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INSTRUMENTED GEOTECHNICAL SITES: CURRENT AND FUTURE TRENDS

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ABSTRACT

A goal of engineering seismology research is to generate analytical and empirical models for accurate prediction of ground shaking, pore water pressure generation, ground deformation and soil-foundation-structure interaction (SFSI), and to help engineers understand how these predictions will affect the built environment. The development of simulation capabilities that can reproduce these effects at various strain levels requires well-instrumented test sites where actual ground response, pore pressure, and deformation can be monitored during earthquake shaking to provide benchmark case histories for verification of the simulation models. In the U.S. alone, there are many "extensive" geotechnical strong motion array facilities available for use in calibration and validation of our modeling techniques. An update on these facilities including recently deployed arrays, and a summary of the current research activities using these facilities will be presented. In particular, the experimental field site facility that is part of the National Science Foundations George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) will be highlighted. This facility includes two permanently instrumented field sites for the study of ground response, ground failure, soil-foundation-structure interaction, and liquefaction. The current and future trend for instrumented sites seems to be moving to the simultaneous monitoring of both the geotechnical and structural components at a given site. This integration of the two sub-disciplines within earthquake engineering provides opportunities for new collaborations. The performance analysis of instrumented structures incorporating geotechnical and structural aspects should provide advances in our ability to predict the effects of earthquakes on the built environment.

Keywords: geotechnical strong motion array, engineering seismology, site response, test sites.

INTRODUCTION

Over the last two decades there has been significant activity in terms of the construction and operation of instrumented geotechnical sites. This summary paper is a continuation of the work presented almost decade ago (*Archuleta and Steidl*, 1998) that outlined the results of borehole array studies in the United States. Two issues come to mind when thinking about the last two decades of activity with instrumented geotechnical sites. First, the need for increased coordination among the agencies and organizations that install, maintain, and disseminate the data form these instrumented sites. This has been repeatedly expressed in the proceedings and reports from various workshops and conferences. Second is the lack of collaboration between the structural and geotechnical engineering communities to improve the design and performance of structures by integrating the components of the problem from both disciplines. Until recently, these components had been treated separately.

This workshop contribution will begin with a discussion of the geotechnical strong motion array (GSMA) activities in the United States, including a list of what is thought to be the current operational sites broken into categories. Then some examples of the current experimental activities using these

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sites will be provided. Lastly, some discussion of the future opportunities and challenges that the community faces in trying to deal with the two issues of coordination and collaboration mentioned above.

EXISTING GEOTECHNICAL STRONG MOTION ARRAYS IN THE UNITED STATES

In taking a look at the Geotechnical Strong Motion Array (GSMA) sites in the United States, the first question to ask is how to define a GSMA in the first place. In this case, any strong motion station that contains both a surface and a sub-surface borehole sensor qualifies. However, the GSMA's are further sub-divided into three categories.

Extensive Arrays (4+ borehole sensors):
An "extensive" GSMA is a site with four or more borehole accelerometers in addition to the surface sensor. Using this definition, 14 such sites are found. These sites are operated by a mix of agencies and institutions, including; the United States Geological Survey (USGS), the California Geological Survey (CGS/CSMIP), California Department of Transportation (Caltrans), the National Science Foundation (NSF), and the University of California at Santa Barbara (UCSB).

The site name, region, and responsible agencies are listed for each of these extensive array sites in Table 1. Note that these sites are primarily in California, with the exception of one site in Anchorage, Alaska. This is primarily reflective of the high cost of installing and operating extensive GSMA's and the probability of obtaining useful strong motion data over the life span of the array. The high seismicity regions of the United States have historically been the most heavily instrumented, though this is changing somewhat with the new Advanced National Seismic System (ANSS). This is not to say that having strong motion records in the lower seismicity regions like the Central and Eastern United States is not important, however, the potential to "catch" a significant event does play into the funding agencies decisions regarding where to allocate resources for these "extensive" facilities.

Table 1. Extensive Array sites in the United States

Site Name	Location	Agency(s)
Bessie Charmichael School	Bay Area – Northern California	USGS
Borrego Valley	Southern California	UCSB
Delaney Park	Anchorage, Alaska	ANSS/USGS/UAF
Embarcadero Plaza	Bay Area – Northern California	USGS
Eureka Array	Northern California	CGS/CSMIP/Caltrans
Garner Valley	Southern California	UCSB/NEES
Hayward, San Mateo Bridge	Northern California	CGS/CSMIP/Caltrans
Hollister Observatory	Central California	UCSB
Levi Plaza	Northern California	USGS
Melloland Array El Centro	Southern California	CGS/CSMIP/Caltrans
San Diego Coronado Bridge	Southern California	CGS/CSMIP/Caltrans
Treasure Island NGES site	Bay Area – Northern California	CGS/CSMIP/NSF
Vincent Thomas Array	Southern California	CGS/CSMIP/Caltrans
Wildlife Liquefaction Array	Southern California	UCSB/NEES

As an example of an extensive array we show the recently deployed Anchorage ANSS Delaney Park Array and instrumented structure, the Atwood Building, located 500 meters from the geotechnical array. Figure 1 shows the location of Delaney Park in relation to the Atwood building in the skyline behind the park. Figure 2 shows a schematic of the vertical array with seven 3-component accelerometers located at depths from the surface down to 61 meters. The instrumentation of the Atwood building is also shown in Figure 2. This is an ideal case where the input motion to a well-instrumented structure is provided through a GSMA located so as to provide the free field input motions to that structure. This instrumented site represents the new trend in collaborative geotechnical and structural engineering monitoring sites.

