2.12 INSTRUMENTAL ARRAYS FOR MONITORING OF LIQUEFACTION BEHAVIOR

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ABSTRACT

Instrumented sites provide essential information for understanding and modeling of ground response, pore pressure rise, and ground deformation. For example, significant new lessons were learned from responses at the Wildlife Liquefaction Array (WLA) including (1) soil softening due to pore pressure rise 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) occurred due to liquefaction-induced ground oscillation; and (4) ground oscillation generated a continued rise of pore water pressures after strong ground shaking ceased.

A new and expanded instrumented liquefaction array was developed 70 m downstream from the old WLA site as part of the George E. Brown Network for Earthquake Engineering Simulation (NEES). The new site is equipped with five downhole accelerometers, three surface accelerometers, eight piezometers and three flexible casings and a network of bench marks. The flexible casings and bench marks are for measurement of permanent ground deformation.

The Garner Valley Downhole Array (GVDA), which was enhanced for the NEES project is also underlain by potentially liquefiable layers. At that site, accelerometers have been placed above and below the liquefiable layers and four new piezometers have been placed within the liquefiable layers.

INTRODUCTION[1]

Liquefaction of subsurface sediment may lead to two possible hazards: (1) unacceptably large ground deformations or ground failure and (2) modification of seismic waves propagating through the liquefying layer. The latter modifications affect ground motions with which bridges, buildings, pipelines and other constructed works must withstand. To better understand and model these liquefaction-induced hazards, records from instrumented sites are needed to provide a database of actual pore pressure and ground responses and ground deformation.

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[1]Authors note: Much of the text and figures for this paper are adapted from previous papers describing the WLA and GVDA sites [1] [2].

In this paper, we evaluate and show the benefit of instrumental records from the Wildlife Liquefaction Array (WLA) that was installed by the lead author and his colleagues at the U.S. Geological Survey (USGS) in 1982 [3]. Those instruments recorded responses during two significant earthquakes in 1987: the November 23 Elmore Ranch event (M_w = 6.2; a_{max} = 0.16*g*) which produced no significant rise of pore water pressure; and the November 24 Superstition Hills event (M_w = 6.6; a_{max} = 0.21*g*) which generated widespread liquefaction at the site.

Because of the wealth of data gained and lessons learned from these responses, WLA was re-instrumented at a locality about 70 m downstream from the 1982 site as part of the George E. Brown Network for Earthquake Engineering Simulation (NEES) project. The new locality was chosen because of failure of piezometers at the old site, disturbance that occurred during post earthquake investigations, and increased potential for ground deformation at the new site. The new site is located adjacent to a steep bank of the Alamo River that flows through the area.

LESSONS LEARNED FROM THE WILDLIFE LIQUEFACTION ARRAY

The primary purpose for instrumenting the Wildlife Liquefaction Array (WLA) in 1982 was to record ground motions above and below a liquefiable layer and pore water pressures within the liquefiable layer during earthquake shaking. That goal was achieved during the 1987 Elmore Ranch and Superstition Hills earthquakes. Figure 1 shows the general location of WLA (Wildlife liquefaction array) and epicenters and magnitudes of the three important earthquakes that have shaken the site. The magnitude 5.9 event is the 1981 Westmorland earthquake that generated numerous sand boils at the WLA site. Because of this liquefaction episode, WLA was selected for instrumentation in 1982. The magnitude 6.2 and 6.6 events are the 1987 Elmore Ranch and Superstition Hills events, respectively, that triggered the installed instruments. Figure 2 shows the general stratigraphy at WLA and the locations of instruments placed in 1982. As noted, a forced balance accelerometer (FBA) was installed at ground surface in an instrument shelter while a companion downhole FBA was wedged into the bottom of a casing immediately below the liquefiable layer. Five electronically transduced piezometers were installed in the liquefiable layer. More details on the site and the instrumentation are given in Bennett et al. [3] and Youd and Holzer [3].

Ground Motions and Pore Pressure Response

Acceleration and pore-pressure records from the 1987 Superstition Hills earthquake are reproduced in Figure 3. These records contain accelerations recorded above and below the liquefiable layer and pore pressures recorded within that layer. Some notable aspects of the records are as follows:

- A sharp rise in pore pressures began with the arrival of the peak acceleration pulse (a_{max} = 0.21*g*) that propagated through the site 13.6 sec after instrumental triggering.
- Discordance developed between incoming acceleration pulses recorded by the downhole FBA and those measured by the surface FBA as pore water pressures developed. Beyond about 15 sec, the predominant period of the surface motions lengthened relative to the downhole record and coherence between downhole and surface motions degraded.

