Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

In-place calibration of USGS pore pressure transducers at Wildlife Liquefaction Site, California, USA

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ABSTRACT: 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, alone among instrumented sites. Some unusual aspects were observed in the data, including long rise times of the pore pressures resulting in a time lag between the strong ground shaking and maximum pore pressure development.

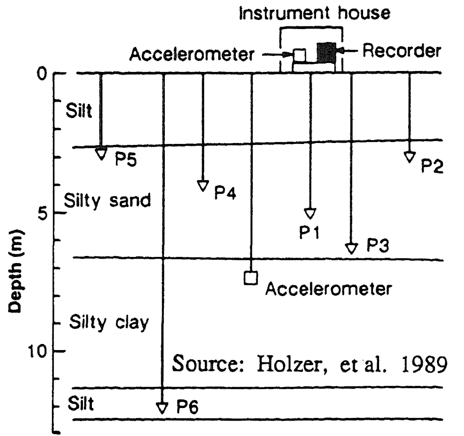
It was not clear from the data obtained whether the liquefaction process at the Wildlife Site was different from that observed in other saturated sand deposits, or if the pore-pressure transducers were not responding correctly. In December 1989, the authors performed an in-situ dynamic calibration of the USGS piezometers installed at the Wildlife Site with respect to reference pore-pressure transducers showing that only one of the transducers was performing nearly correctly. Several hypotheses have been examined to explain the data recorded during the earthquake, including particularly transducer malfunction due to air bubbles in the transducer chambers.

INTRODUCTION

Formulation and calibration of analytical techniques to predict liquefaction occurrence and its effects require data measured in the field during earthquakes. Among the few sites instrumented with accelerometers and pore pressure transducers only the Wildlife Site in Imperial Valley, Southern California liquefied during an event. The acceleration and pore-water pressure data recorded there during the 24 November 1987 Imperial Valley earthquake and the field observations of sand boils at the site shortly after the earthquake clearly demonstrate that liquefaction occurred. However, the pore pressure records all showed very long rise times (~90 seconds) to attain maximum pressures (Holzer et al., 1989). In spite of this the original data have been used as a basis for verification of numerical computations in several studies to date (Keane and Prevost, 1989; Dobry et al., 1989). None of the numerical computations matched the slow rise of pore pressure indicated by the Wildlife Site transducers. The authors do not comment on this aspect of the comparison. Because the data have some unusual aspects, preliminary investigations were undertaken by the authors to determine whether or not the piezometers used to measure pore-water pressures functioned properly during the earthquake. The results of these studies have been discussed in detail elsewhere (Earth Technology Corporation, 1991; Hushmand et al., 1991). They will be briefly summarized here before an analysis of the transducer function is presented.

The Wildlife Site was investigated and instrumented following the Westmorland earthquake (26 April 1981, $M_w = 5.9$) which generated some features of liquefaction and lateral spreading phenomena such as sand boils and fissures at the ground surface. A cross-sectional view showing instrument locations and soil stratigraphy at the site is presented in Figure 1. All but one of the six piezometers are at various depths within the silty sand layer that is considered to have liquefied during the 1981 event. The sixth piezometer, P6, is located in a deeper silt layer below a 5 m thick silty clay layer underlying the liquefiable deposit. Two 3-component accelerometers are also installed at the site, one at the ground surface and the other at a depth of 7.5 m, just below the liquefiable soil deposit. The silty sand layer is approximately 4 m thick and is overlain by a 2.5 m thick surficial silt layer within which the water level is at a depth of 1.2 m.

On November 24, 1987, the Elmore Ranch and Superstition Hills earthquakes ($M_s = 6.2$ and $M_s = 6.6$) shook the area around the Wildlife Site. Pore pressure records were obtained during the first earthquake but did not show any pore pressure increases. The Superstition Hills earthquake



Source: Holzer, et al. 1989

Fig. 1. Stratigraphic cross-section of array and schematic of instrument deployment.

generated substantial increases in the pore-water pressures up to 100 percent of overburden pressure, resulting in liquefaction of the soil (Holzer et al., 1989). The acceleration and pore-pressure time histories that were recorded during the Superstition Hills earthquake are shown in Figure 2. Piezometer P4 malfunctioned during the earthquake and the record was omitted.