Figure 1. The Delaney Park GSMA with the instrumented Atwood Building in the background

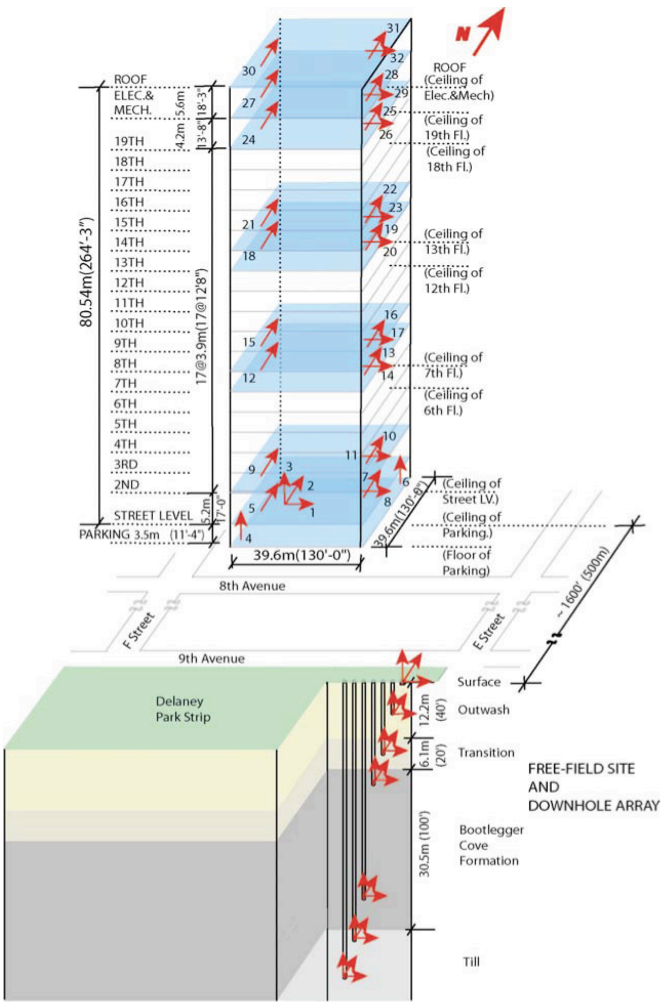

Figure 2. Schematic representation of the GSMA and Structural Array monitoring at Delaney Park and the Atwood Building in Anchorage, Alaska.

Moderate Arrays (2-3 borehole sensors):
The second category of GSMA facilities in the United States is "moderate" arrays, or sites with two or three borehole accelerometers in addition to a surface sensor. The list of 15 such arrays provided in Table 2 is again heavily weighted towards California. However, looking at these less extensive (and therefore less expensive) arrays, the lower seismicity regions begin to be represented here, with three moderate array sites located in the Central and Eastern United States, in this case operated by the University of Kentucky and Northeastern University, respectively. The same agencies and institutions that operate the previously discussed extensive arrays operate the remaining twelve sites.

An example of the moderate class of GSMA is the Southern California Earthquake Centers (SCEC) Long Beach Water Replenishment District (WRD) site in Southern California. This site has a relatively deep borehole accelerometer at 350 meters, an intermediate depth accelerometer at 30 meters, and the surface accelerometer. This is a typical soft deep-basin site in Los Angeles with "engineering rock" just barely being encountered at 350 meters depth.

Table 2. Moderate Array sites in the United States

Site Name	Location	Agency(s)
Carquinez Bridge	Northern California	CGS/CSMIP/Caltrans
Corona Array	Southern California	CGS/CSMIP/Caltrans
Foster City, San Mateo Bridge	Bay Area – Northern California	CGS/CSMIP/Caltrans
Half Moon Bay	Northern California	CGS/CSMIP/Caltrans
La Cienega Array	Southern California	CGS/CSMIP/Caltrans
Long Beach Water District	Southern California	UCSB/SCEC
Northeastern University	Eastern US	Northeastern University
Olmstead Locks and Dam	Central US	University of Kentucky/ACOE
Paducah, KY	Central US	University of Kentucky
Parkfield, Turkey Flat	Central California	CGS/CSMIP/Industry
Rohnert Park	Northern California	CGS/CSMIP/Caltrans
San Francisco Bay Bridge	Bay Area – Northern California	CGS/CSMIP/Caltrans
Sassafras Ridge, KY	Central US	University of Kentucky
University of California, Riverside	Southern California	UC/SCEC
Winfield Scott School	Northern California	USGS

Surface Borehole Pair (1 borehole sensor):
The third category of GSMA sites in the United States is the Surface Borehole Pair. The list below of 17 such sites are again a combination of Central US and California sites, weighted heavily toward Southern California (Table 3). The majority of these sites were targets of opportunity where an existing strong motion station was being drilled and logged to collect geotechnical site characterization data, and another agency (SCEC for example) would leverage the drilling and logging costs to justify funding the installation of well casing in the hole and the installation of a borehole sensor. Since many of these sites exist because site characterization was occurring at the station, information regarding the soil profiles at these sites is available. Having good site characterization data is critical for future analysis of strong motion records obtained at these GSMA sites.