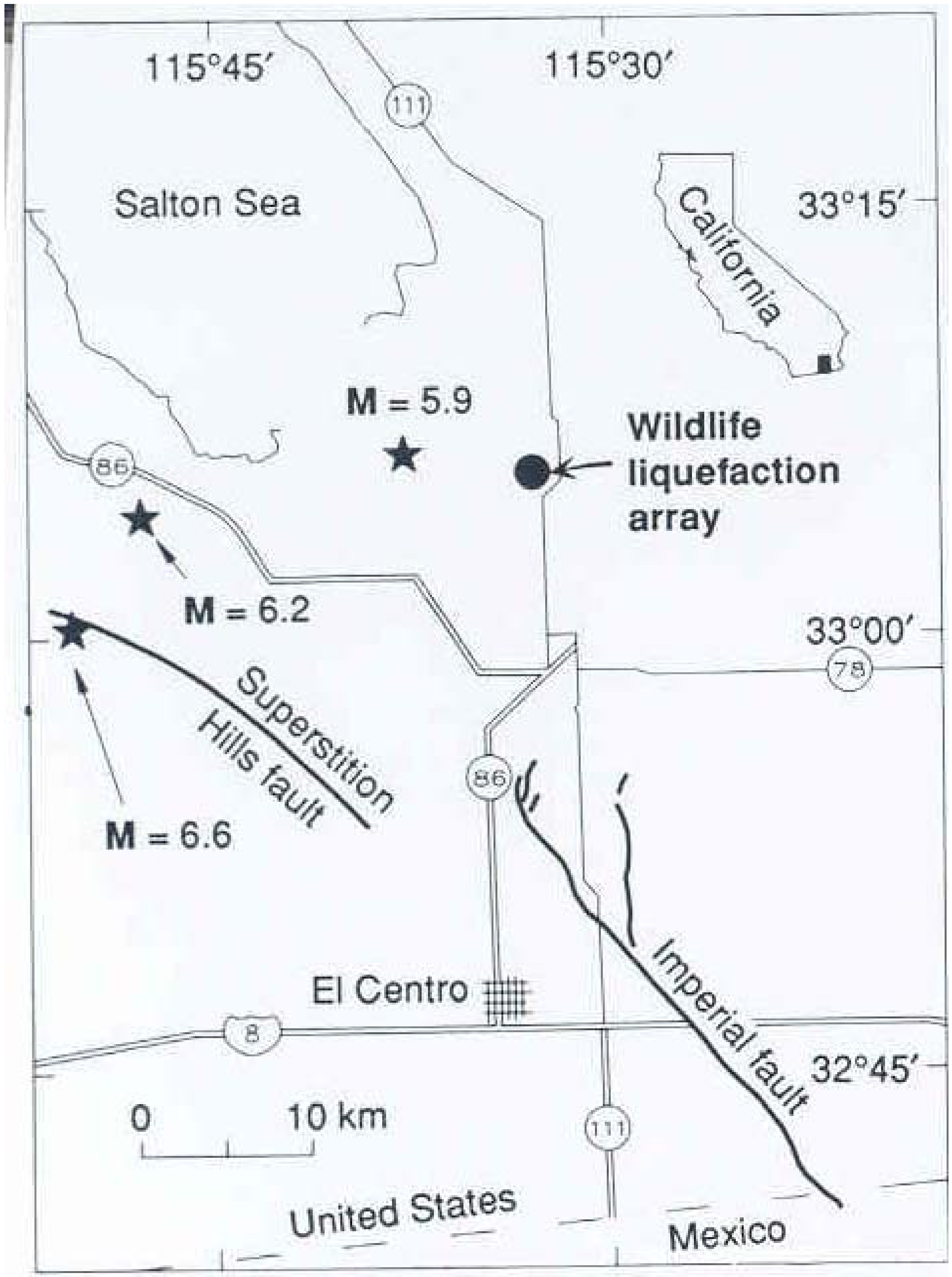


Figure 1. **Map of Imperial Valley with marked location of WLA site and epicenters of the following earthquakes: 1981 Westmorland (M = 5.9), 1987 Elmore Ranch (M_w = 6.2) and 1987 Superstition Hills (M_w = 6.6) [5].**

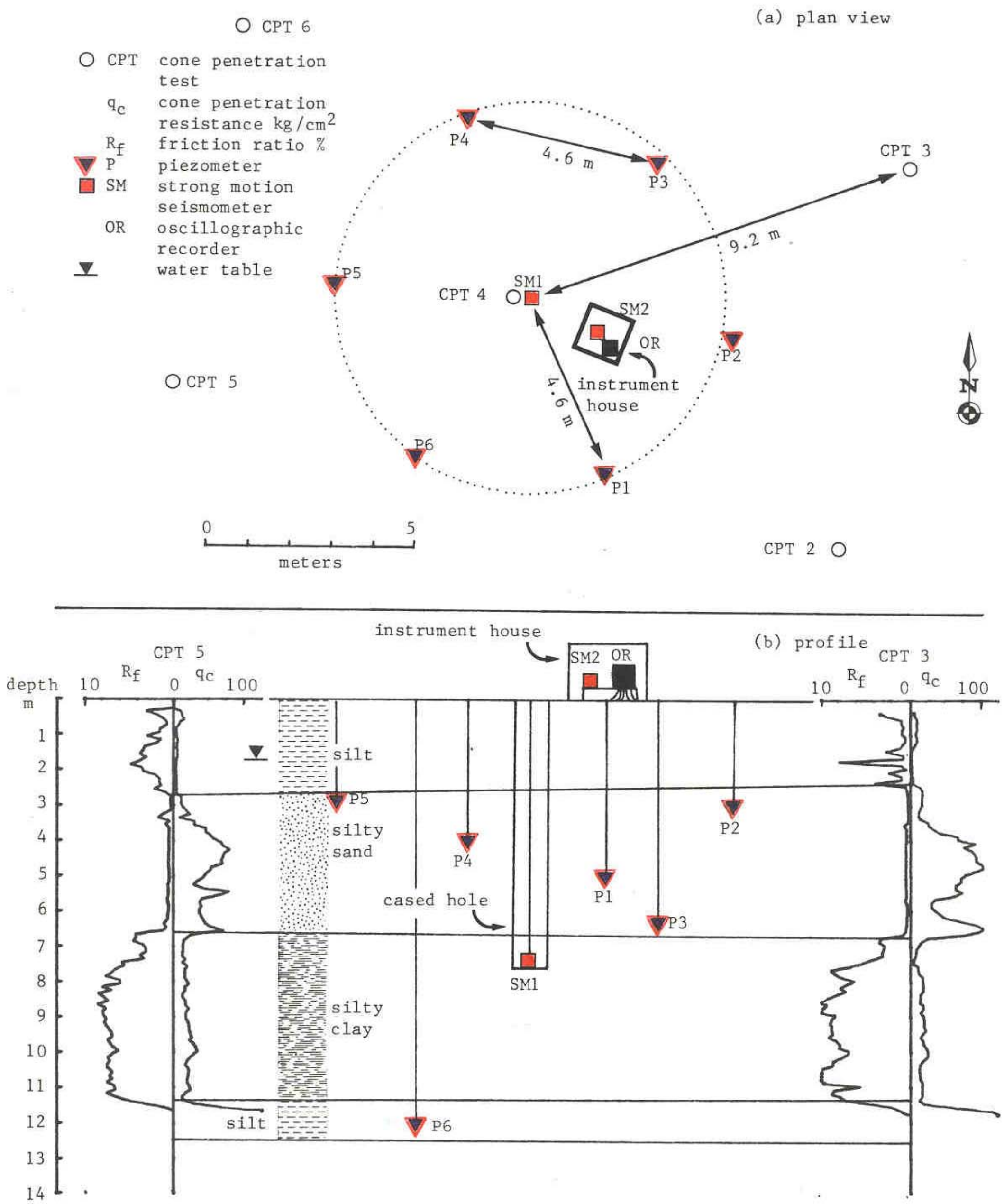


Figure 2. **Site plan (a) and cross section (b) showing sediment layers and 1982 instrument locations at WLA [3].**

