Thessaloniki-GREECE 2007

4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1251

# INSTRUMENTATION OF THE WILDLIFE LIQUEFACTION ARRAY

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## ABSTRACT

In 2003-04, the Wildlife Liquefaction Array (WLA) was re-instrumented as part of the US National Science Foundation (NSF) Network for Earthquake Engineering Simulation (NEES). This site was selected because of the need for additional field recordings, high liquefaction susceptibility, and a history of moderate and larger sized earthquakes in the region. The new and old sites are instrumented with 8 downhole accelerometers, 4 surface accelerometers, 11 piezometers, and 3 flexible displacement casings and a network of 30 survey monuments for measurement of ground deformation. The downhole accelerometers are at depths of 3 m (above the liquefiable layer), 5.5 m (within the liquefiable layer), 7.5 m (below the layer), and 30 m and 100 m. To allow ease of removal and replacement, pressure transducers at WLA are installed beneath packers installed about 600 mm above the bottom of 50-mm diameter casings with 300-mm long slotted sections and end caps at the base. SPT tests were conducted at 0.9 m intervals with the final SPT at the depth at which the slotted section is installed. No. 3 Monterey sand was placed around the lower part of the casing forming a 0.4-m to 0.6-m thick sand pack. A charge of bentonite chips was poured down the hole to form a 0.6 m to 0.9 m thick seal above the sand. The holes were then grouted the ground surface. Prior to installing pressure transducers, permeability tests were conducted in each casing by filling it with water and timing the fall of the water as it seeped into sediment surrounding the sand pack.

Keywords: earthquakes, field site, field tests, instrumentation, liquefaction, piezometers

## INTRODUCTION

US Geological Survey personnel (Bennett et al., 1984; Youd and Holzer, 1994) initially instrumented the Wildlife site in 1982. The site is located within the Salton Sea Wildlife area, a California State game refuge (33$^{o}$ 05.843’ N, 115$^{o}$ 31.827’ W). The site is approximately 6 km north of Brawley and 160 km east of San Diego, California (Fig. 1). WLA is in a highly active seismic area, where 6 earthquakes in the past 75 years generated observed liquefaction effects at or within 10 km of the instrumented site.

The 1982 instrumentation consisted of one surface and one downhole force-balance accelerometer (FBA) and six electrically transduced piezometers. The downhole FBA, at a depth of 7 m was immediately below a 4-m thick liquefiable layer. Five of the six piezometers were set within the liquefiable layer; the sixth was set at a depth of 12 m in a dense sandy silt layer (Bennett et al., 1984; Youd and Holzer, 1994).

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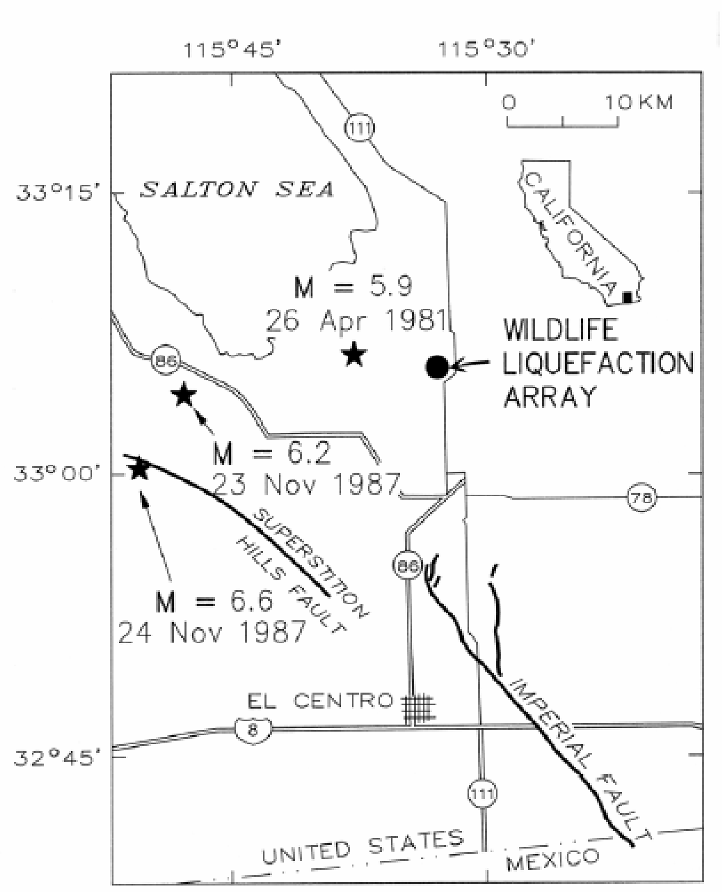


**Figure 1. Locations of Wildlife Liquefaction Array (WLA) and principal earthquakes that have shaken the area since 1980 (after Holzer et al., 1989)**

The 1982 WLA instruments recorded accelerations above and below the liquefied layer, and pore water pressures within that layer as liquefaction developed during the 1987 Superstition Hills earthquake (Holzer et al, 1989). From these records, Youd et al. (2004) note four major lessons learned: (1) soil softening led to lengthening of period of transmitted ground motions; (2) soil softening also led to attenuation of short-period spectral accelerations (< 0.7 sec); (3) amplification of long period motions (> 0.7 sec) generated by Love waves caused high amplitude (> 100 mm) ground oscillations; and (4) these ground oscillations led to large cyclic shear deformations that continued to generate pore water pressure after strong ground shaking ceased.

