.*, 1989). Acceleration and pore-pressure data were recorded at the Wildlife Site during the magnitude 6.6 Imperial Valley earthquake of 24 November 1987 which resulted in liquefaction of the site. However, some unusual aspects were observed in the data, including long rise times of the pore pressures and a time lag between the strong ground shaking and maximum pore pressure development. Conditions associated with installation of the pore-pressure transducers might have been the cause of the anomalies observed in the data. In December 1989 tests were carried out by the authors at the Wildlife site to check the condition of the USGS pore pressure transducers and recording system. The results of the assessment tests have been presented and discussed in the literature (Hushmand, *et al.*, 1991, 1992; Youd and Holzer, 1994; Scott and Hushmand, 1995b).

Although some concerns have been shown with respect to accuracy of the data (Holzer *et al.*, 1988, 1989; Hushmand *et al.*, 1991), the data set recorded at the Wildlife site has been extensively used by researchers to check, validate, or improve various constitutive models and analytical techniques to predict liquefaction (e.g. Keane and Prevost, 1989; Vucetic and Thilakaratne, 1989). Additionally, some attempts have been made to validate measured response of the transducers by correlating limited acceleration measurements at the site, (accelerations were measured only below, and on the ground surface a few feet above the top of the liquefiable soil layer) to the recorded pore pressures and by using a theoretical hypothesis to explain the liquefaction phenomenon observed at this site (Zeghal and Elgamal, 1994). Detailed evaluation of the Wildlife data and possible causes for unusual response of the pore pressure transducers leads to a different conclusion (Hushmand *et al.*, 1991, 1992; Scott and Hushmand, 1995b).

One suggestion which resulted from the Wildlife in-situ calibration study was that it would be desirable to develop a standard procedure for testing current and future dynamic pore pressure installations in the field, after placement, and preferably, at regular intervals thereafter. Such a research site, instrumented with accelerometers and pore pressure transducers, is expensive to establish and maintain, and maintenance will probably have to continue for years before sufficiently strong ground motion occurs to trigger the system and generate pore pressures large enough to be interesting. Regular checks would ensure the reliability of the system, and enable faulty transducers and recording equipment to be replaced. Additionally, there is very little or practically no information available in the literature for a standard method of preparation and installation of piezometers for dynamic measurement of pore pressures (Dunnicliff, 1994; personal communication). Unfortunately, research studies to improve and standardize design, field preparation, and installation of dynamic pore pressure transducers have been largely neglected, while many sites have been instrumented or planned to be instrumented with piezometers without in-depth investigation of installation procedures and behavior of transducers in soils. Particularly, piezometer tip design, saturation and deairing in the field, and post-installation testing and evaluation of piezometer response in soils are critical to ensure reliable and consistent performance of the transducers. Improper deairing and presence of air bubbles in the piezometer tip can result in slow response of the transducer and delay in measuring pore pressure build up (Gibson, 1963; Hushmand *et al.*, 1992).

Liquefaction was observed at Treasure Island in San Francisco Bay during the 1989 M7.1 Loma Prieta earthquake, and later under a grant from NSF a site was selected on the Navy Base there for a pore pressure transducer array, which was installed along with a data acquisition system in August, 1991 (de Alba *et al.*, 1994). Under a contract with the USGS, the authors designed and fabricated a new pore pressure measuring probe at the California Institute of Technology ("Caltech Piezometer") and used it as the reference transducer in a series of in-situ tests adjacent to the NSF test facility to investigate field preparation and installation techniques and assess performance of several types of USGS transducers. The original USGS proposal was directed toward checking the performance of the NSF site pore pressure transducers, but the authors were informed that the NSF site committee would not permit this. It is understood that a number of these transducers are no longer functioning. The tests at the adjacent area were performed in February 1994 and involved installing the "Caltech Piezometer" and various pore pressure transducers in the soil and generating impact loads by dropping a weight on ground surface using a drill rig. Following the impact tests, another series of experiments at a nearby site involved the use of explosive charges to generate transient pore pressures in the soil. The following summarizes some of the design aspects of the probe, test procedure and results of the field experiments at Treasure Island, and findings and conclusions of the study. More details are provided elsewhere (Scott and Hushmand, 1995a).