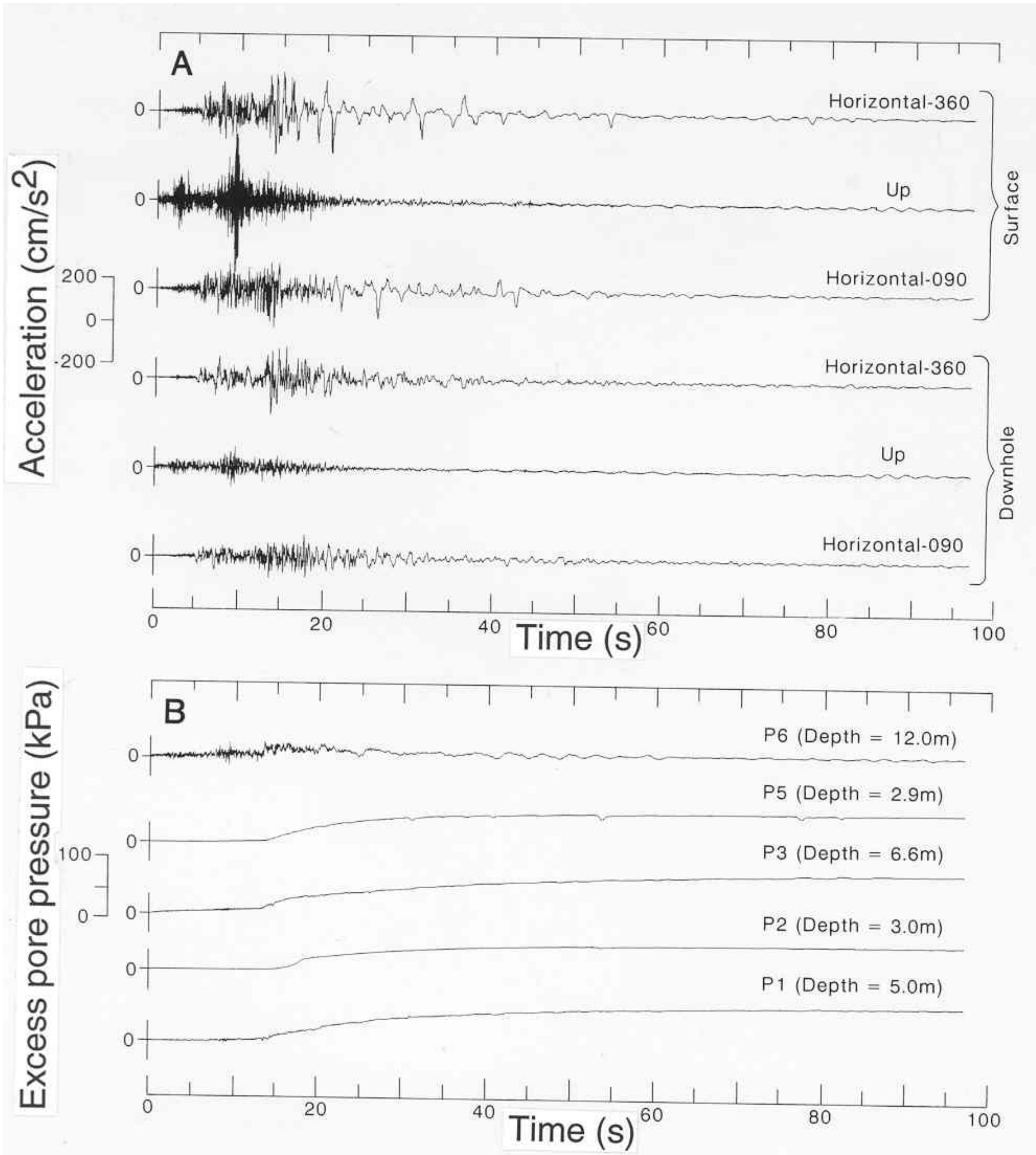


Figure 3. **Instrumental recording from (A) WLA accelerometers and (B) WLA piezometers during November 24, 1987 Superstition Hills earthquake (M = 6.6) [14].**

- Beyond 20 sec, the surface motions were dominated by long period oscillations with periodic sharp acceleration spikes indicating abrupt decceleration and reversal of direction of the ground movement. These acceleration spikes were caused by dilatent responses within the liquefied layer. Although dilatency of moderately dense sediments during static shear is well understood and has been demonstrated in laboratory tests, the responses from WLA were the first recordings of dilatent behavior due to liquefaction and ground deformation at a liquefied field site.
- The continued rise of pore pressures after cessation of strong ground shaking had not been seen before and led to considerable controversy and discussion of this issue [4][5][6]. This unexpected delay in the rise of pore pressures led to one of the most important lessons learned from the 1987 records.

The continued rise of pore pressure after the cessation of strong ground shaking was due to cyclic shear deformation within the liquefying layer caused by ground oscillation. These oscillations not only continued after cessation of strong ground shaking but increased in amplitude during the interval between 15 sec and 40 sec. The increase of oscillation amplitude corresponds with the interval of most rapid rise of pore pressure (Figure 4). Because cyclic shear deformation is the primary generator of soil compaction under drained conditions [7] and the primary generator of pore pressures under undrained conditions [8], the continued rise of pore pressure should not have been surprising but expected based on the fundamental principles.

Spectral Response

To analyze the influence of liquefaction on ground motions transmitted through liquefying or liquefied layers, Youd and Carter [9] compared ground motions and response spectra determined from motions recorded at ground surface (termed actual motions and spectra) with motions and spectra predicted from acceleration recorded by instruments installed immediately below the liquefiable layer (termed predicted motions and spectra). To generate the predicted motions and spectra, the motions recorded beneath the liquefiable layer were propagated upward to the ground surface using the program PROSHAKE (a modification of SHAKE for use in a Windows environment). In this analysis, Youd and Carter used shear-wave velocities measured before the earthquakes with no modulus reduction to account for soil softening due to increased pore pressure. Thus, the motions predicted at ground surface are those that should have occurred in the absence of increased pore pressures and liquefaction.

Elastic acceleration response spectra, calculated from both the actual and predicted ground motions, are plotted and compared in Figure 5. Large predicted spectral peaks, at periods between 0.2 sec and 0.5 sec, are absent in the actual spectra, indicating that incoming motions that would have generated these peaks did not propagate through the softened layer. Conversely, at periods greater than 1.0 sec, the actual spectra are larger than the predicted spectra, indicating amplification of motions in that period range due to ground oscillation. Although liquefaction-induced reduction of ground response for periods less than 0.5 sec is suggested in the 2000 NEHRP building code [10], the recorded responses from WLA and other instrumented sites confirm this phenomenon [9].