The important findings from the 1987 records and many subsequent analyses of the recorded data demonstrate the need for additional field records. As a consequence, a project was funded in 2003-2004 by the US National Science Foundation (NSF) Network for Earthquake Engineering Simulation (NEES) to expand and re-instrumented the Wildlife site. The name was also changed to the Wildlife Liquefaction Array (WLA). This site was selected because of the proven liquefaction susceptibility of underlying sediments, the long history of moderate and larger earthquakes in the region, and potential to generate lateral spread.

As part of the project, a new area 65m downriver (northward) from the 1982 site was instrumented with 6 downhole accelerometers, 3 surface accelerometers, 8 piezometers, 5 Slope Indicator casings, 3 flexible casings, and a network of 30 survey benchmarks. The latter instruments and benchmarks are for measurement of ground deformations. Five of the six downhole accelerometers are locked into the bottom of 100-mm diameter PVC casings at depths of 3 m (above the liquefiable layer), 5.5 m (within the liquefiable layer), 7.5 m

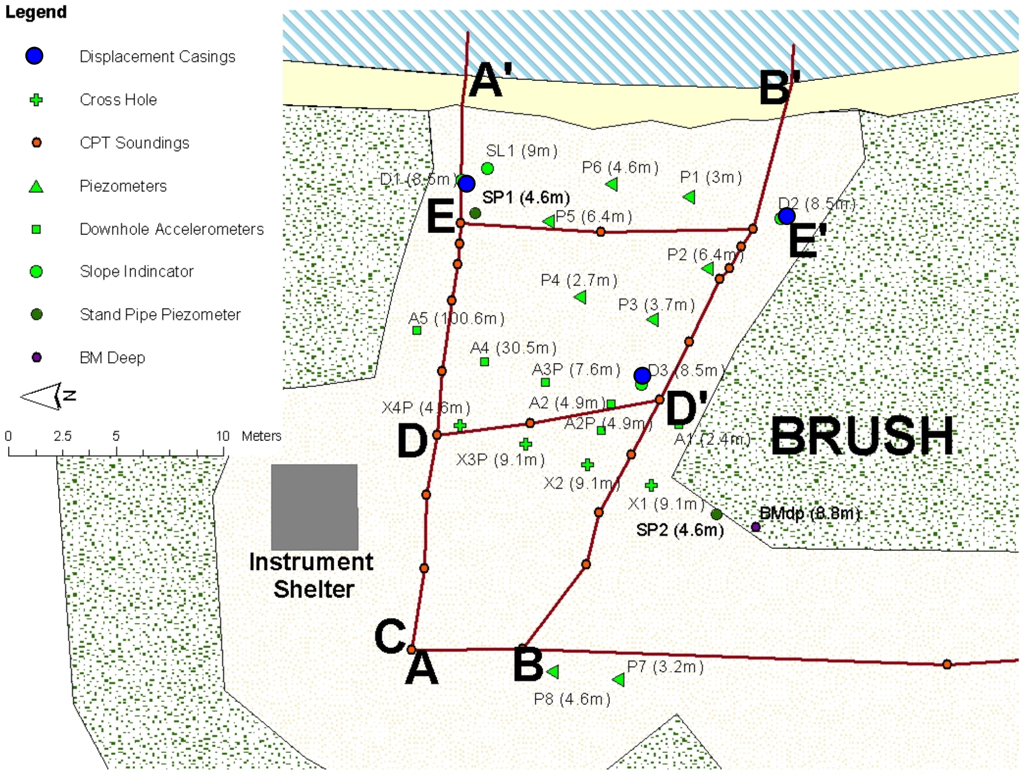


**Figure 2. Map of WLA showing locations of instruments and CPT soundings installed at the site**

(immediately below the layer), 30 m and 100 m. The sixth accelerometer at a depth of 5.5 m (within the liquefiable layer) is locked into a flexible casing to test differences in response between instruments placed in stiff and flexible casings within liquefiable layers. The new site provides a clear area within rather dense tamarisk brush for placement of instruments; the site is also in close proximity to the incised Alamo River, enhancing potential for lateral ground deformation during future earthquakes (Fig. 2).

In addition to the instruments placed in the new area, the old area was re-instrumented with one new surface accelerometer, two downhole accelerometers at depths of 3 m and 7.5 m, three new piezometers, at depths of 3.0 m, 4.5 m and 5.7 m. These instruments replace units that had failed or were obsolete.

The 100-m deep accelerometer at the new site is a Kinemetrics FBA ES-DH (3-component) with a built in compass; all other downhole accelerometers are Kinemetrics Shallow Borehole EpiSensor (SBEPI) 3-component units. The downhole SBEPI units were oriented using a compass temporarily attached to the top of the sealed accelerometer package. This compass was detached after orientation or each SBEPI for reuse in additional installations.