SITE AND SOIL CONDITIONS

The Treasure Island location is shown in Figure 1 taken from Bennett (1994); it is located in the Naval Reserve at the north end of Yerba Buena Island in San Francisco Bay, California. Treasure Island was constructed of hydraulic fill in 1936/1937 for the 1939 Golden Gate Exposition. The actual test site is a level area adjacent to Fire Station #1 (Building 157) on the base (Figure 1). Fourteen weight drop (impact) tests were performed at this site. The comparison tests described here were performed in essentially the same soil deposit as the NSF array site a distance of about 50 ft (15 m) to the north at the Fire Station site. The final series of tests (two weight drop and five explosive) was performed at an unused playing field on the Naval Reserve at the corner of H and 11th Streets a short distance away from the Fire Station (Figure 1). The Fire Station site soil consists of layers of hydraulically filled loose silty sand and sandy silt with occasional clay seams to a depth of about 38 ft (11.6 m). Field Standard Penetration Test (SPT) blow-counts averaged about 5 from about 12 to 33 ft (3.7 to 10.1 m) depth. Higher values of SPT are indicated at shallower depths (de Alba, *et al.* 1994). Cone Penetration Tests (CPT) at the site also showed similar results. Sandstone and shale bedrock is at about 300 ft (91.4 m). Water table is at 5 ft (1.5 m) below ground surface in the upper loose sand layer; the test transducers were installed at various depths in the upper silty sand layer, as described later. Two SPT/CPT's at the playing field site gave a similar soil profile and water table, but with a slightly greater depth of sand and silt to about 43 ft (13.1 m) over Bay Mud. More details on the site profiles are given elsewhere (Scott and Hushmand, 1995a; Bennett, 1994).