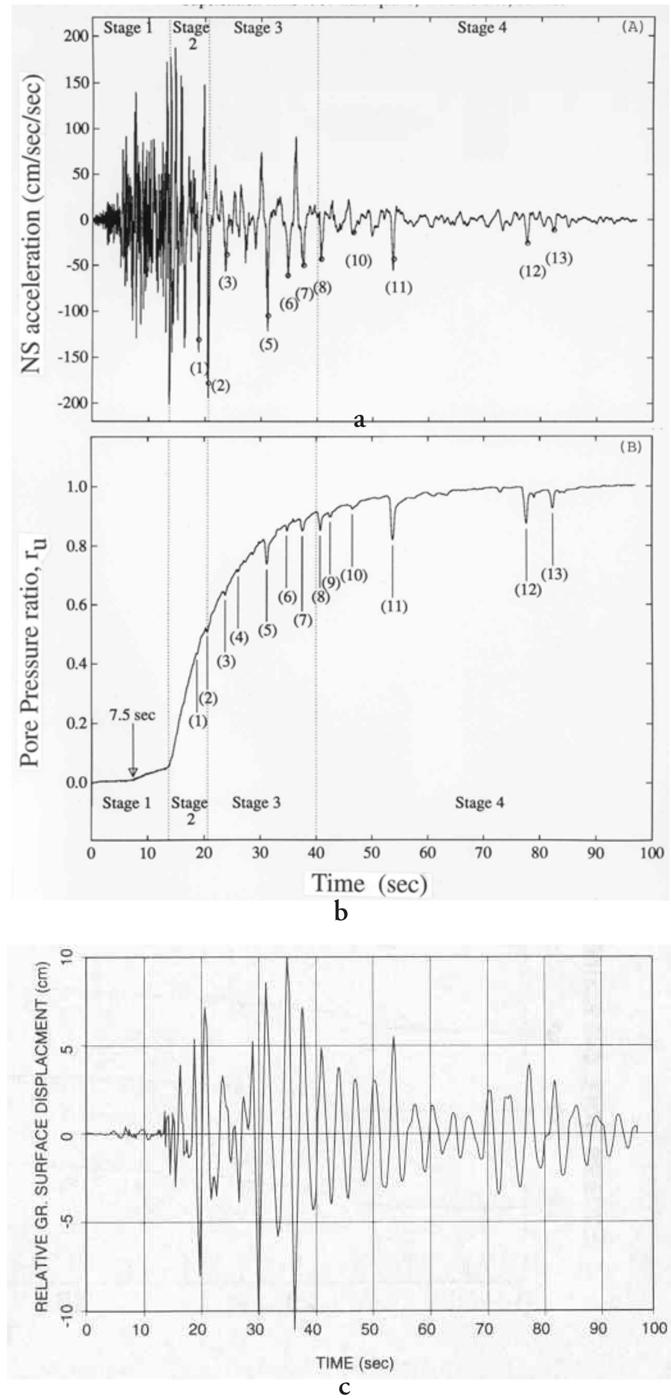
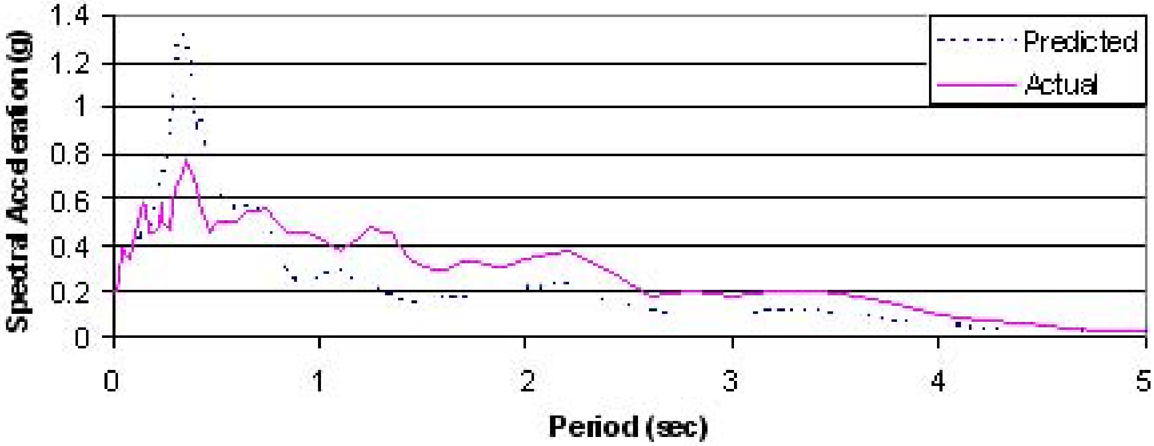


Figure 4. **(a) acceleration at ground surface; (b) pore water pressure ratio, r_u, from Piezometer 5; and (c) calculated differential ground displacement between accelerometers showing that major increase of pore pressure occurred after strong ground shaking ceased but large ground oscillations continued (plots from: Thilkartne and Vucetic [14], Zegahal and Elgamal [15], Youd and Holzer [4].**

(a)



(b)

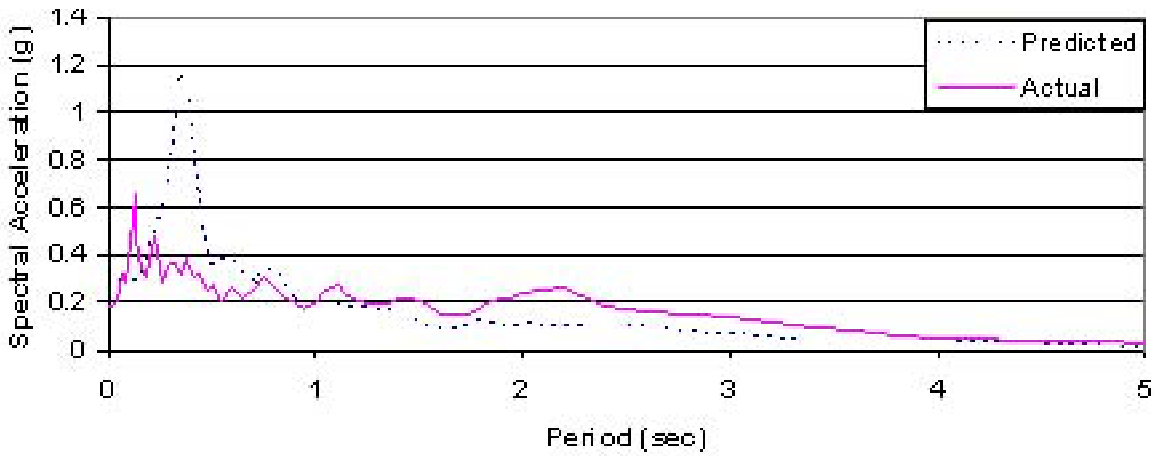


Figure 5. Predicted and actual 5 % damped elastic response spectra for WLA during 1987 Superstition Hills earthquake (M=6.6) (after [9]); (a) North-South motions and (b) East-West motions.

These observations and lessons learned from pore pressure and acceleration records recorded at WLA during the 1987 earthquakes demonstrate the great value of instrumented sites. More records are needed, however, to provide an adequate database for development and verification of empirical and analytical procedures for prediction of pore pressure generation, ground response, and ground deformation at liquefied sites.

RE-INTRUMENTATION OF WLA

The new WLA is located near the west bank of the Alamo River, 13 km due north of Brawley, California, and 160 km due east of San Diego (Figure 1). The site is within the Imperial Wildlife Area, a California State game refuge, where the installed instruments are secure against man-made disturbance.