Observations from the accelerometers and pore pressure transducers installed at the site are recorded in a central instrumentation hut using 6-channel 24-bit Quanterra Q330 data loggers (Fig.3). The instrumentation, data acquisition, and communication systems are powered by solar cells and rechargeable batteries at this remote location. The data is streamed continuously, at 200 samples per second, in real-time back to UCSB using the NSF funded High Performance Wireless Research and Education Network (HPWREN) and the Antelope software package. The continuous data is stored for 6-12 months on disk array and then archived to backup tapes. Segmented event data is processed and remains online.

**Figure 3. Photo of WLA with instrument hut and stainless steel boxes over instrument casings**

## GEOTECHNICAL INVESTIGATION

The following subsurface investigations were conducted at the site: 24 CPT soundings were placed at the new site to define sediment stratigraphy beneath the area. 24 boreholes were drilled for placement of casings. SPT tests were conducted in many of these holes and Shelby tube samples were taken from one hole. Split-spoon samples were retrieved from each SPT test for laboratory index testing and soil classification. An OYO suspension logger was lowered down the 100-m deep accelerometer hole (before it was cased) to log P- and S-wave velocities and other geophysical properties. The water table ranges between 1 and 2 m depth, depending on rainfall and depth of water in the river. Results from the investigations are listed on the University of California at Santa Barbara NEES website: (http//:www.nees.ucsb.edu).

CPT tests were preformed in accordance with ASTM D 3441-86 by Thomas Noce, USGS, using a USGS CPT rig. The CPT tips were subtraction types; one of the tips had capability for pore-water pressure measurements; another had capability for seismic velocity measurements. Pore pressure measurements were made in two soundings (CPT32 and CPT40). P- and S-wave velocity measurements were made in two other soundings (CPT31 and CPT38). All of the CPT soundings reached depths of 8 m to 12 m, except those with seismic velocity measurements which were pushed to depths of 18 m.

SPT tests were preformed in accordance with ASTM D 1586-84. Liners, 35-mm internal diameter brass tubes, were inserted into the split-spoon sampler. The extracted liners were capped in the field and transported to the Soil Mechanics Laboratory at Brigham Young University where the samples were extruded, photographed and tested.

The hammer used in the SPT was a Longyear auto safety hammer®, which is characterized by an energy ratio of about 90 percent. This energy ratio is much higher than the average of 60 percent for typical rope and cat-head driven hammers used in the US, the basis for energy correction applied in calculation of the corrected and normalized blow counts, $(N_1)_{60}$. To generate an energy ratio near 60 percent, which also increases the sensitivity of the SPT, the drop height for the SPT tests was reduced from 762 mm to 635 mm by the inclusion of a 127-mm long sleeve in the hammer mechanism. This reduction in drop height led to an equivalent hammer energy ratio very near 60 percent (Youd et al., in press). Thus, all of the SPT were made with a 635 mm drop height, except for several tests in Borehole X2, where the height was varied to measure hammer energy for various drop heights.

Fig. 4 is a cross section showing sediment layers as interpreted from CPT data. Fig. 5 is a cross section showing liquefiable layers determined from application of the procedures of Youd et al. (2001) to CPT and SPT data collected from the site for a 6.5 earthquake with a peak horizontal surface ground acceleration of 0.4 g. An earthquake of that magnitude is likely near the site within several years. These analyses confirm that a 3-m to 3.5-m thick liquefiable layer pervasively underlies the site. An approximately 3-m thick layer of nonliquefiable fine-grained sediment caps the liquefiable layer.

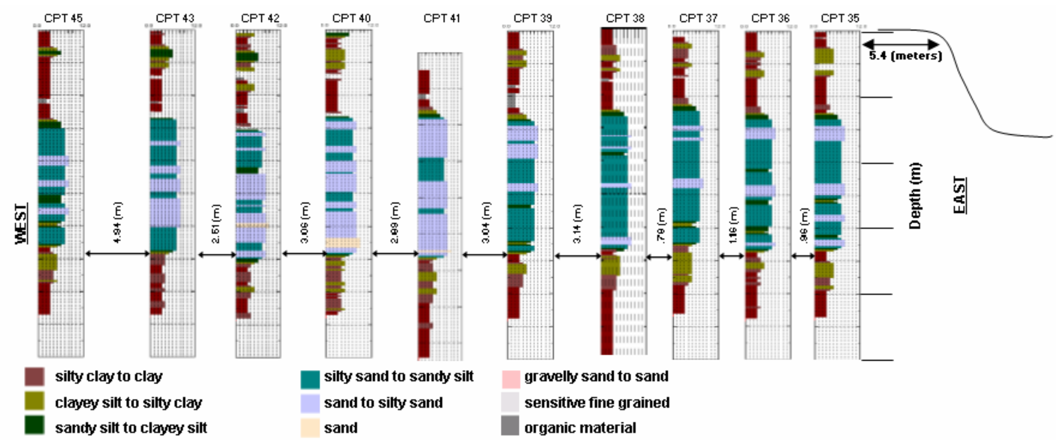


**Figure 4. Cross section showing stratigraphy beneath WLA along section B-B' (Fig. 2); this general stratigraphy is pervasive across a wide area**