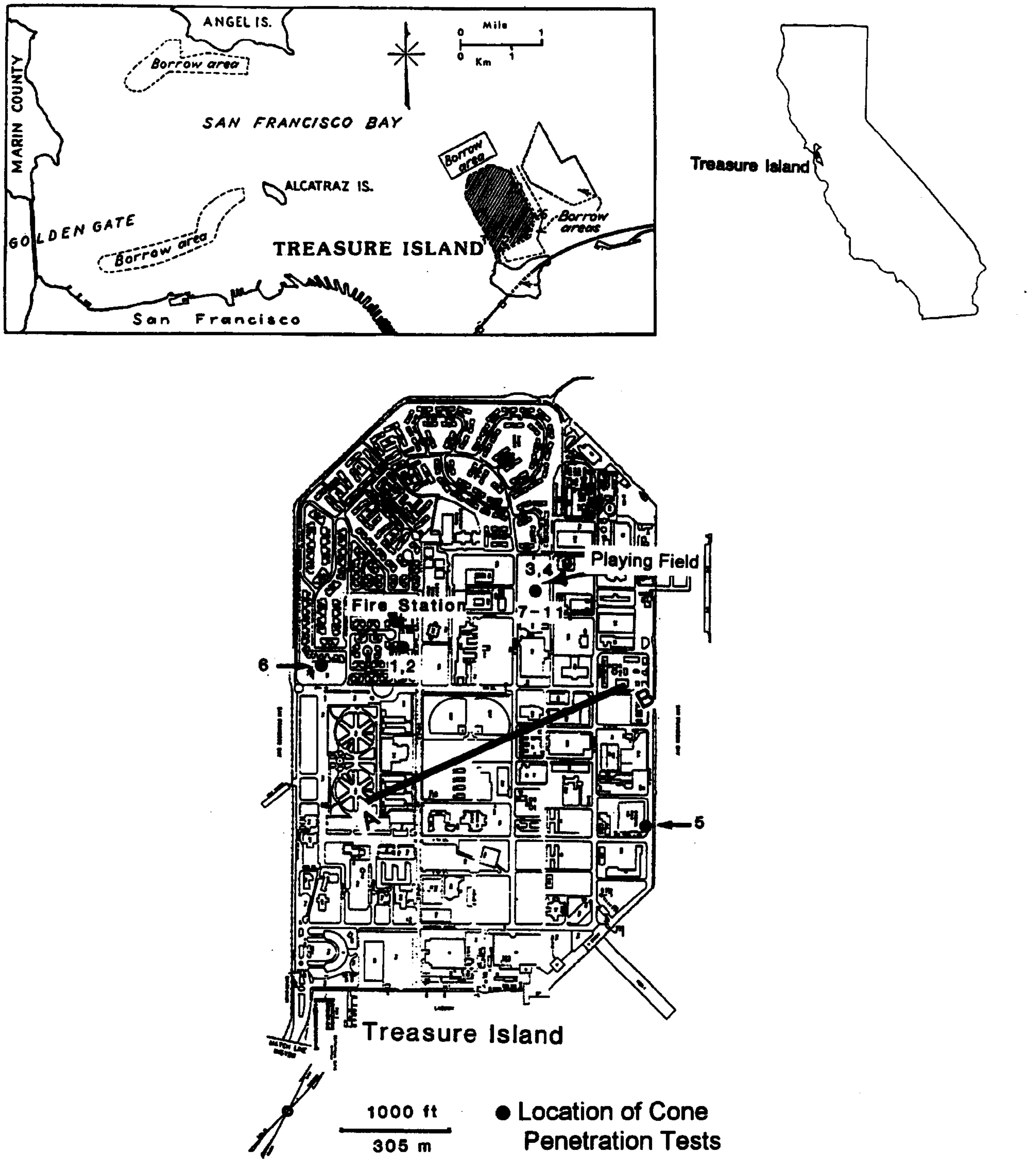


Figure 1. Portion of San Francisco Bay - Treasure Island, Showing Test Sites

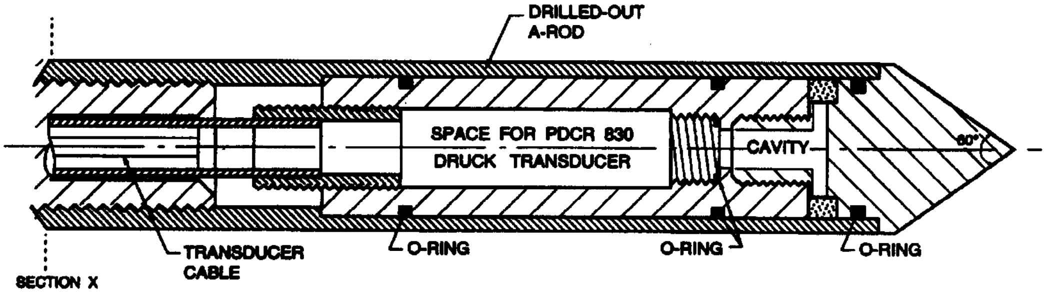
The impact point of the test weight, whose drop height was also varied, was located at a range of distances from the transducers. Both the drop weight and the first three explosions generated transient pore pressures of several psi (1 psi ~ 6.9 kPa) at a maximum. However, the last two explosion tests, utilizing larger explosive charges, generated very high transient pore pressures (up to about 50 psi [~ 345 kPa]); the first of these resulted in permanent damage to one of the USGS transducers.

DESIGN OF CALTECH TEST PROBE

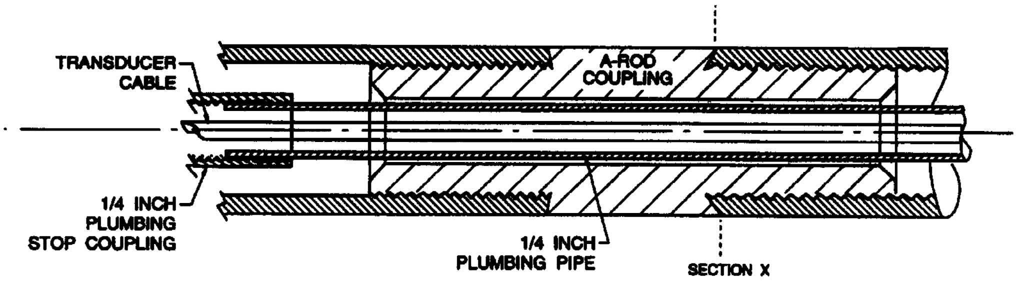
There are several desirable features to incorporate in a transient soil pore pressure probe, so that it requires a minimum of ancillary equipment and causes minimal ground disturbance.

1. The working section should be capable of being subjected, in the field, to saturation with deaired water, including heating under vacuum, prior to installation.
2. When saturation is completed, the section of the instrument, including the transducer pressure-sensing diaphragm and the porous plug which conducts pore pressure from the soil environment to the diaphragm, should be sealed off under water, so that no water or soil can enter the equipment until it is installed in the ground at the desired depth.
3. Installation in the soil should not require a bore-hole or predrilling; the equipment should be capable of being pushed to the required depth with a conventional drilling rig or smaller apparatus.
4. When the pressure sensor has reached the required depth, it should be possible easily to arrange for the exposure, by positive mechanical means, of the saturated porous plug to the adjacent soil and water.
5. The response time of the system should be rapid; pore pressure jumps during earthquake strong motions, other vibrations, or shocks such as generated by explosions may occur in milliseconds or less. This requires a) the sensing diaphragm to be limited in its displacement under water pressures of up to say, 50 psi (~ 345 kPa), so that the volume of water entering the chamber ahead of the diaphragm to cause the deflection is small; and b) the permeability of the porous plug to be high enough that the combination of diaphragm volume change and plug permeability result in a short system transient time. This must be balanced by the necessity of providing a porous plug which does not permit fine grained soil to enter the internal water chamber.
6. It should be possible, while the probe is embedded in the soil at one depth, to close it up and advance it to a greater depth without returning it to the surface for another deairing and saturation cycle. This will protect the porous plug in the event the probe has to pass through gravel or clay layers to a deeper sand stratum.
7. The probe should be capable of easy calibration in the field and laboratory before and after a test program.
8. It should be simple, rugged, and readily capable of attachment to conventional soil drilling equipment.