Because the piezometers installed in 1982 failed some time after the 1987 earthquakes and the site was disturbed by post-earthquake subsurface investigations, we developed a new site for the NEES project at a locality 65 m down river (northward) from the old site. The localities of both the old and new sites are marked on Figure 6, and a scaled map of the sites is reproduced in Figure 7. Also noted on the map are localities of 24 CPT soundings performed by USGS during April 2003 and previous soundings placed at the old site. These soundings define sediment stratigraphy. Figure 8 is a stratigraphic cross section beneath line B-B' (new site) developed from the CPT data. This cross section delineates a continuous silty sand layer between depths of 2.5 m and 7.0 m sandwiched between overlying and underlying silty clay layers. Figure 8 also indicates the position of the free face of the river bank. Figure 9 is a view of the steep river bank and the USGS CPT rig working at the site.

To test the liquefaction susceptibility of sediments beneath WLA, we applied the procedure for evaluating liquefaction resistance published by Youd et al. [11] to the CPT data from line B-B' using a magnitude 6.5 earthquake and peak ground acceleration (a_{max}) of 0.4*g*. This magnitude and peak acceleration is a likely scenario. The results of the liquefaction analysis (Figure 10) indicate that much of the granular layer would liquefy during such an earthquake. With the nearness of the incised river channel, liquefaction to this extent would likely lead to ground deformation and lateral spread toward the open face.

The symbols marked on Figure 11 indicate locations of instruments placed at the site. The purposes of the downhole and surface FBA arrays are to monitor ground response during future earthquakes. The piezometers are to monitor pore water pressure changes generated in response to ground shaking and ground deformation. The piezometers are field-proven ParoScientific devices placed in sealed into 50-mm diameter casings placed at various depths. The piezometers can be readily withdrawn and reset for calibration, maintenance or replacement purposes. The lateral displacement casings are flexible pipes that were surveyed with a positioning sensor after installation and will be resurveyed after significant earthquake shaking. The intent of these casings is to detect depths and amounts of permanent ground deformation, including thicknesses and distribution of shear zones.

The downhole accelerometer array consists of four Kinematics Shallow Episensor FBA's placed at 2.4 m (immediately above the liquefiable layer); 4.8 m (within the liquefiable layer); 7.0 m (immediately below the liquefiable layer); and 30 m. A Kinemetrics Hyposensor FBA was placed in the deep hole at 97 meters. The deep hole was also logged with geophysical probes to a depth of 100 m prior to installing the FBA. P- and S-wave velocity logs from that survey are plotted on Figure 12. Bedrock strata are more than

Figure 6. Aerial view of WLS showing localities of old and new sites.

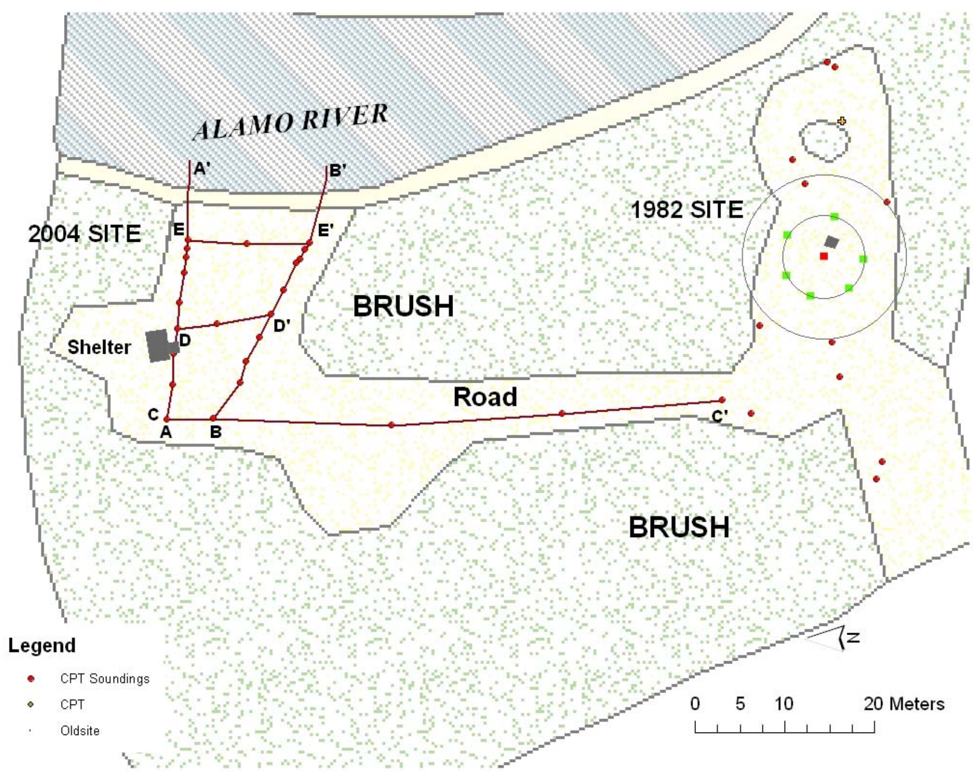


Figure 7. Map of 1982 and 2004 WLA sites showing general configurations and localities of CPT soundings.

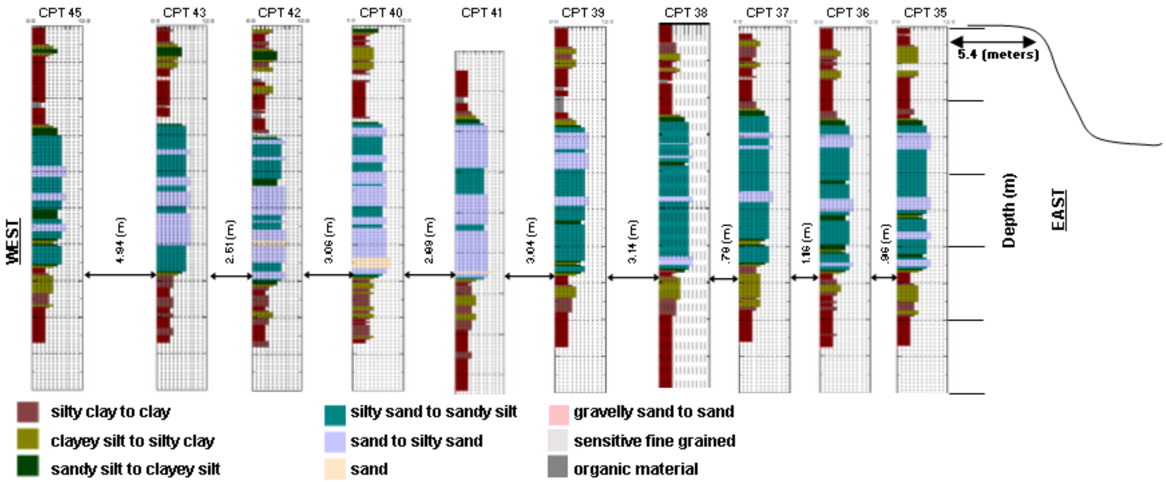


Figure 8. Stratigraphic cross section along line B-B' the 2004 WLA site; sediment units are interpreted from CPT tests conducted and analyzed by USGS personnel.