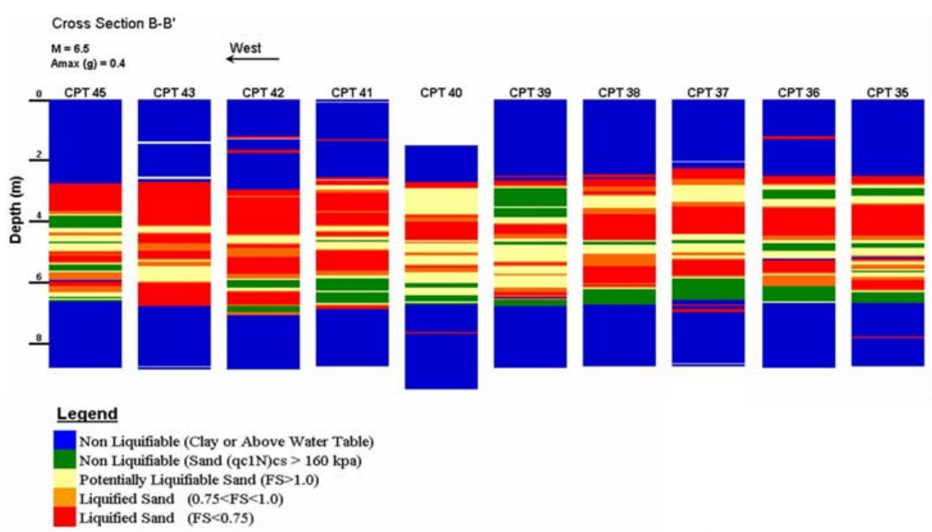


**Figure 5. Cross section showing profiles of liquefiable sediment in cross section B-B' determined from analysis of CPT data using procedure of Youd et al. (2001) for a magnitude 6.5 earthquake and 0.4 g peak horizontal surface ground acceleration**

## ACCELEROMETERS

The downhole accelerometers are installed in casings, capped at the bottom to prevent intrusion of sediment, and filled with clean water to reduce buoyancy. After the casings were pushed down and seated firmly on the bottoms of the boreholes, 2 to 3 kg of Monetery No. 3 sand (rounded particles) was poured down the hole to form an anchor to hold the casing in place. A tremmy pipe was lowered to the top of the sand, and bentonite-cement grout was pumped into the hole, displacing the drilling mud and water, filling the annulus around the casing. The grout has approximately the same stiffness as the surrounding sediment. Later, three-component accelerometers, sealed in a stainless steel tube, were lowered and set on the bottom of each casing, with a centering device around the instrument to assure verticality. The assemblies were then oriented with a compass. After orientation, clean, 5-mm diameter rounded aquarium gravel was poured down the casing to surround and slightly cover the sealed accelerometer tubes, locking them in place. Tests on the aquarium gravel indicate only a small difference between maximum and minimum void ratios. Thus the gravel locking the instruments in the casings, although only slightly compacted, is nearly at maximum density and will deform and settle only slightly during earthquake shaking. The slight angularity of the aquarium gravel also creates beneficial interlocking between particles, aiding the locking of the instruments in place. This locking procedure has proven effective at other instrumented sites strongly shaken by earthquakes.