In an attempt to conform with these conditions, the probe illustrated in Figure 2 was designed and built. The



(a) Transducer Tip



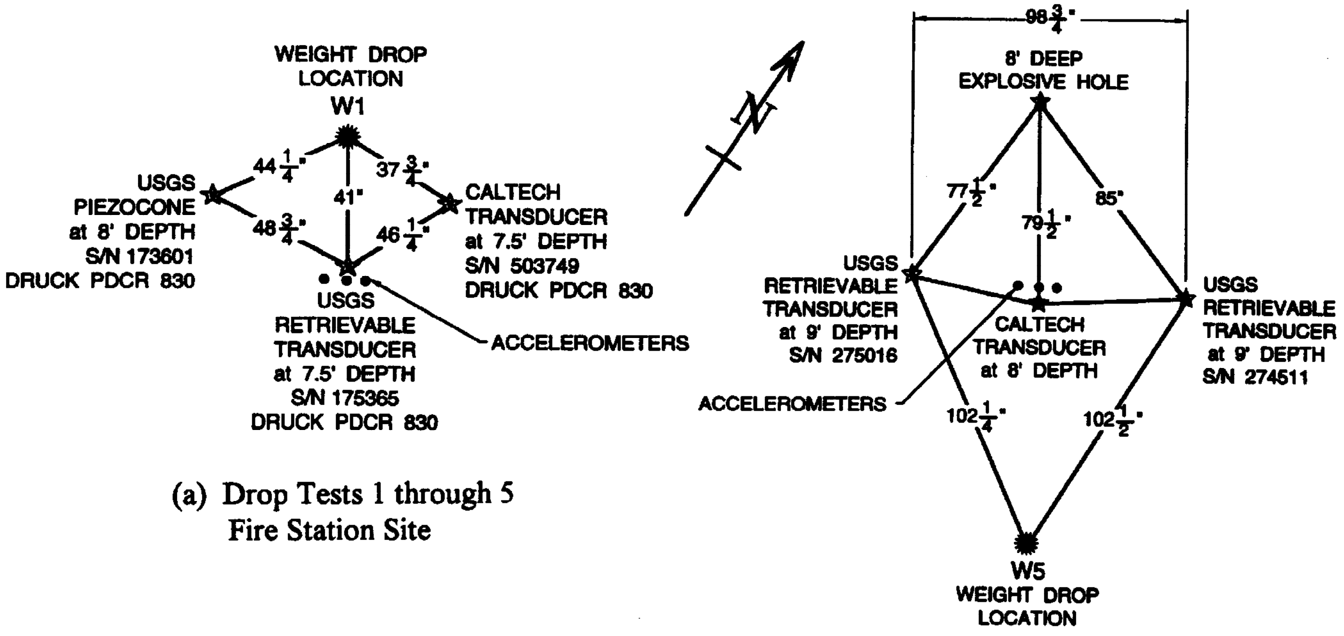
(b) A-rod and Pipe Connections

Figure 2. Caltech Probe: (a) Tip with Transducer; (b) A-rod and Pipe Connections

conical tip is attached to the porous plug, its holder and the pore pressure transducer (Druck PDCR 830), whose cable passes through a 1/4 inch (6.4 mm) standard black iron pipe, which is attached to the block containing the transducer plug and tip. The 1/4 inch pipe passes through a protective envelope which is connected to an A-rod coupling. The coupling permits the device to be attached to standard A-rods as used by drill rigs. The 1/4 inch pipe is extended by pipe sections and its own couplings inside the A-rods. In practice at a site, after thorough preliminary deairing and saturation of the disassembled probe, it is assembled under the deaired water and the closed-up system is withdrawn, attached to drill rod and pushed into the ground to the required depth. Then the A-rod is clamped at the drill-rig, and the 1/4 inch pipe pushed hydraulically until it stops against the final A-rod coupling, extending the required distance to expose the porous plug to the soil. To test transducers installed at various depths, the system can be closed in order to advance the probe to deeper soil. Detailed description of the Caltech probe design and field preparation and installation is provided in a comprehensive report of the Treasure Island tests (Scott and Hushmand, 1995a).