The following observations can be made from Figure 2. The recorded time histories show that a rapid increase of excess pore pressures began to develop immediately after arrival of the peak acceleration of 0.21g (surface record), about 13 seconds after initiation of recording. Pore pressures rose rapidly initially but the rate of increase slowed down considerably thereafter. At the end of the strong shaking at time t=22 sec, the increased pore-water pressures above the hydrostatic pressure, as measured by Piezometers P1, P2, and P3, are less than half of the effective overburden pressure (total overburden minus hydrostatic pressure). At time t=30 sec, the increased pore pressures, except for P5, which exhibited the most rapid, but still slow, response, are still considerably less than the effective overburden pressures. These piezometers finally measured 100 percent of the overburden pressures (i.e., the theoretical onset of liquefaction) at the end of the recording period (t=97 sec), long after the shaking had effectively ceased. Ignoring the pore-pressure records, the measured horizontal surface accelerations (top traces in Figure 2) suggest that liquefaction may have occurred around t=20 sec because the character of these accelerograms changes to long period motions. The observed delay in the pore-water pressure responses suggests that the piezometers were probably not measuring the actual free-field pore-water pressures. Pore pressure increases (but not liquefaction) recorded at other sites during previous earthquakes (Ishihara et al., 1981; Shen et al., 1989) all characteristically show pore pressures increasing incrementally as the strong ground motion occurs. Frequently the pore pressure jumps can be directly correlated with individual acceleration cycles on the accelerometer record. In addition, in model studies in geotechnical centrifuges, where excess pore pressures were generated by model earthquake-like inputs, this typical ratcheting upward behavior is also observed (Hushmand et al., 1988). It is possible that insufficient de-airing and saturation of the transducer may have caused the problem.

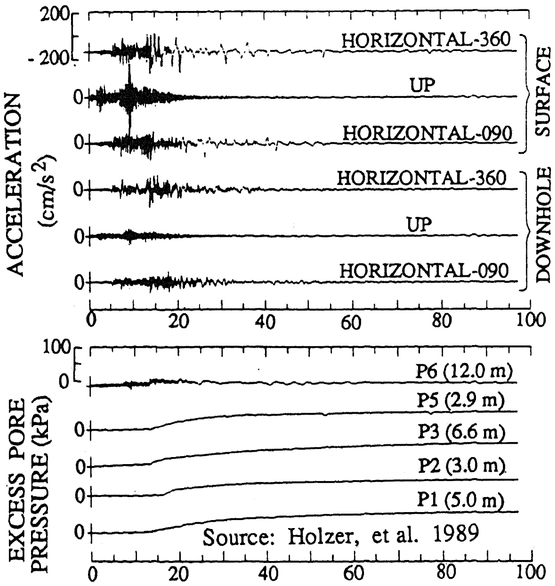


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Fig. 2. Acceleration and pore pressure time histories recorded at Wildlife liquefaction array, earthquake of November 24, 1987 (Ms = 6.6).

According to Youd (Youd et al., 1989) 10-cm holes were drilled in the soil with a rotary rig at locations P1 through P6. Each piezometer was placed inside a steel cylinder with a cone tip (Fig. 3) and then placed in a bucket of water, which was not de-aired. A plastic bag was placed around the assembly to hold the water, the assembly was removed from the bucket, placed into the 10-cm hole to the required depth, and advanced a further 15 centimeters. Normally in laboratory tests, the pore-pressure gauge assembly is saturated with de-aired water in a process which usually includes the application of a vacuum and possibly heating to the system.

In a comprehensive research study (Earth Technology, 1991), field tests at the Wildlife Site were conducted to investigate the responses of the USGS transducers by comparison with a carefully calibrated reference transducer.

TESTING EQUIPMENT AND PROCEDURE

The pressure transducer used in the USGS piezometers (Fig. 3) was a Data Instruments Model AB pressure transducer (Youd et al., 1989). In the post-earthquake field study the reference piezometer assembly was the "BAT^{TM} system," a new system for ground water monitoring (Torstensson 1984). The responses of the transducers to the pore pressures generated were recorded by a digital field data acquisition system.