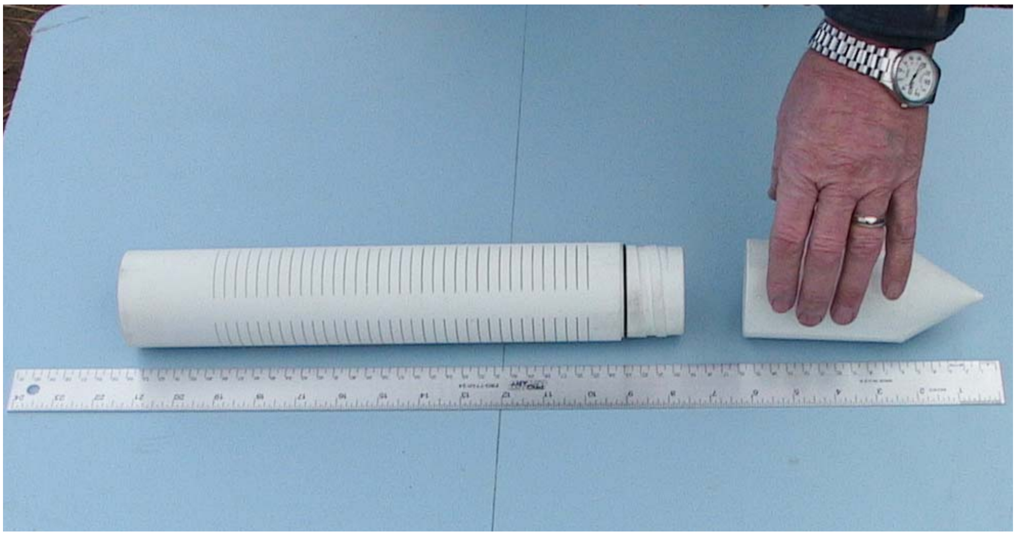

**Figure 6. Section of slotted piezometer casing and pointed end plug installed in at WLA**

## PIEZOMETERS

Past instrumented liquefaction sites have been plagued with piezometer failures necessitating expensive drilling of new hole for replacement piezometers. To make retrieval and replacements easier, the piezometers at WLA are placed in cased holes with a 300-mm long slotted section at the base. The procedure for installation of casings and transducers was as follows: A hole was drilled to the desired depth with a rotary bit and drilling fluid composed of water and Polymer (Polymer breaks down with time leaving clear water in the borehole). In all of the piezometer holes, SPT were conducted in the granular layer at 0.9 m intervals as the hole was drilled. In particular, an SPT was conducted at the depth at which the slotted section of casing was placed. Following the SPT at the slotted-casing depth, the borehole was deepened by 150 mm, cleaned, and prepared for installation of the casing. The casing was assembled by attaching 0.3-m long segment of slotted casing with a solid conical tip to the bottom of the needed length of unslotted casing (Fig. 6). The pointed tip provides a 100-mm long cavity below the slots in the casing. The assembled casing was then lowered down the borehole and the tip pressed firmly into undisturbed sediment at the bottom. No. 3 Monterey sand was then poured down the hole to surround the casing and develop a 0.4-m to 0.6-m thick sand pack. The height of the sand pack was measured by lowering a weighted tape into the hole. Once the required thickness of sand had been placed, a charge of bentonite chips was poured down the hole to cover the sand pack and form a 0.6-m to 0.9-m thick seal. The purpose of the bentonite chips was to provide an impermeable seal immediately above the sand packs which would also resisted erosion when the annuluses above the pack was filled with water-bentonite-cement grout, which was pumped into the borehole though an 18-mm diameter grout pipe.

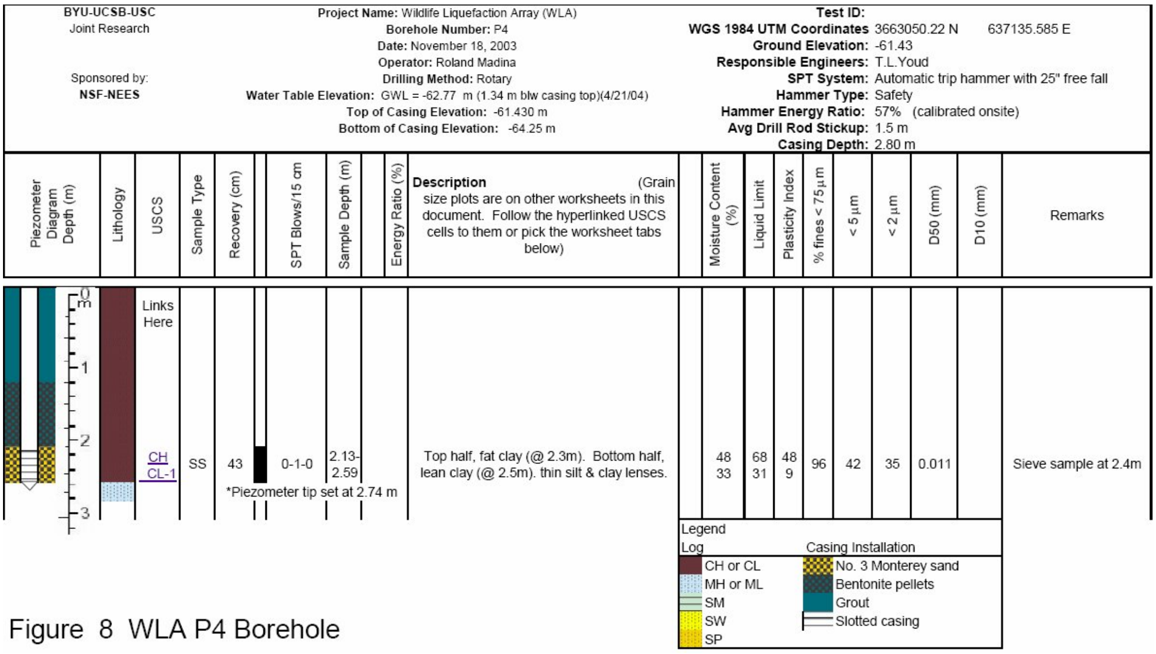


**Figure 7. Log of WLA borehole P4 with diagram at left showing the components in the piezometer installation**

A photograph of a slotted section and end plug is reproduced in Fig. 6. A diagram of an installed casing, sand pack, and bentonite-chip plug and grouted borehole is plotted in left column of the borehole log in Fig. 7. Borehole logs for the cased holes at WLA, along with grain-size and Atterberg limit data from specimens tested in the laboratory, are listed in a section entitled “GIS Compatible Map” on the University of California at Santa Barbara NEES website.