Many of these sites are also collaborative with existing monitoring networks where much of the infrastructure (power and communications) is already in place at the site for the existing strong motion instrument. While these sites will not provide the extensive array multi-level detail within the soil column needed to calibrate complex nonlinear simulation models, these sites are still extremely useful. They provide the input motion at a depth where the material behavior during strong shaking in significant earthquakes is expected to remain in the linear stress-strain regime. Thus, they are the control motion that can at a minimum be used to evaluate the degree of nonlinear soil behavior as observations are made at different excitation levels. Assuming that the behavior during small earthquakes is linear throughout the soil column, changes in the site response transfer function from borehole to surface as input motions increase with larger earthquakes can be interpreted as changes in the material behavior (*Tsuda and Steidl, 2006; Assimaki and Steidl, 2007*). With enough of these observations at various sites, over a range of input motions and site classifications, average site response correction factors can be determined and used in seismic code provisions. Currently, these factors are based primarily on theory, not empirical data. So while these surface-borehole pair sites may not be extensive enough for some research applications, they do make an important contribution.

Table 3. Surface Borehole Pair Sites in the United States

Site Name	Location	Agency(s)
Central Fire Station	Southern California	USGS/UCSB
Cerritos College	Southern California	USGS
Griffith Park	Southern California	UCSB/SCEC
Jensen Filtration Plant	Southern California	UCSB/SCEC/USGS
Kentucky Bend, KY	Central US	University of Kentucky
Mira Catalina School	Southern California	UCSB/SCEC
Obregon Park, Los Angeles	Southern California	CGS/CSMIP/UCSB
Pacific Park Plaza, Emeryville	Bay Area – Northern California	USGS
Ridgely, TN	Central US	University of Kentucky
Rinaldi Substation	Southern California	UCSB/SCEC
Stone Canyon	Southern California	UCSB/SCEC
Superstition Mountain	Southern California	UCSB/SCEC/USGS
Tarzana, Ceder Hill	Southern California	CGS/CSMIP
University of California, Los Angeles	Southern California	USGS/ANSS
University of California, Santa Barbara	Southern California	UC/SCEC
University of California, San Diego	Southern California	UC
Wonderland Avenue School	Southern California	UCSB/SCEC

HIGHLIGHTS OF ACTIVITIES AT THE NEES SITES

The U.S. National Science Foundation George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) program provides an unprecedented infrastructure for research and education, consisting of networked and geographically distributed resources for experimentation, computation, model-based simulation, data management, and communication. Rather than placing all of these resources at a single location, NSF has distributed its resources among 15 equipment sites throughout the US. To insure that all earthquake engineering researchers can effectively use this equipment, the equipment sites are operated as shared-use facilities, and NEES will be implemented under a new paradigm, as a network-enabled collaboratory. As such, members of the earthquake engineering community are able to interact with one another, access unique, state-of-the-art instruments and equipment, share data and computational resources, and retrieve information from digital libraries without regard to geographical location.

One of these 15 NEES equipment sites is the NEES@UCSB facility, which includes two permanently instrumented field sites constructed for the study of ground response, ground failure, soil-foundation-structure interaction, and liquefaction. The two sites are located in Southern California. Both sites are located close to major faults and have previous histories of recording ground motions and pore-water pressures. They also have a history of site characterization studies, and both sites are underlain by soft, liquefiable ground. These field sites are well suited for ambient noise studies, passive earthquake monitoring, and active testing using mobile shakers.

Garner Valley Downhole Array

The NEES 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 instrumented site is located in a narrow valley within the peninsular ranges batholith east of Hemet and southwest of Palm Springs, California. This seismically active location is 7km from the San Jacinto Fault and 40 km from the San Andreas

Fault. The valley is 4-5 km wide at its widest and about 10 km long. The valley trends northwest-southeast parallel to the major faults of southern California. The valley floor is at an elevation of 1310 m and the surrounding mountains reach heights slightly greater than 3,000 m. A panoramic view of the GVDA field site is shown in Figure 4, taken at the completion of the NEES construction in Fall of 2004. The details of the geotechnical site conditions and instrumentation at the GVDA facility can be found at the NEES@UCSB website (http://nees.ucsb.edu/), and in previous studies of the observations from this site (*Archuleta et al., 1992; Steidl et al., 1996; Bonilla et al., 2002*).

Figure 4. The GVDA site in 2004 after the NEES program upgrade.

The NEES GVDA facility exemplifies the trend of instrumented sites moving to multi-disciplinary collaborations between seismologists, geotechnical, and structural engineers. The reconfigurable structure (Figure 4) constructed at the GVDA site is instrumented with pressure cells under the four corners of the foundation, vertical displacement transducers on the four corners, accelerometers on the corners, bottom slab, and top slab, and a rotational sensor on the bottom slab. In addition, a downhole accelerometer and pore pressure transducer are installed below the foundation. The new structure is intended for improving our understanding of soil-foundation-structure interaction (SFSI). Figure 5 is a schematic of the structure and the different input forces that can be used in response testing.