TEST PROCEDURE AND SEQUENCE

Overall, 21 tests (14 at Fire Station and 7 at playing field) were performed. In Tests 1 through 5 at the Fire Station two USGS transducers, referred to as “piezocone” (Druck PDCR 830, Serial Number 173601) and “retrievable” (Druck PDCR 830, S/N 175365) were tested by reference to the Caltech piezometer. However, in subsequent tests the piezocone was not used (transducer did not respond) and only retrievable USGS piezometers (additional transducer, Druck PDCR 830, S/N 274511) were tested against the Caltech probe. The USGS retrievable transducers were assembled and installed in the field at the same time as the Caltech probe was installed at the site (Figure 3). The saturation of the USGS probe consisted of only boiling the porous filter in regular tap water for about 2 to 3 hours and then assembling the probe under water. The design of the USGS retrievable probes is completely different from that employed at the NSF site. It is understood that, depending on the calibration results described here, USGS retrievable probes may be used in instrumentation of a new site in San Francisco and also to substitute for some of the probes at the NSF site that have failed.



(a) Drop Tests 1 through 5
Fire Station Site

(b) Drop Tests 15 and 16; Blast Tests 1 through 5
Playing Field Site

Figure 3. Detail of Test Arrangement

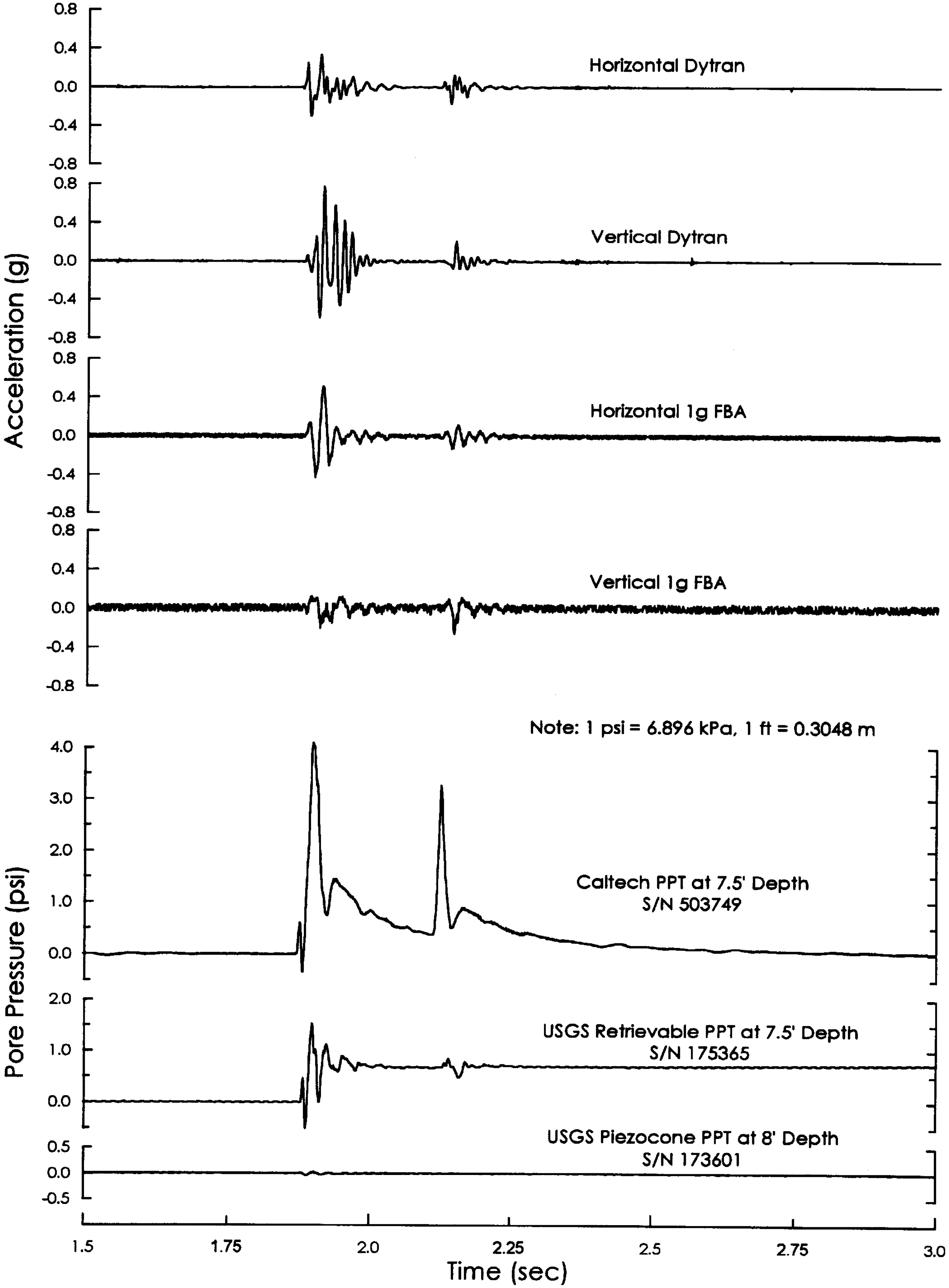
At the Fire Station site, the USGS drill rig was used to drill and core holes for the USGS transducers, which were deaired to a limited extent with a short procedure, and installed in the holes. At the same time, accelerometers were placed on the ground surface to measure the accelerations generated due to the impact of the drop weight on the soil surface. After the preparation described above, the Caltech probe was then pushed into the ground to the required depth. The drop point was approximately equidistant from the three probes, which were installed to the same depth. Figure 3a illustrates the layout of the Drop Tests 1 through 5 at the Fire Station site. For a drop weight, a cylindrical piece of concrete weighing 1300 lb. (590 kg) was employed. It was dropped onto a square steel plate to prevent excessive penetration into the soft soil and to cause a sharp impact. The drop heights varied from 27 to 64 inches (0.7 to 1.6 m). Initially a low drop height was used, and the height increased in subsequent tests. At the open field site, five blast tests, using an explosive charge as the energy source, were performed. The same probe setup procedure was used as for the drop tests. The amount of explosive charge was varied and replacements of USGS transducers were made for the different tests. Before beginning the blast tests, the USGS transducers were tested in two Drop Tests, 15 and 16, carried out at low drop heights to ensure minimum soil disturbance. Following these drop tests, Blast Tests 1 through 5 were performed with a range of explosive energies. Blasting charge ranged from 3 gr (1 blasting cap) to 122 gr (primer cord) of explosive, buried at depths of 8 and 9 ft (2.4 and 2.7 m) using the same shot point. Figure 3b shows the layout of transducers, shot point, and accelerometers; the piezometer depth is also indicated. In the above tests, the horizontal distance of the piezometers ranged from 38 inches to almost 16 ft (1 to 4.9 m), and their embedment depth from 7.5 to 15.5 ft (2.3 to 4.7 m).

LABORATORY TESTS

It is important to calibrate the Caltech pore pressure probe both before and after field tests (especially those involving blast loading, which may subject the transducer diaphragm to very high transient pressures) and to check the integrity of the O-rings sealing the transducer and the outside sleeve periodically. Accordingly, a piece of apparatus was designed which can be used for this purpose in laboratory and in the field and is also convenient for deairing and saturating the probe. Laboratory checks after the field tests showed no leakage past the sealing O-rings and also provided a check of the transducer condition and its calibration. Details of the laboratory tests are described elsewhere (Scott and Hushmand, 1995a).