Approximately one year after the casings were placed, pressure transducers were installed in the casings beneath specially designed packers that seal the casing just above the slotted section. The transducers are Special Order 8WD020-I ParoScientific® units with a pressure range of 0 to 300 kPa absolute. The packers, custom designed and manufactured by Robert Steller, allow the electrical cable to pass through a hole in the center of packer with O-rings to provide a watertight seal. A second O-ring, in a slot around the circumference of the packer, compresses against the casing forming a tight seal as a nut on the packer is tightened (Fig8). That nut can be loosened by a special rod and wrench system to remove the packer and transducer when recalibration or replacement is required.

The packers are installed about 600 mm above the cavity in the end plug. The pressure transducer dangles about 150 mm below the packer. Centering spiders prevent the transducers from swaying or impacting the wall of the casing during earthquake shaking. A photograph of an assembled transducer-packer system, being saturated in a bucket of water, is reproduced in Fig. 9. The bucket has a hole in the bottom that attaches to the casing, allowing the packer and transducer to be lowered through the bucket and into the casing while remaining saturated. Because the slotted casing prevents direct contact between the transducer with the soil, there is no need for the porous stone end-caps supplied with the transducers; these caps were removed prior to installation to eliminate any possibility of trapping air in the porous filter.

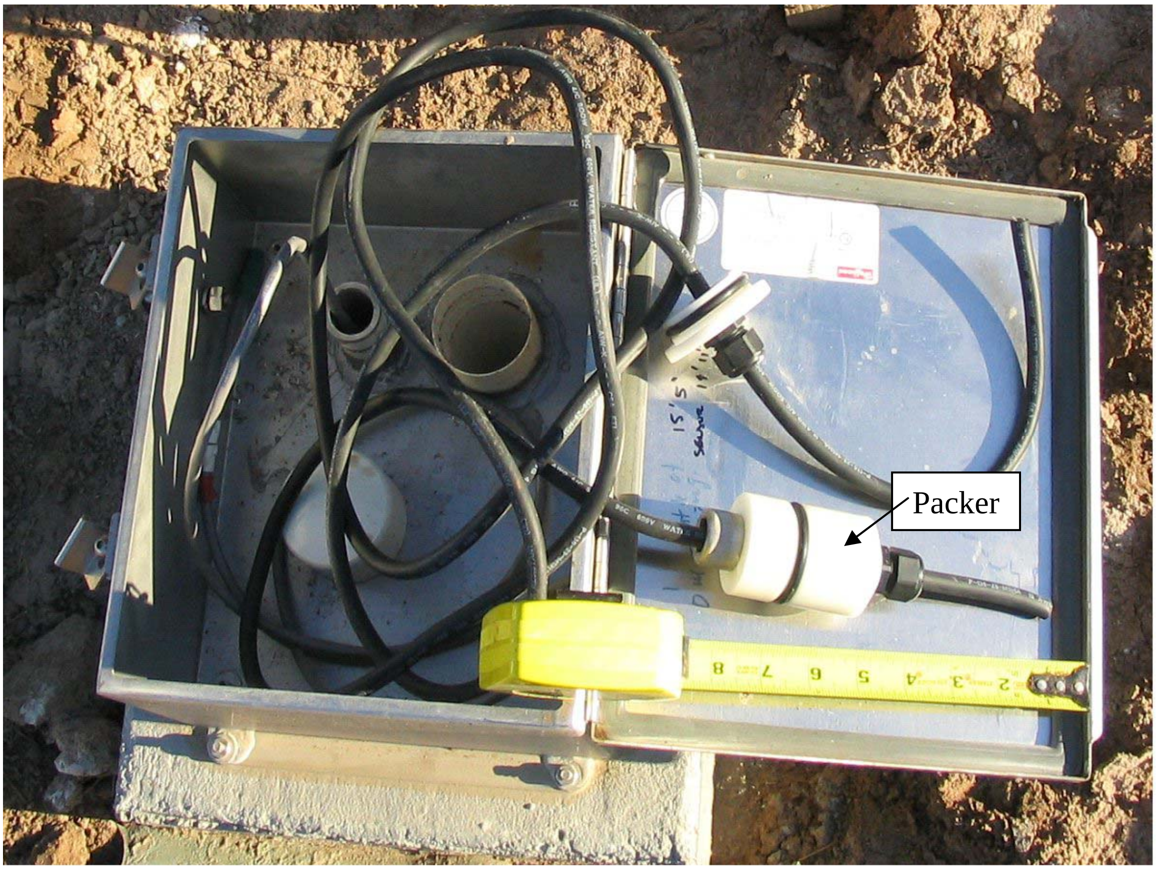


**Figure 8. Photograph of packer (above measuring tape) used to seal pore-pressure transducer (not attached) and cable in piezometer casing; photograph also shows fixtures at top of casing, including concrete pad, stainless steel protective box, piezometer casing, and electrical conduit (small casing through bottom of box)**

Field permeability tests were conducted in each of the piezometer casings except P-7, which contained a few hundred millimeters of sediment that could not be flushed at the time of testing. This sediment was flushed out before the transducer was placed. Also, permeability tests were not conducted in the three piezometer casing placed at the old site. For the permeability tests, the distance from the top of the casing to the static water level was measured with a tape measure. A pressure transducer was then lowered to a position about 500 mm above the bottom of the casing. The casing was filled to overflowing with clean water; the water level was then allowed to fall freely as water seeped into surrounding sediment. Water-pressures measured at the transducer level were recorded for 15 min or longer for each test.