Figure 9. View of incised river channel at 2004 WLA site with USGS truck conducting a CPT test.

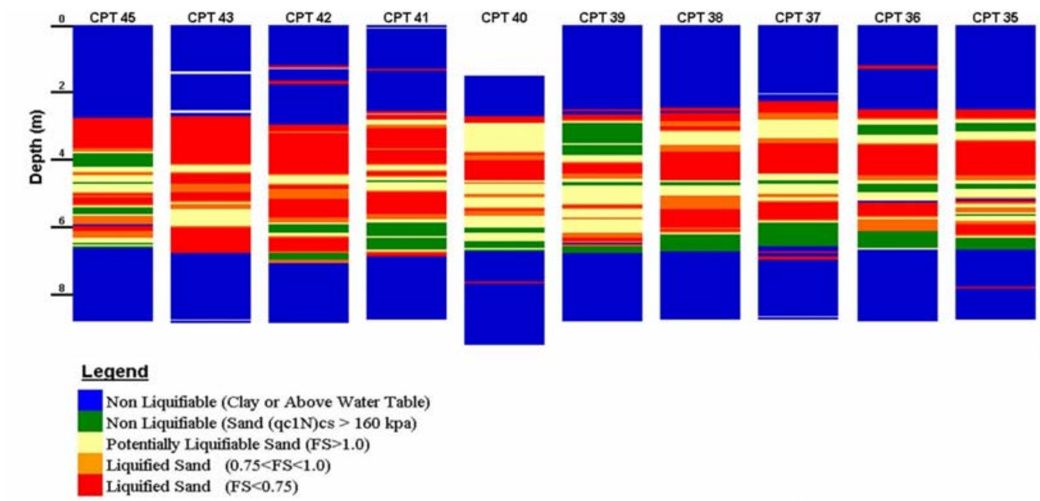


Figure 10. Interpretative cross section B-B' at WLA showing layers that are and are not predicted to liquefy during a magnitude 6.5 earthquake generating 0.4*g* peak horizontal acceleration at ground surface

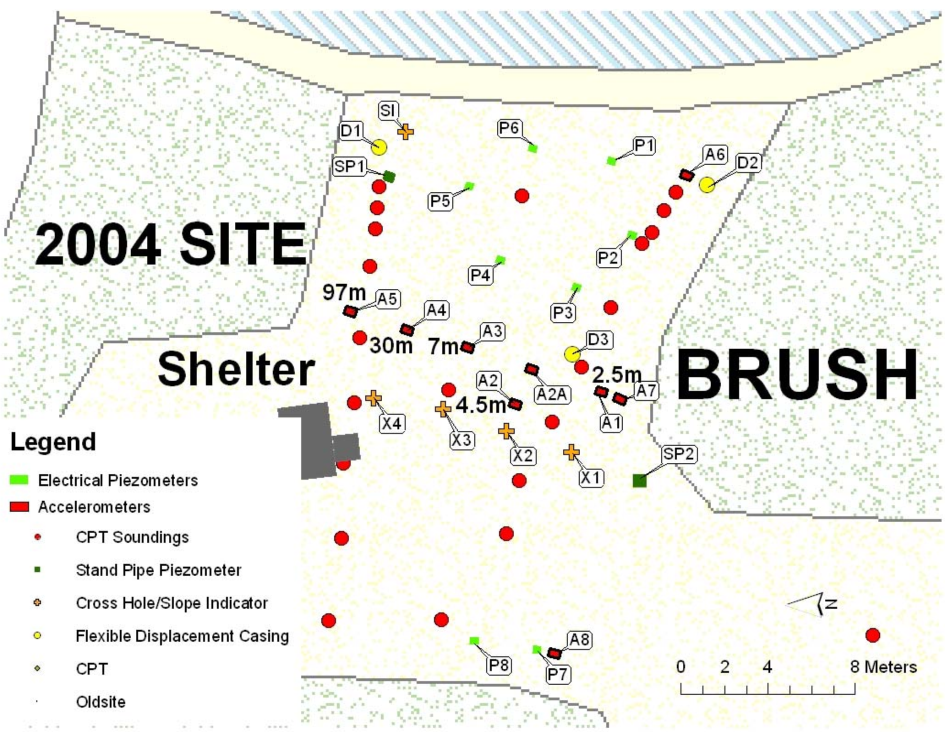


Figure 11. Map of 2004 WLA site with marked localities of installed instruments.

1000 m deep beneath WLA; no attempt was made to place an instrument at that depth. The California Department of Transportation, however, has placed a FBA in bedrock beneath the Meloland overpass, a locality about 30 km south of WLA. In the event of a large earthquake, estimates of bedrock motions at WLA can be made from the Meloland records.

In addition to the downhole instruments, an array of three surface FBA's was installed with one FBA near the river bank, a second within the downhole array 15 m west of the river bank, and a third 26 m west of the river bank. These instruments are mounted on small, approximately 0.5 m^2, concrete pads anchored into the underlying soil. A Kinemetrics/BRTT Antelope data acquisition system, installed in a small instrumentation structure erected at the site, records the data from all of the instruments. The recorded data is both stored on site and streamed in real time by radio link to the University of California at Santa Barbara (UCSB) and to the NEES grid, making the data accessible and readily available to interested individuals.

GVDA

The Garner Valley Downhole Array (GVDA) is located in southern California at a latitude of 33° 40.127' north, and a longitude of 116° 40.427' west. The instrument site is in a narrow valley within the Peninsular Ranges Batholith 23 km east of Hemet and 20 km southwest of Palm Springs, California. The valley is 4 km wide and about 10 km long. The valley trends northwest-southeast parallel to the major faults in the region. The valley floor is at an elevation of 1310 m and the surrounding mountains reach elevations slightly greater than 3000 m. Figure 13 is a topographic map of GVDA showing the boundaries of the site, installed instrumentation, and CPT sounding points.

As noted above, GVDA is in a seismically active region that lies only 7 km from the main trace of the San Jacinto fault. Historically, the San Jacinto is the most active strike-slip fault system in southern California with a slip rate of 10 mm/year. The absence of large earthquakes in the past 120 years leads to high probability for magnitude 6.0 or larger earthquakes in the next 10 years, the operation phase of NEES. Surrounding networks of high-gain velocity transducers provided by the USGS/Caltech southern California seismic network (SCSN) and the U.C. San Diego Anza network provide excellent coverage of the local and regional seismicity [12].