RESULTS

The results of the drop weight and blast tests performed at the two Treasure Island sites were represented by acceleration and pore pressure plots, prepared directly from output of the data acquisition system. Results of only a few tests are presented and discussed here; in particular, the blast tests are omitted. A complete presentation and discussion of the results is provided in the project report (Scott and Hushmand, 1995a). For each test, the surface accelerations recorded by the group of accelerometers - two Dytran, three Kinemetrics FBA's - included in the instrumentation package, and the pore pressures were plotted over two different time scales, first over an interval of 8 seconds to give a picture of the initial stages of pore pressure dissipation, and then to an expanded scale of 1.5 seconds to demonstrate the transient nature of the pore pressure more clearly. Figure 4 shows results of the Drop Test 1 plotted over the expanded scale of 1.5 seconds. A number of interesting aspects of the tests can be seen from this figure. The weight drop height in this test was 27 inches (0.7 m), at a horizontal distance of 3 to 4 ft (0.9 to 1.2 m) from Caltech and two USGS transducers, which were placed at depths of 7.5 and 8 ft (2.3 and 2.4 m), 2.5 to 3 ft (0.8 to 0.9 m) below the water table. Assuming a soil unit weight of 110 pcf (1761.8 kg/m^3), the increase in water pressure required to produce liquefaction at the transducer level is 4.6 to 4.8 psi (31.7 to 33.1 kPa). The figure shows that the initial impact of concrete block with steel plate was followed by a bounce and second impact about 0.24 seconds after the first. The Dytran accelerometers indicate peak surface horizontal and vertical accelerations of about 0.3 and 0.75g respectively; the FBA instruments somewhat less, probably as a result of a lower frequency response. The duration of the stronger impact was about 0.13 seconds, and its vibration effects had dissipated entirely before the second strike occurred. The Caltech pore pressure record shows clearly the effect of the second impact superposed on the decaying pore pressure of the first blow. A second spike appears and the exponential decay is raised about 0.3 psi (2.1 kPa) before resuming. In this test, the recording duration of 8 seconds (buffer capacity was limited due to high sampling rate) was adequate for showing the Caltech transducer's decaying



Note: 1 psi = 6.896 kPa, 1 ft = 0.3048 m

Figure 4. Pore Pressure and Acceleration Time Histories Recorded during Drop Test 1

transient response, but not for the transient exhibited by the USGS retrievable piezometer (S/N 175365), which also shows the two impacts, but seems to increase in the 6 seconds following the impact. The transient response of this transducer is smaller than that of the Caltech system. Only the slightest response of the USGS piezocone is apparent, and the transducer is evidently malfunctioning. The response of the piezocone continued to be almost non-existent in the first 5 drop tests and it was replaced by another retrievable probe. The dynamic transient response of the first retrievable transducer (S/N 175365) through the first 5 tests was consistently smaller than that of the Caltech probe, and the long-term dissipation transient of the USGS device steadily decreased through the test sequence to a negligible value in Test 5. It is interesting that the peak response of the Caltech probe in Test 1 approaches the theoretical liquefaction pressure of the soil. In the first 5 drop tests, the residual pore pressure generated decreased towards the end of the sequence, but the USGS retrievable transducer (S/N 175365) recorded even a faster drop in the residual pore pressures. The transient peak pore pressures were always higher in the Caltech device, but the dissipation after impact was much faster than in the USGS device, which indeed had to be rezeroed in the data acquisition equipment prior to each subsequent test, because the apparent residual pressure had not dissipated. Possible electrical problems of the USGS transducer might have been another source of the large direct current (DC) offsets observed before each test. Figure 5 illustrates the response of two retrievable USGS transducers in Drop Test 15 at the playing field site. Surprisingly, we observe that these transducers in spite of having identical construction, field preparation, distance from the impact point, and placement depths behaved quite differently. The two drop tests at this site were performed to check and compare response of the USGS transducers before beginning the blast tests. Note that the Caltech transducer response was intentionally not recorded during these tests.