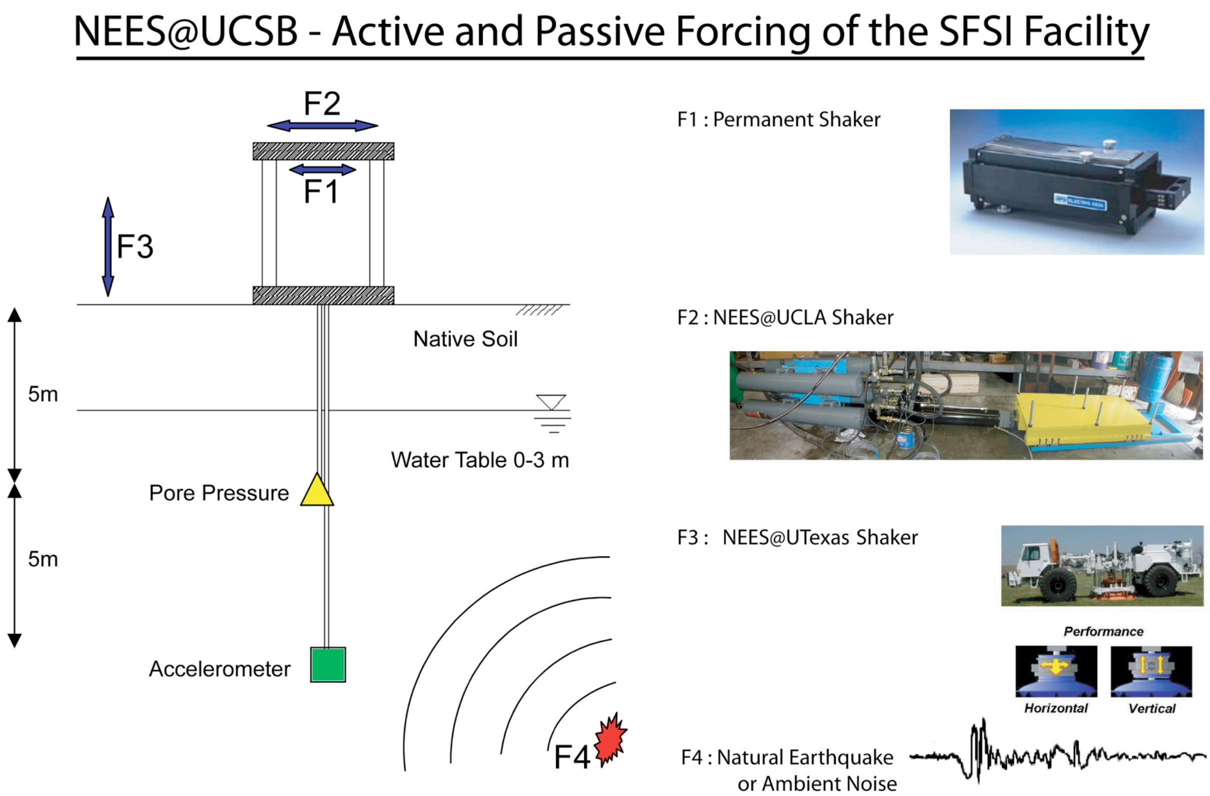

Figure 5. The various input forces used to study soil-foundation-structure interaction at GVDA.

In figure 6, the locations of the various sensors installed on and beneath the SFSI test structure are shown. In addition to the instrumented structure, the soil column at GVDA is heavily instrumented with 6 additional downhole accelerometers (6, 15, 22, 50, 150, and 501 meter depths) and 4 additional pore pressure transducers (6.1, 8.8, 10.1, and 12.4 meter depths).