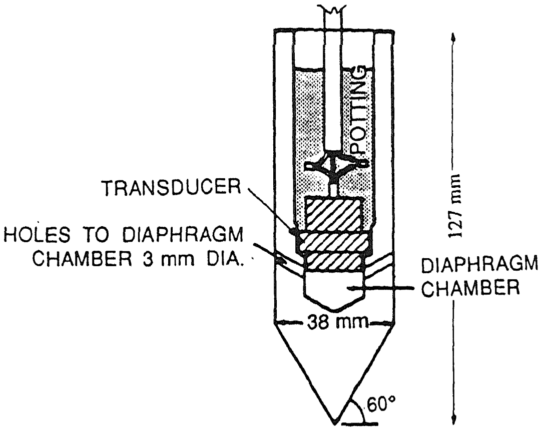

Fig. 3. USGS Piezometer assembly used at Wildlife Site.

The test equipment used for pore pressure generation in the field tests consisted of "popper" and "compressed air" systems. These systems were used to cause pressure pulses in water in wells drilled 2.1–2.4 m away from each of the in-place USGS transducers, and thus to stimulate pore pressures in soil around the USGS transducers and the reference transducer, which was installed about 0.6 m away from the in-place transducer.

The four in-place USGS transducers, which are located in the liquefiable silty sand layer and which functioned during the 1987 earthquake, were tested. Figure 4 shows the schematic drawing of the popper test configuration. As is seen from the figure, the popper was lowered in water in the well approximately to the depth of transducers and then popped. In the compressed air tests the set up was similar but with the difference of applying the burst of compressed air in the space above the water surface in the well. Test details are given in the previously published report and paper (Earth Technology 1991; Hushmand et al., 1991).

TEST RESULTS

A total of 14 tests was conducted in the field to examine the response of the transducers P2, P1, P5, and P3 sequentially. The complete presentation of the field test results is given elsewhere (Earth Technology, 1991; Hushmand et al., 1991). Only a few samples of the test results are presented and discussed here.

Figure 5a illustrates the response of Transducer P2 in a popper test. As is seen from the figure, the pore pressure increase was recorded by the BAT^{TM} device up to the end of the popping at 90 seconds, and the BAT^{TM} subsequently shows an exponential form of pressure decay. Approximately one-tenth of the pressure increase of the BAT^{TM} is indicated by P2, together with a time delay, compared to the BAT^{TM}, of about 35 seconds. It is clear, however, that P2 measured a portion of the pore pressure rise during the test. Another feature of Transducer P2 response is the very slow decay of the recorded pressure after the pressure reaches its maximum value. It seems reasonable to conclude that Transducer P2 was functioning at the time of the test, but the pore pressures it records are attenuated (with respect to the BAT^{TM} device, and possibly differently with respect to a "true" pore pressure transducer) and subject to delay.

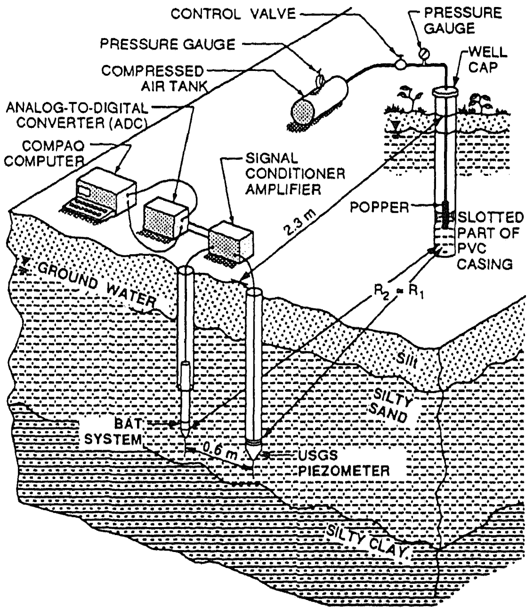

Fig. 4. Schematic drawing of popper field test.