The following equation was used to calculate the hydraulic conductivity, k (Cedergren, 1989):

$$k(cm/s) = \frac{r^2}{2 * L * (t_2 - t_1)} * \ln\left(\frac{L}{R}\right) * \ln\left(\frac{H_1}{H_2}\right) * 100 \qquad \text{Eq (1)}$$

where r = radius of the casing, R = radius of the sand pack, L = length of the sand pack, $t_1$ and $t_2$ = times at the beginning and end of the time interval, respectively, and $H_1$ and $H_2$ = water heights above the static water level corresponding to $t_1$ and $t_2$. Calculations of hydraulic conductivity were made for both 15 sec and 60 sec time intervals across the entire time record. A permeability versus time chart was plotted for each test. The chart from piezometer P-4 is reproduced in Fig. 10. Plots for all tests are contained in files posted on the UCSB NEES website.

Theoretically, the calculated hydraulic conductivities should be constant with time and height of water column or head, but the plots indicate decreasing hydraulic conductivity with decreasing head. At the end of the tests, when head differences were small (millimeter range), the calculated hydraulic conductivities became somewhat erratic. Cedergren (1989) recognized these problems and suggests that only the first third of the time record should be used in the calculation. Using this suggestion, the plots provide hydraulic conductivity values consistent with the general accuracy of field permeability tests. As a further check, the calculated hydraulic conductivities were compared with tabulated hydraulic conductivity values for various soil textures. For example, the calculated hydraulic conductivity for WLA P4 (Fig. 10) is about $2x10^{-3}$ cm/sec, a value is typical of "very fine sands, organic and inorganic silts, and mixtures of sand silt an clay, (Terzaghi and Peck, 1967); this is the type of sediment (ML) into which the slotted section of casing in P-4 was placed.

## LATERAL GROUND DEFORMATION

Slope Indicator (SI) casings, 50 mm diameter, were installed primarily for future cross-hole shear wave velocity tests, but they will also serve casings for measurement of permanent ground displacement following earthquakes. Five more rigid Slope Indicator® and three more flexible drain-pipe casings were set. The bottoms of the casings are set below the liquefiable layer at 10 m depth. A linear array of four SI casings, spaced 3 m apart parallel to the downhole accelerometer array, were placed for measurement of shear wave velocities at that locality, including velocities through the liquefiable layer. A fifth SI casing was installed near the river bank specifically to measure permanent ground displacement at that locality after a future earthquake (Fig. 2). The following procedure was used to install the casings. Boreholes were drilled to a 10 m depth using rotary procedures and bentonitic drilling mud. SPT were conducted in two of the boreholes (X1, X2) specifically to measure hammer energies transmitted to the drill rod. After the holes were drilled and cleaned, casings with bottom-caps, were lowered to the bottoms of the boreholes. An approximate 0.6-m thick pack of Monterey No. 3 sand was then installed around the bottom of each casing to anchor then to the surrounding sediment. Bentonite-cement grout was then pumped down the annulus between the casing and surrounding sediment to couple the casings to the ground.

The three more-flexible casings (Fig. 11) were near the river bank on either side of the site and near the downhole accelerometer array (D1, D2 and D3, Fig. 2). The greater flexibility of these casings, compared to the SI, should allow these casing to deform more faithfully with movements in the softened sediment than the more rigid SI casings. The flexible casings were fabricated from 100-mm diameter, 10-m long sections of Corex® drain pipe with non-water tight end caps. To retain a generally straight alignment during installation of the casing, a 10-m long, 76-mm diameter section of PVC pipe was inserted into the flexible casing and then a 10-m long section of drill rod inserted into the PVC casing. The entire assembly was then raised to the vertical with a winch and lowered to the bottom of a pre-drilled borehole. The PVC casing and drill rod were sufficiently stiff and heavy to keep the casing straight and in place while bentonite-cement grout was pumped through a tremmy pipe into the annulus around the casing. The grout was allowed to set before the PVC casing and drill rod were extracted. The casing was later surveyed with a downhole electronic positioning instrument to record the as-installed shape of the casing. The results of these surveys are on file with the site manager (Jamison Steidl) at UCSB.