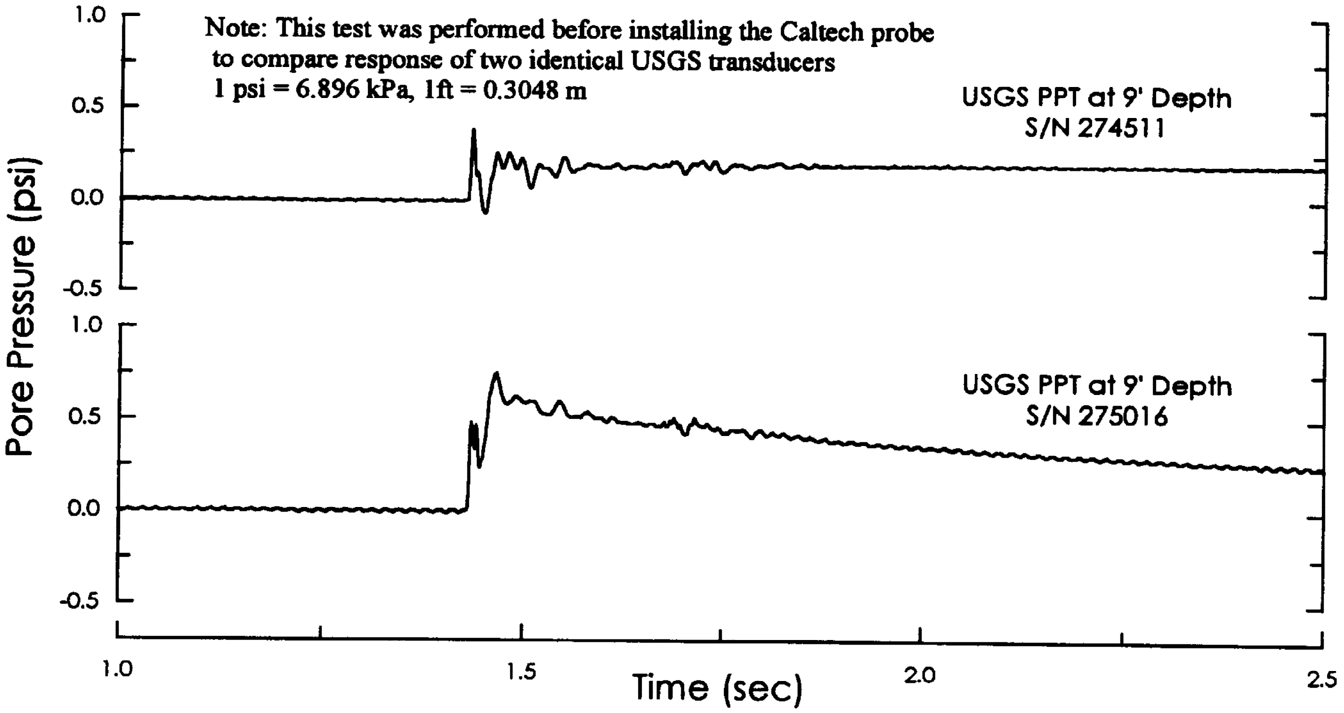

Note: This test was performed before installing the Caltech probe
to compare response of two identical USGS transducers
1 psi = 6.896 kPa, 1ft = 0.3048 m

Figure 5. Pore Pressure Time Histories Recorded during Drop Test 15

CONCLUSIONS AND RECOMMENDATIONS

The proposed testing method (drop weight or explosive charges) seems to work quite satisfactorily to calibrate and check dynamic response of piezometers in the field. The Caltech piezometer provided a ready means of introducing a deaired, saturated probe into the ground to any required depth in the field and appeared to perform well in all the tests conducted. It proved possible to close the filter tip of the probe after a few readings at one depth in the soil and advance it to a greater depth at which the tip was uncovered again, without observable change in its performance. On the other hand, the performance of the USGS piezometers deployed was quite variable. No useful signal was observed from the piezocone in the first few drop tests and its use was discontinued. The retrievable probes varied in their performance. One of them (S/N 175365) exhibited a steadily increasing offset, but decreasing long term dissipation transient in Tests 1 through 5. The test results suggest that a useful test would have incorporated several identical probes at the same depth and horizontal distance from the drop point. This was achieved, to some extent, at the playing field site, where Drop Tests 15 and 16 were recorded by the two USGS retrievable transducers, which exhibited very different responses. The ease of on-site preparation, calibration, and installation of the "Caltech Piezometer" suggests a number of possible uses for it. These are:

1. The probe can be installed in permanent instrumented sites for long-term monitoring of seismically-induced pore pressures in soils.
2. It can be used to test the pore-pressure piezometers at different existing instrumented sites or at future sites. If such tests are not performed, any results from a long-awaited earthquake may be lacking or questionable.
3. The probe or probes could be transported and deployed after an earthquake in which signs of liquefaction or high pore pressures are evident. It is quite possible that useful long-term transients could be detected hours or even days after the event. This would serve to provide quantitative indications of the pore pressures generated, and dissipation properties of the site soils. The soil behavior in aftershocks would also be recorded.
4. Dynamic compaction of hydraulic or liquefiable natural fills can be monitored during compaction by installing a few of the probes. Pore pressure variations measured at different depths in the fill during compaction can be used as a measure of soil improvement achieved. The probes can be relocated easily.
5. Combined with impact of a weight, or modest explosive charges, a few of the "Caltech Probes", together with accelerometers would be useful for establishing the potential of the in-place soils at a given site for liquefaction or pore pressure increase, both before and after mitigation efforts, thus providing practical evidence of liquefaction potential at field sites when currently only laboratory tests and empirical liquefaction analyses are available.

Liquefiable sites around the world, instrumented with pore-pressure transducers, with excess pore pressures triggered by natural or artificial events, can provide an extensive and valuable database on the behavior of liquefiable soils. These data can be used to improve our understanding of the liquefaction phenomenon and can help in producing analytical methods to predict liquefaction and to reduce and mitigate its destructive effects.

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