The performance of Transducer P5 is shown in Figure 5b, and is seen to compare well with the behavior of the BAT^{TM} transducer, both with respect to amplitude and decay. In another compressed air test at pressure of 60 psi, Piezometer P5 and the BAT^{TM} transducer again responded very similarly. Therefore, if the BAT^{TM} transducer is taken as a standard, then Transducer P5 appears to be performing reasonably correctly at the time of the field test.

Transducers P1 and P3 had very poor pressure response compared to the BAT^{TM} response. Although in some of the tests, pressure rise response

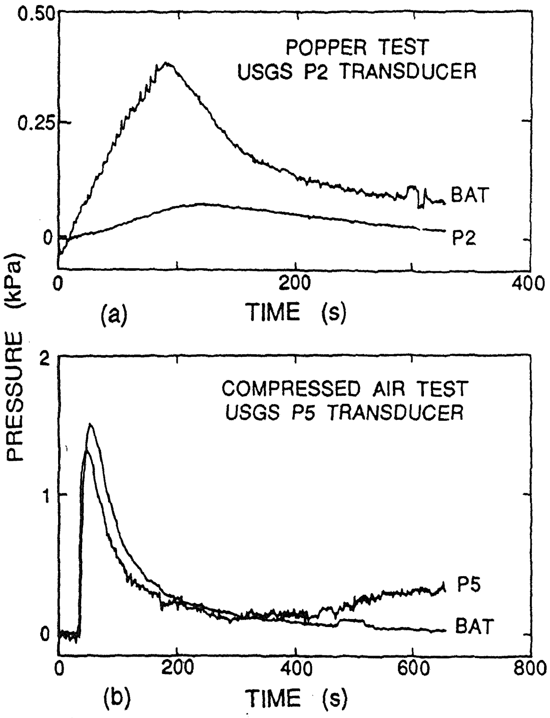

Fig. 5. Comparison of pore pressure time histories recorded by BAT and USGS P2 and P5 transducers.

of Transducer P1 was approximately similar to the BAT^{TM} response, it consistently recorded an erratic pore pressure pattern after the peak pressure (decay response). The pressure response of Piezometer P3 was entirely erratic in the tests. It was concluded that, at the time of the field study, P3 had effectively ceased to function, although a signal was obtained from it at the time of the 1987 earthquake.

SUMMARY OF FACTS

a) *1987 Earthquake*

The ground motions from the M6.6 November 1987 Superstition Hills earthquake were recorded at the surface and at 7.5 m depth at the site, where the peak horizontal accelerations were 0.21g and 0.16g respectively, and the approximate duration of strong ground motion was 15 seconds. Four pore pressure transducers indicated a slow pore pressure buildup without fluctuations to maximum values at the level required to indicate liquefaction about 90 seconds after the initiation of strong ground motion. Slow decays of the pore pressures occurred after the earthquake, with little change observed at 19 minutes after the event, but complete dissipation by 29 hours (Holzer et al., 1989). The soil at the site contained a substantial portion of silt in the layer in which the transducers were placed. Some compaction of the soil around the transducers may have occurred during installation. Properties of permeability, compressibility, and consolidation coefficient of the site soil have not been determined in laboratory tests. Evidence of widespread site liquefaction in the form of sandboils and sand sheets on the ground surface was observed after the earthquake (Holzer et al., 1989).

b) *1989 Field tests*

The field experiments as described above were performed in December 1989, to check the behavior of the pressure transducers at the site. All but one (P5) of the existing transducers exhibited a small response, no response or erratic response and were considered to be substantially inoperative at the time of the test. It is not known if this behavior was a result of degradation in the two years since the earthquake. The one remaining transducer (P5, at a depth of 2.9 m) exhibited response almost identical to the control transducer. However, at the time of the earthquake, its behavior was not qualitatively different, except for its response being somewhat more rapid, than the other 3 transducers subsequently found to be faulty.