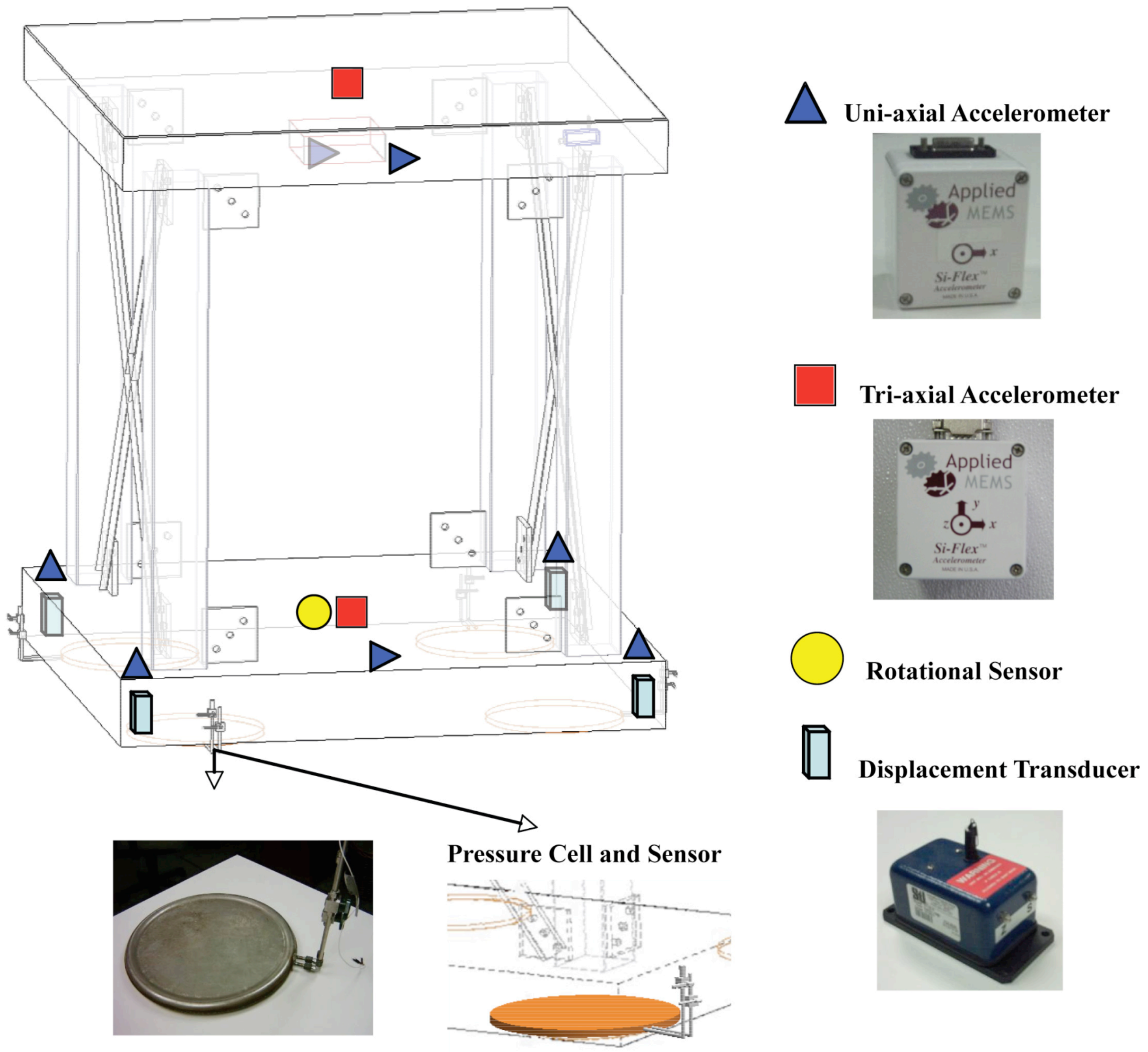

Figure 5. Instrumentation at the GVDA SFSI Facility

The SFSI test structure instrumentation is designed to easily capture both rocking and torsional modes of the structure. It was also designed to be re-configurable, so that the stiffness could be modified by adding or removing bracing on any of the 4 sides. The mass of the structure can also be modified through the addition of weight on the roof slab, or even the addition of a second story. A permanent shaker is mounted under the roof slab, and can be operated remotely, providing an excellent tool for teaching SFSI and structural dynamics concepts. The shaker is also used in research by exciting the structure on a regular basis and comparing the response with environmental factors like soil saturation and temperature. A weather station is installed at the GVDA site to provide rainfall data and temperature data, and soil moisture probes are installed below the foundation of the structure.

Liquefaction array monitoring at GVDA

In addition to the SFSI test facility and ground response sensors at GVDA, pore pressure monitoring in the near surface soil layers is providing new observations to help better understand the liquefaction phenomena and nonlinear material behavior in general. The largest motions recorded so far at the GVDA site are just at the level where the onset of nonlinear soil behavior might be expected, around 0.1 g peak ground acceleration. Observations from the liquefaction array sensors are beginning to show the build up of pore pressure at this level, and then show the slow decay back to the background level. A recent M5.1 earthquake near Anza, CA produced a quality set of observations showing this behavior (Figure 7). Interestingly, the shallow transducers show increases in pore pressure during the strongest shaking, while the deeper transducer seems to show an opposite effect. It is expected that these observations will be used for many years to come as simulation techniques are tested and new physics based models are proposed to model this behavior.

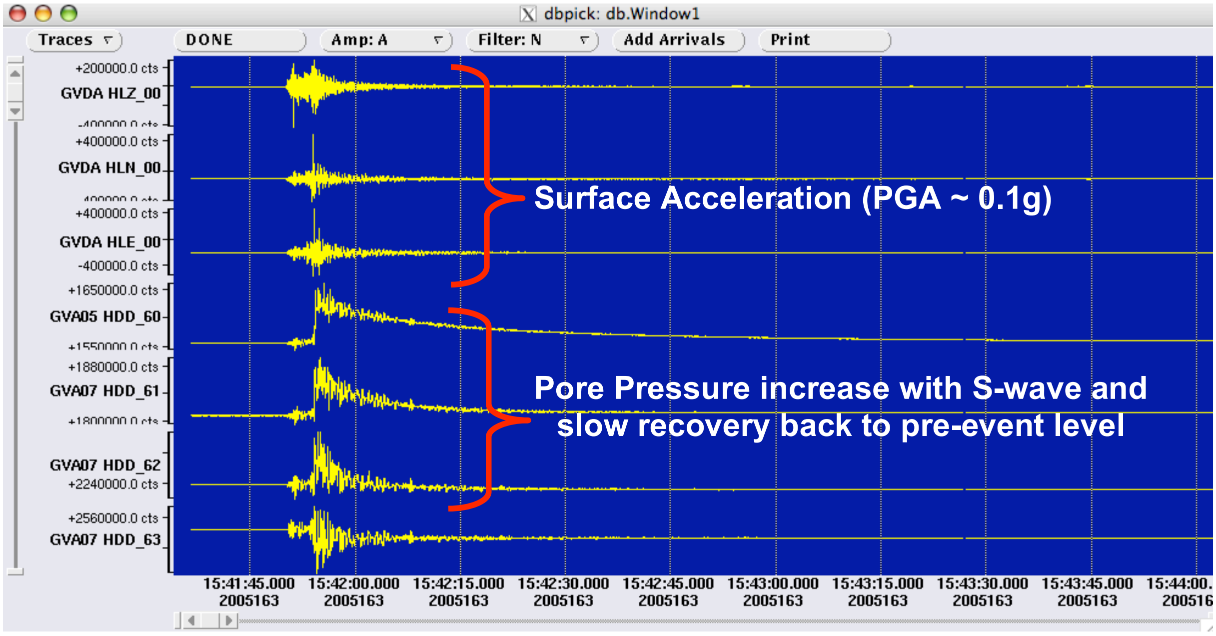

Figure 7. 150 seconds of surface ground acceleration and sub-surface pore pressure observations from the 2005 M5.1 Anza event recorded at GVDA

Wildlife Liquefaction Array

The Wildlife Liquefaction Array (WLA) is located on the west bank of the Alamo River 13 km due north of Brawley, California and 160 km due east of San Diego. The site is located in the Imperial Wildlife Area, a California State game refuge. This region has been frequently shaken by earthquakes with six earthquakes in the past 75 years generating liquefaction effects at or within 10 km of the WLA site. Based on this history, there is high expectation that additional liquefaction-producing earthquakes will shake the WLA site during the 10-year operational phase (2004-2014) of the NEES program. Figure 8 is a view of the WLA site after construction was completed in Fall 2004.