The near-surface stratigraphy beneath GVDA consists of 18 m to 25 m of lake-bed alluvium overlying 60 m to 70 m of weathered granite, which in turn overlies granitic bedrock. Sediments in the upper 18-25 m consist of alternating layers of sand, silty sand, clayey sand, and silty gravel. The alluvium gradually transitions into decomposed granite at depths between 18 m to 25 m. The decomposed granite classifies as gravely sand [13]. The ground water levels range from near surface in wet seasons to a few meters depth during dry seasons.

Geotechnical properties were defined with split spoon samples from SPT tests and data from the CPT soundings; SPT have been conducted to depths as great of 30 m and CPT soundings reached depths as great as 18 m. Figure 14 is a stratigraphic cross section delineating of sediment layers to a depth of 18 m.

To test liquefaction susceptibility of granular layers beneath GVDA, we applied the CPT procedure for evaluating liquefaction resistance as published by Youd et al. [12]. Results from the liquefaction analysis for a magnitude 7.0 earthquake and an a_{max} of 0.4*g* are plotted on Figure 15. For these likely seismic

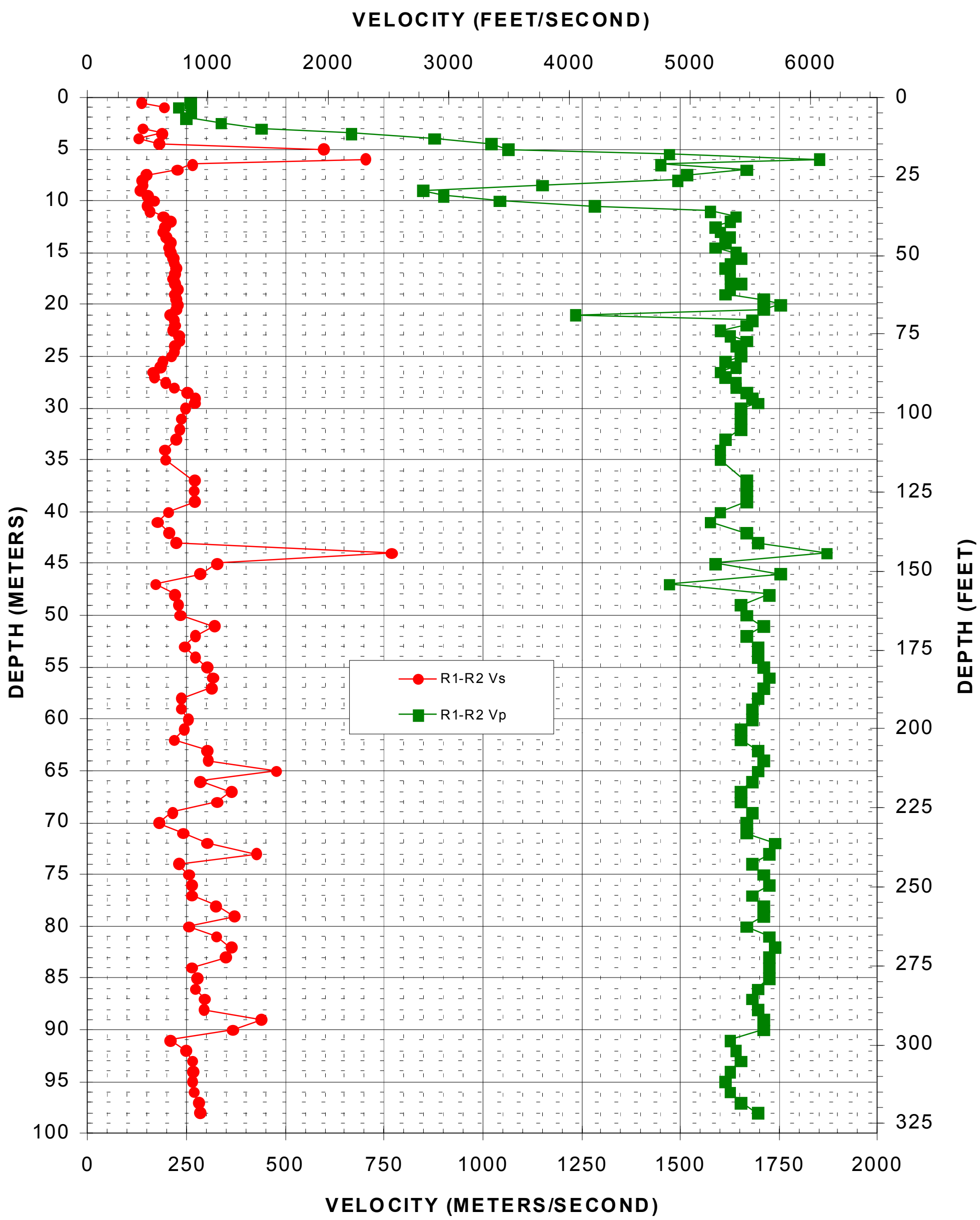


Figure 12. **P- and S-wave velocities measured with OYO suspension logger in the 100-m deep borehole drilled for the 07-m FBA at WLA.**

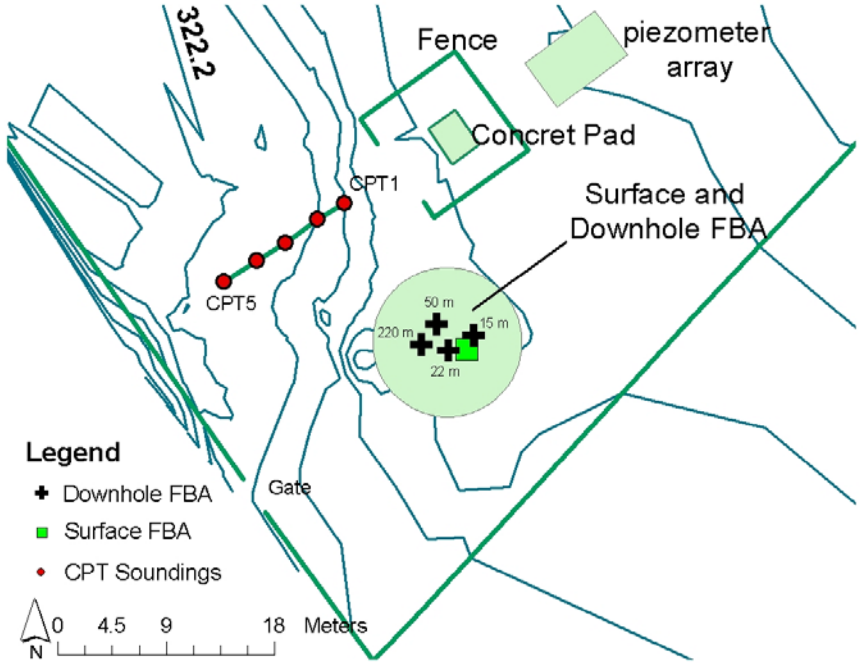


Figure 13. Map of GVDA site showing localities of accelerometers, piezometers, and CPT soundings.