HYPOTHESES REGARDING 1987 PORE PRESSURE RECORDS

1. The pore pressure transducers behaved correctly.

a) Since all other pore pressure records obtained from transient events in the field, in centrifuge and shaking table tests, and in laboratory cyclic tests indicate immediate response of the pore pressure to the cycles of stress (or strain) the soil behavior at Wildlife Site is qualitatively different from that observed in all other instances. No mechanism is known by which a soil element could be subjected to a rapid shearing strain, and respond with a delayed pore pressure rise. Loss of contact between soil particles caused by the excitation must result in an immediate transfer of particle support to the pore liquid.

b) The soil at the site liquefied non-homogeneously during the earthquake. Two extreme versions of this response may be taken for discussion. In the first, almost all of the site liquefied except for isolated regions which did not liquefy. However, in a *saturated* soil, the elevated pore pressures generated by liquefaction of the bulk of the soil would be transmitted immediately into regions which were not liquefied as a result of the ground shaking. Even in the very improbable event that all the functioning pore pressure transducers were located in locally nonliquefiable regions (the probability is increased if it is assumed that the transducers densified the soil around them by their installation), they would still be able to record the pore pressure rise caused by liquefaction. There is no diffusion process involved in the pore pressure rise of a saturated soil element surrounded by elevated pore pressures.

The second extreme possibility is that only small regions of the site liquefied, and the pore pressure transducers were all located in material which did not liquefy as a result of the ground shaking. It is apparent, however, that the evidence of cracking and extensive coverage of the ground by ejected sand, in the location of the installation, points to widespread liquefaction at the site.

2. The pore pressure transducers behaved incorrectly.

All pore pressure transducers (Fig. 3) require an increase of pressure in the chamber adjacent to the sensing element for the element to respond to pressure. Water has to flow into this space in the instrument for the pressure to increase, because of the volume flexibility of the space, the water in it, and the deflection of the diaphragm. The less volume of admitted water for a given pressure indication, the stiffer the gauge and the faster the response. Stiff systems are therefore desirable. An estimate, based on Figure 3, of the stiffness of the USGS pressure transducers even in a saturated condition, is about 23 kPa/mm^3, which is low. The design of the devices (Fig. 3) includes a fairly large cavity (volume ~3000 mm^3), ahead of the sensing diaphragm plus two open access ports 3 mm in diameter and about 10 mm long. The causes of malfunction of the instrument itself could be: (a) plugging of the access ports by soil of low permeability (clay) or incomplete rupture of the plastic sheath during installation. Either of these eventualities could cause a resistance to the necessary flow of water into the chamber, and this would increase the response time. Plugging of the access ports by the sand or silty sand of the liquefiable layer into which the transducers were placed would not have a substantial effect on their performance, since presumably this material has nearly the same permeability as the surrounding soil through which the water has to pass anyway. (b) The presence of an air bubble or bubbles in the diaphragm chamber, as a result of inadequate drainage of the device prior to installation. This is considered the most likely source of degraded transducer performance, and has been subjected to analysis, as described below.

PORE PRESSURE TRANSDUCER RESPONSE ANALYSIS

For brevity the analysis is confined here to the P5 transducer, since it was the only one functioning in the check tests of 1989, and exhibited the best response (although still poor) in the earthquake of 1987. It was imbedded in the upper part of the silty sand layer 2.9 m below ground surface, with the water table at a depth of 1.2 m below the surface (Holzer et al., 1989). It is assumed that the surrounding soil actually liquefied during the earthquake with a pore pressure increase to the full total stress of 55.3 kPa at the transducer location during the time interval of strong earthquake motion. In the analysis, this is taken to be a step change of pore pressure, since the duration of strong shaking is relatively short compared to the time taken for the transducer to reach the maximum pore pressure. If the transducer is considered to contain an air bubble of radius a, with an internal pressure equal to the static water pressure at the transducer level of 16.7 kPa, then the idealized problem consists of such a spherical bubble imbedded in an infinite soil mass, in which the water pressure increases suddenly from an initial value of 16.7 kPa to a final value of 55.3 kPa. The compressibility of the air bubble is so great that the compressibility characteristics of the transducer are negligible by comparison. Over this pressure range, the bubble radius decreases but not enough to significantly influence the results. The compressibility of the bubble (volume change per unit of pressure increase) is taken to be constant at its initial value; the real nonlinear variation is not significant at this level of analysis. A problem closely approximating this situation has been solved (Gibson, 1963) and the solution is shown in Figure 6, where a product of dimensionless system stiffness ratio (transducer/soil) μ and time factor T ($c_v t/a^2$) forms the horizontal axis, and the pore pressure ratio, expressed dimensionlessly, is given vertically. If the system stiffness ratio is constant (approximately true), then a plot of the field data to the same dimension of logarithmic scale of time can be overlaid on the theoretical solution, and translated in the time direction until it fits one of the curves of stiffness shown. Not surprisingly, in view of the softness of the air bubble, the plotted data are found to fit the $\mu = 0$ (zero stiffness ratio) curve surprisingly closely, if the 10 second time