## SUMMARY

Because of the successful recording of pore water pressures within and ground motions above and below a layer that liquefied during the 1987 Superstition Hills, California earthquake, the Wildlife

Liquefaction Array (WLA) was expanded and reinstrumented as a NSF-NEES site during 2003-2004. The instrumentation includes:

**Figure 9. Pressure transducer, sensing element upward without filter, being saturated in bucket of water in preparation for installing the assembly in casing below the bucket**

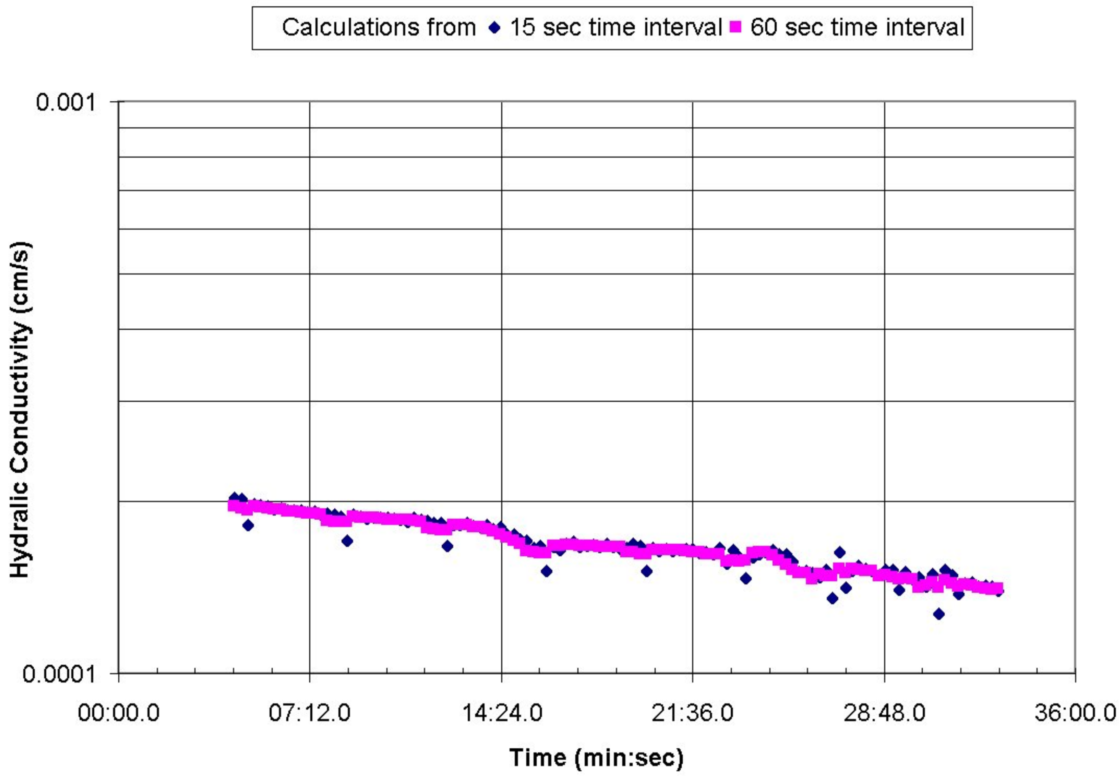


**Figure 10. Calculated hydraulic conductivity from test in piezometer casing P4 at WLA**

**Figure 11. Demonstration of flexibility of corrugated drain pipe installed for future survey of lateral ground displacement versus depth through liquefiable layer**

1. Accelerometers: Six downhole accelerometers are installed in a new area as follows: Five are locked into bottoms of 100-mm diameter PVC casings at depths of 3 m (above the liquefiable layer), 5.5 m (within the liquefiable layer), 7.5 m (immediately below the layer), 30 m and 100 m. The sixth accelerometer, at a depth of 5.5 m (within the liquefiable layer), is locked into a flexible casing to test differences in the responses between instruments placed in stiff and flexible casings in liquefiable layers. Also, two new downhole accelerometers are installed at the old (1982) site at depths of 3 m (above the liquefiable layer) and 7.5 m (below the liquefiable layer). An array of three surface accelerometers are installed on the new area to provide data on variances of ground motions across the site, beginning at the bank of the incised Alamo River and extending for 100 m westward from that feature. A new surface accelerometer was also placed at the old site.
2. Piezometers: Eight piezometers are installed in the new area and three new piezometers are installed in the 1982 site. These piezometers are at depths ranging from 2.9 m (top of liquefiable layer) to 7.0 m (base of liquefied layer). Because of failures of piezometers at previous sites and the high cost of replacement, a new installation system was developed for WLA: The piezometers consist of 50-mm diameter PVC casing with a 300-mm-long slotted section at the base. A sand-pack surrounds the slotted casing with a bentonite seal above. Pore-pressure transducers are suspended on their electrical cables beneath specially designed packers, with stabilizers to prevent swaying during earthquake shaking within the casings. These transducers care easily removable if recalibration or replacement should be required.
3. Ground displacement: Five 50-mm diameter Slope-Indicator casings (PVC) and three more-flexible 100-mm diameter drain-pipe casings were installed and surveyed as a reference for determining ground displacement versus depth following future earthquakes. An array of 30 benchmarks was also installed and precisely surveyed, including GPS measurements, as reference points from which vectors of surface ground displacement can be determined following future earthquakes.

4. With this array of instrumentation, valuable records of ground motions, pore-water pressures, and ground displacements will be recorded and freely made available following future earthquakes.

## ACKNOWLEDGEMENTS

Funding for this project was provided by NSF-NEES Grant No. . Drilling for the project was provided by Pitcher Drilling Co., Inc., Tim Boyd, Supervisor, and Roland Molina, Driller.

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