Figure 8. The NEES WLA facility just after construction was completed in 2004.

The extensive instrumentation at this site includes 4 surface accelerometers, 6 downhole accelerometers, 11 sub-surface pore pressure transducers, and numerous benchmarks and inclinometer casings for monitoring lateral ground displacements. In this paper, we will focus on some of the experimental activities that have taken place since its inception in 2004, and refer the reader to other publications which contain detailed information on the instrumentation and geotechnical properties of the site (*Youd et. al., 2004; Youd et. al., 2007*).

Both earthquakes and active testing using the NEES@UTA "T-Rex" mobile shaker have been used to examine the response of the WLA site. In the late summer of 2005 the "T-Rex" shaker excited the WLA site and provided a useful test of the system, as well as some provocative observations of pore pressure during local shaking. Figure 9 shows the location of the shaker relative to the accelerometer and pore pressure instruments at the WLA site.

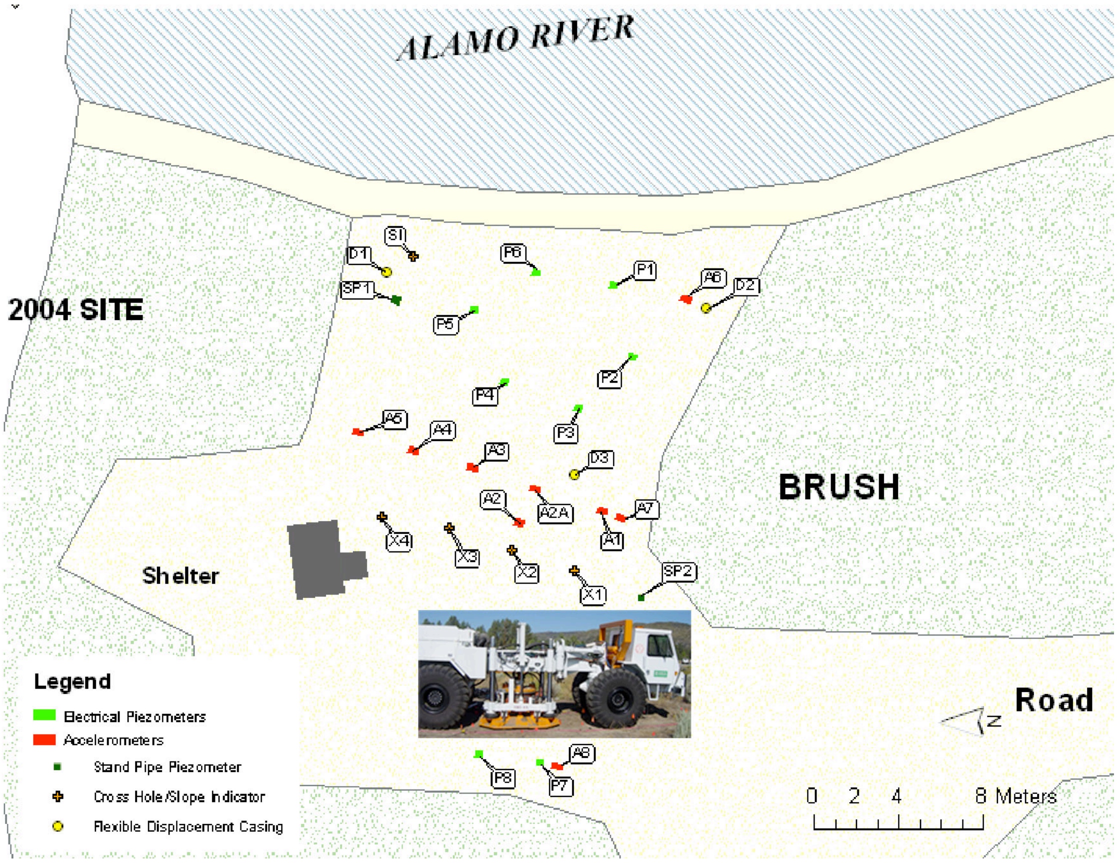

Figure 9. The WLA instrumentation and T-Rex shaker location during testing in 2005.

The active shaking from the NEES@UTA shaker only lasts for approximately 10 seconds, however the pore pressure signals that are generated by the active source last for minutes. Pore pressures at the two transducers located closest to the shaker (P7 and P8 in Figure 10) show an immediate increase in pore pressure and slow decay back to the pre-shake level that takes more than 20 minutes. Another interesting observation is that just following the initial pulse, the deeper of the two closest transducers (P8) also shows another slight pressure increase, which can be explained by a pressure wave generated at the source and spreading out and propagating through the sand layer as it dissipates. All of the transducers that are located at or near the top of the sand layer at the site (*see Youd et al., 2004, 2007 for details of the soil layers*) show an impulsive initial arrival, including the two located further from the shaker (P4 and P1), with the amplitude of the pulse decreasing with both lateral and vertical distance from the source. The time histories shown in Figure 10 are sorted by distance from the shaker source with the top trace being the closest and bottom trace the furthest. Pore pressure continues to rise for as much as three minutes after the shaking has stopped at the deeper and further transducers. Even at 10 minutes after the source has stopped the pore pressures have still not dissipated back to the pre-shake level.