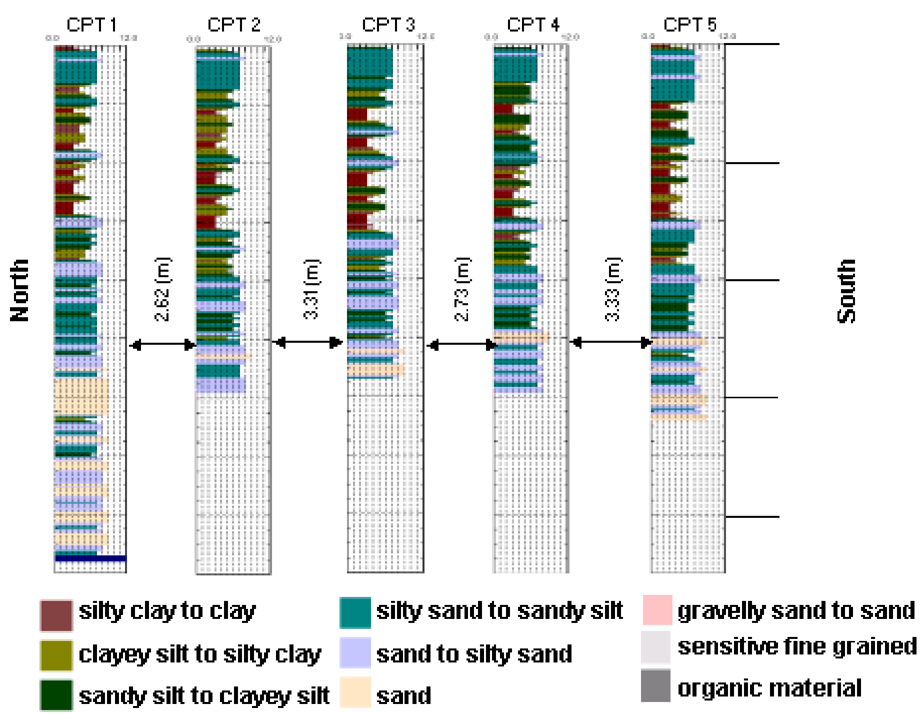


Figure 14. Stratigraphic cross section beneath line of CPT soundings at GVDA site; sediment units are interpreted from CPT data analyzed by USGS personnel.

parameters, liquefaction of several soil layers would likely occur beneath the site.

Four shallow pore-pressure piezometers were placed in liquefiable layers as part of the NEES project. These instruments will monitor pore pressure rise and the onset of liquefaction during future earthquakes. The transducers are sealed into 50-mm diameter PVC casings using the procedure used at WLA. The piezometers are ParoScientific models that have proven to be durability under field conditions. As with the WLA site, data from GVDA is stored on site and streamed through the southern California HP WREN system to U.C. Santa Barbara and the NEES grid.

SUMMARY COMMENTS

Significant new lessons were learned from the recorded responses at the Wildlife Liquefaction Array (WLA) including:

(1) soil softening led to lengthening of period of transmitted ground motions;

(2) induced ground oscillation led to continued increase of pore water pressures after strong ground shaking ceased;

(3) soil softening led to attenuation of short-period spectral accelerations (< 0.7 sec); and

(4) the induced ground oscillations led to amplification of long period motions (> 0.7 sec).

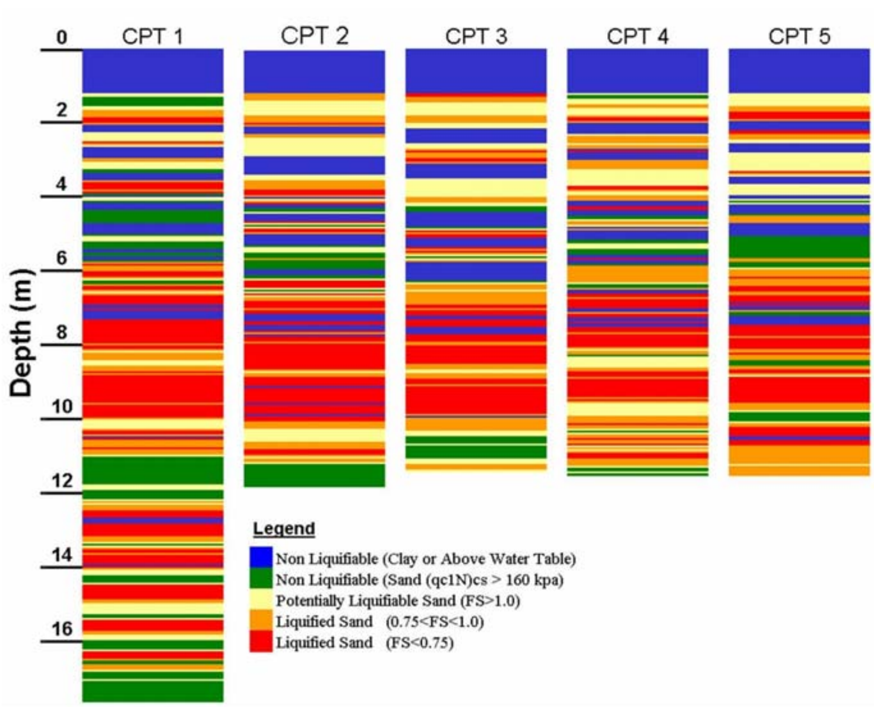


Figure 15. Interpretative cross GVDA showing layers that are and are not predicted to liquefy during a magnitude 7.0 earthquake generating 0.4 g peak horizontal acceleration at ground surface

As part of the NEES project, we have instrumented and are operating two field sites for monitoring of ground response, pore pressure rise, the onset of liquefaction, and ground deformation. These sites are the WLA 13 km north of Brawley, Imperial County, California, and the Garner Valley downhole array (GVDA) 20 km southwest of Palm Springs, California. Both sites are connected to the ANSS network of strong motion seismometers. Both sites are instrumented with downhole arrays of force balance accelerometers (FBA's) to depths as great as 97 m and 500 m at WLA and GVDA, respectively. Arrays of surface accelerometers have also been installed at both sites. Both sites are underlain by layers of liquefiable sandy sediments which have been instrumented with electrically transduced piezometers for monitoring of static and dynamic pore water pressures. Data from both sites are streamed out in real time to the University of California at Santa Barbara and to the NEES grid.

As one of 15 NEES experimental research equipment sites, the WLA and GVDA sites are available to interested researchers for conducting of experiments after receiving approval from the NEES Consortium and the site operations staff. Subsurface exploration and insitu experiments are welcome as long as they do not adversely disturb the primary function of the sites, which is to monitor ground motions, pore pressures, and ground deformation during future earthquakes.

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