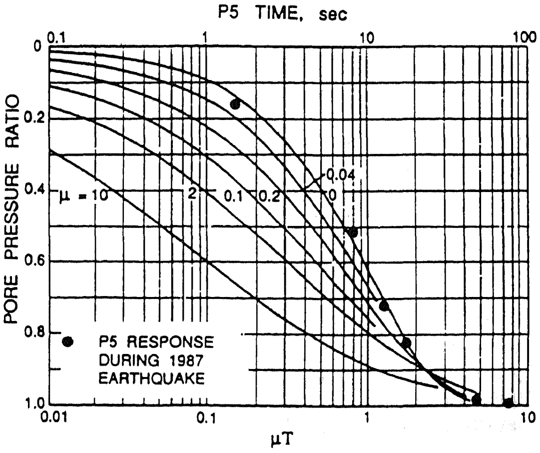

Fig. 6. Comparison of field and theoretical pore pressure ratios for different transducer stiffnesses.

mark is aligned with the $\mu T = 1$ ordinate. For the case of zero stiffness, the product μT reduces to a simpler form. The above matching of real 10 sec time to theoretical dimensionless 1 time leads to an equation relating the soil permeability to the square of the bubble radius. If a variety of bubble radii is selected, a range of permeabilities is produced. For a permeability ranging from 5×10^{-7} to 2×10^{-6} m/sec, equivalent to the silt to fine sand size range, the related bubble size is 5 to 10 mm radius, which can be accommodated in the chamber of the USGS pore pressure device. The correspondence of the field tests with the analytical results both in shape and from a computational point of view lends the analysis some plausibility. Since the other functioning transducers behaved similarly, but with generally different conditions of initial and liquefied water pressures, the analysis may be extended to them. The final question remains; why did P5 behave well in the field verification tests in 1989, while the performance of the other instruments was poor? It is suggested that the air bubble (if bubbles there were) in P5 was smaller than those in P1, P2, and P3, and dissolved, at least partly, in the course of the two years since the earthquake, to leave P5 nearly saturated with water. A calculation of bubble solution rate is possible but requires some chemical measurements of the ground water at the site. These have not been done.

CONCLUSIONS

It is concluded from their response that some of the USGS transducers malfunctioned during the Superstition Hills earthquake of November 24, 1987, in Imperial County, California. In field calibration tests in 1989, P5 was the only transducer out of four which responded consistently similar to a control piezometer during the slow pore pressure variation produced in the field tests. P5 was also the one which recorded liquefaction-level pore-water pressures most rapidly, but still slowly, after the 1987 strong earthquake shaking ended (t=22 sec). Comparison with an analytical solution of pressure transducer response in soil indicates that the presence of a small air bubble in P5 (and also in other transducers in the 1987 earthquake) was the reason for its slow response to the changing ambient pore pressure.

Because of the expense involved in field installations, the rarity of recorded events, and the value of such data in verifying numerical calculational procedures, pore pressure transducers should be installed with great care, and calibrated by the methods developed (Earth Technology Corp., 1991; Hushmand et al., 1991) or other methods after installation and at regular intervals.

ACKNOWLEDGEMENT

This investigation was supported by Grant No. 14-08-0001-G1711 from the United States Geological Survey (USGS). We wish to thank Dr. Tom Holzer and Mr. Ronald Porcella of the USGS for their support in completing this work. Special thanks are also due to Dr. Dennis Ostrom from the Southern California Edison Company for his contribution in performing the popper tests.

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