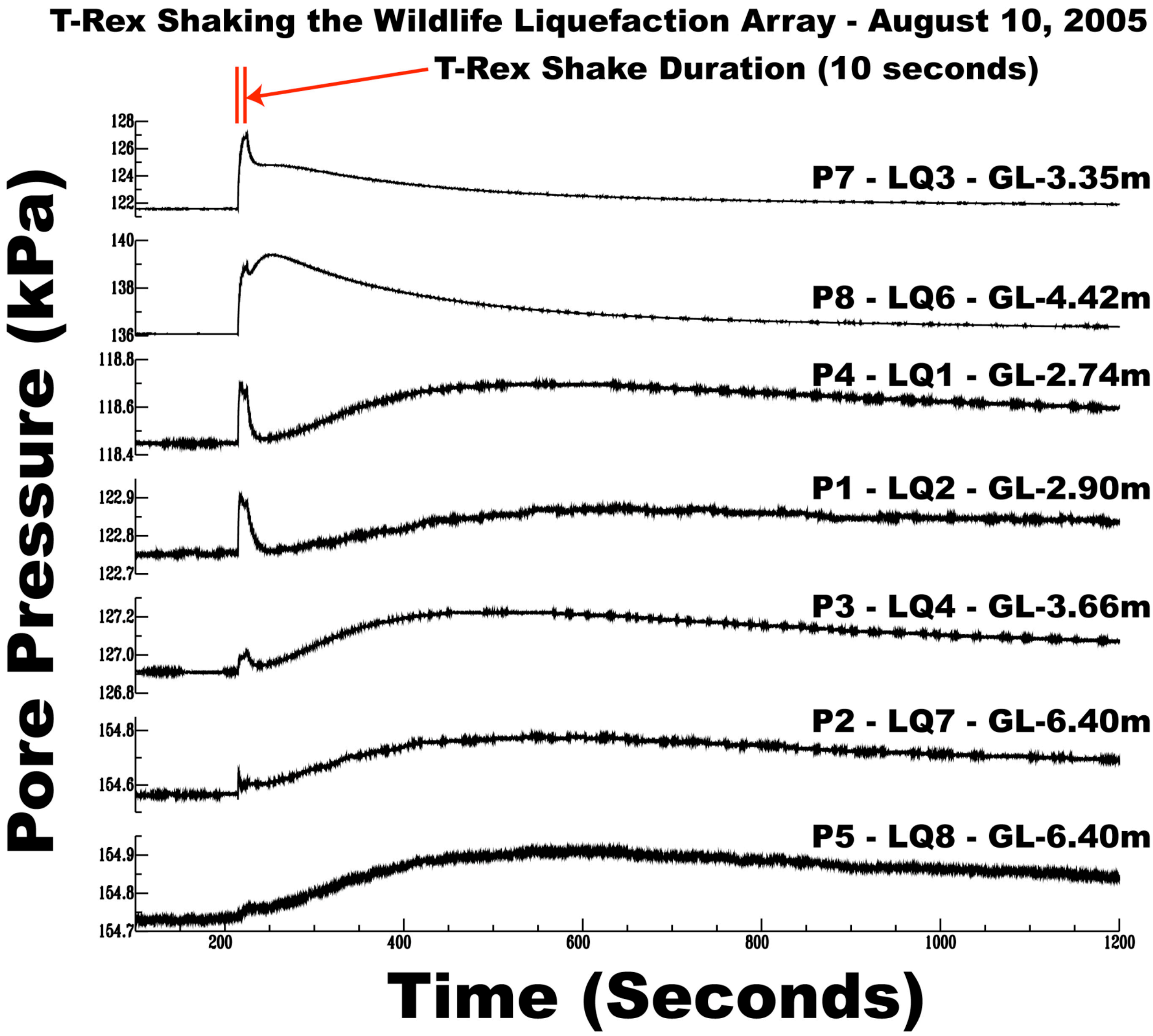

Figure 10. The WLA instrumentation and T-Rex shaker location during testing in 2005.

These active source observations of pore pressure generation and slow dissipation are also seen when earthquakes shake the site. The largest ground motions observed to data at the WLA site are from a local magnitude 5.1 event located approximately 10 km from the site. In addition to the M5.1 event, numerous M3 and M4 level earthquakes also generated very interesting observations at the site. The largest ground accelerations from this swarm of events was only about 10% g, however even these modest levels of shaking, the pore pressure response can clearly be seen in the observations. The observations from the eight pore pressure transducers for a 1-hour period during this swarm of earthquakes is plotted in Figure 11 from shallowest to deepest (top to bottom). Similar to the active source testing, all of the transducers show a clear response to the earthquake activity.

In the earthquake swarm observations, the deeper transducers have a larger dynamic response to the passage of the body waves from the events. All transducers show slight pore pressure increase and slow recovery back to the pre-swarm level. The deeper transducers also have this increased pore pressure, but it's harder to see due to their larger dynamic response. The pore pressure increase during the swarm is approximately 0.2-0.3 kPa, while the dynamic response of the deeper transducers is almost an order of magnitude larger, at approximately 3-5 kPa peak to peak (Figure 11).

In addition to the active source and earthquake monitoring at the WLA site, the benchmarks and inclinometer casings are re-surveyed approximately once per year to obtain a baseline for lateral displacements. The free face of the Alamo river bank located just meters from some of the instrumentation, benchmarks, and casings should provide an excellent source for lateral spread activity in the next large earthquake.

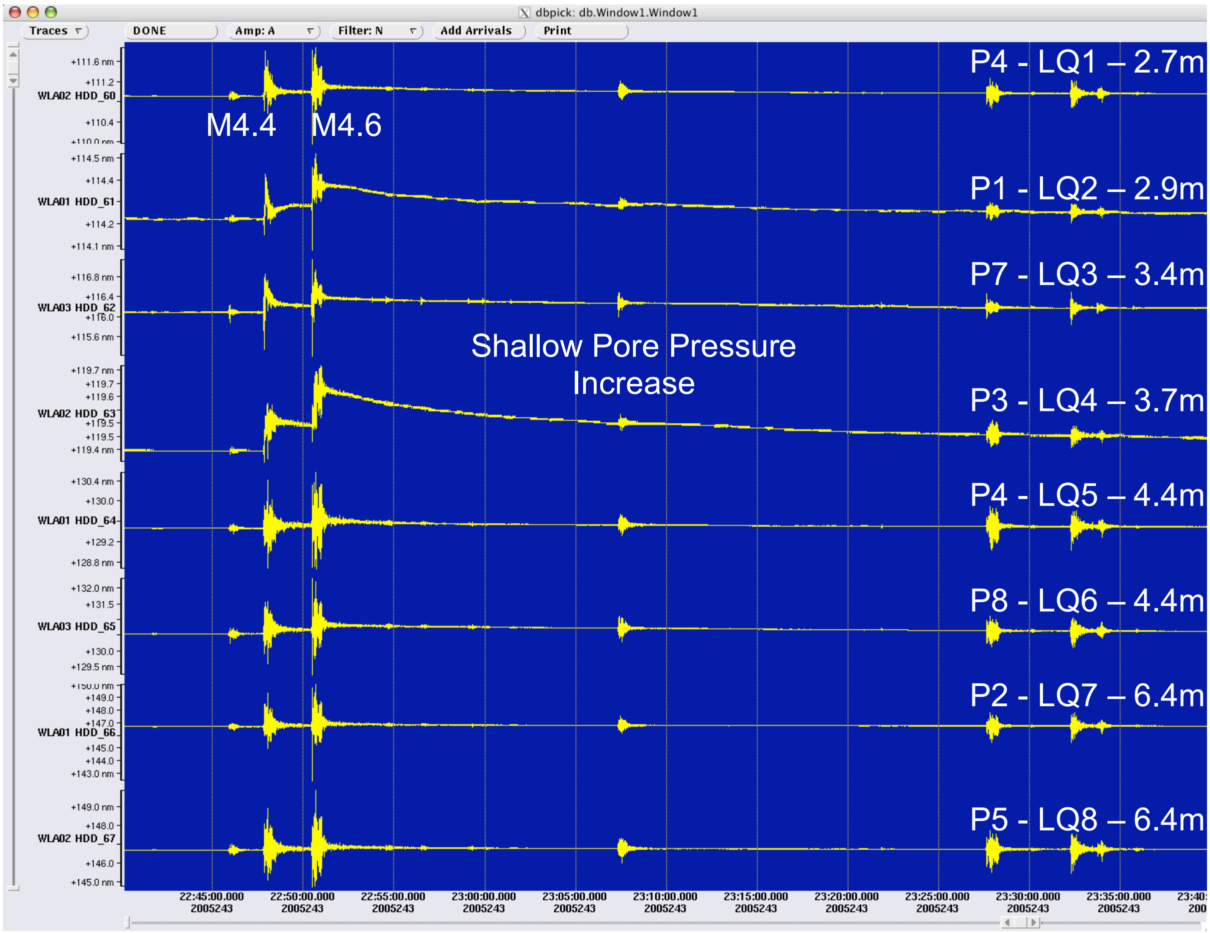

Figure 11. The WLA liquefaction array. Sixty seconds of data showing both dynamic response of the pore pressure sensors and static pressure increase, with slow dissipation when excited by the 2005 Obsidian Buttes earthquake swarm.

CONCLUDING REMARKS

In order to maintain a vital monitoring and research program at instrumented geotechnical sites, often many different funding agencies must be involved, and a very broad scope of work must be envisioned. Coordination and collaboration among seismologists, geotechnical and structural engineers to establish instrumented sites that serve the engineering and scientific goals of each of these disciplines represents the current trend for increasing the number of these facilities. It would be useful to also get the practitioners involved, in both defining the scientific and engineering goals for instrumented sites, and also to get instrumentation planning as part of the design phase for new structures.

At present there is a lack of coordination among the various responsible organizations, both at the domestic level in the United States as well as internationally, when it comes to the operations and dissemination of data from instrumented geotechnical array sites worldwide. The maintenance and operations of the existing instrumented geotechnical site resources and dissemination of their data should be considered a high priority. There is a need for an umbrella organization or working group with representatives from both the national and international agencies with monitoring programs to facilitate the coordination and collaboration between these agencies.

The operations and maintenance of instrumented geotechnical sites, especially in regions of relatively low seismicity, is often a difficult task for the responsible agency or organizations. The lack of recordings of significant events over long time periods can make the funding agencies question the benefit of maintaining these resources. An international organization that regularly re-evaluates the scientific and engineering needs in conjunction with the current inventory of instrumented sites could provide justification needed for agencies to obtain funding for maintaining these facilities.

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