Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
and Symposium in Honor of Professor I.M. Idriss
May 24-29, 2010 • San Diego, California

OBSERVATIONS AND ANALYSIS OF GROUND MOTION AND PORE PRESSURE AT THE NEES INSTRUMENTED GEOTECHNICAL FIELD SITES

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ABSTRACT

The Garner Valley and Wildlife sites are producing a large data set that includes very interesting observations from earthquakes in the magnitude 4 to 7 range, with peak accelerations of ~10%g, at the threshold where nonlinear effects start to become important. In addition, hundreds of smaller earthquakes are recorded each month that provide the control data representing the linear behavior of the site. With the larger motions, we begin to see pore pressure build up on the liquefaction array at both the NEES Garner Valley Array site and at the NEES Wildlife Liquefaction Array site. We present the results of simulated pore pressure generation using the observed ground motions and a nonlinear anelastic hysteretic finite difference model of the soil response. We are able to reproduce this onset of pore pressure generation that occurs under the moderate strain levels associated with these ground motions. Additional work to be completed for this conference includes the development of an empirical model to predict pore pressure generation based on observed ground motions within a saturated soil column using data from the GVDA and WLA field sites. Correlations between pore pressure data and various ground motion parameters derived from accelerometers within the vertical arrays will be shown. Continuing studies on these unique data sets are improving our understanding of the physical process that drives liquefaction.

INTRODUCTION

Downhole earthquake records are critical to engineering seismologists and geotechnical earthquake engineers who work to improve our understanding of ground motions from large, damaging earthquakes and the behavior of soils at large strain levels. While we must still rely primarily on surface observations of ground motion, due to the high cost of drilling and borehole instrumentation, borehole observations provide critical constraints for our methods of interpreting surface observations. Borehole measurements have provided some of the most provocative results on basic seismological and earthquake engineering problems. For example, borehole measurements provided direct *in situ* evidence of nonlinearity (e.g. Seed and Idriss, 1970; Zeghal and Elgamal, 1994; Iai *et al.*, 1995; Sato *et al.*, 1996, Wen *et al.*, 1994; Aguirre and Irikura, 1997; Archuleta, 1998). They have invited a reevaluation of the use of surface rock recordings as input motion to soil columns (Steidl *et al.*, 1996; Boore and Joyner, 1997; Archuleta and Steidl, 1998) and they have provided basic information about scaling properties of the spectra of earthquakes of different magnitudes (e.g., Abercrombie, 1997; Kinoshita, 1992).

Downhole data enable the modeling of liquefaction, particularly at arrays such as the Wildlife Liquefaction Array (WLA) (Youd and Holzer, 1994, Youd *et al.*, 2004, Youd *et al.*, 2007) and the Garner Valley Downhole Array (GVDA) (Archuleta *et al.*, 1992, Steidl *et al.*, 1996) where piezometers are placed in the saturated soils to measure pore pressure along with acceleration (Steidl, 2007, Steidl *et al.*, 2008). Shear stress and strain histories were computed for the 1987 earthquakes at Wildlife in California, where liquefaction was observed (Zeghal and Elgamal, 1994). The authors were able to correlate shear stress and strain with pore pressure measurements from the saturated soils and they found cycles of high shear strain with low shear stress, followed by a hardening response. A more recent study done with WLA data from 1987 suggested that peak ground acceleration is an incomplete predictor of liquefaction (Holzer and Youd, 2007).

The *in situ* observations from vertical array sites like the Garner Valley Downhole Array and the Wildlife Liquefaction Array, which measure both pore pressure and ground motion at multiple depths in the soil column, are critical for the validation and calibration of numerical techniques that simulate nonlinear soil behavior during strong shaking. These observations also help form a better understanding of the engineering characteristics of seismic input that assists in the safer design of the built environment, particularly critical facilities and lifelines where site-specific analysis is often required.

GVDA AND WLA SITE CHARACTERIZATION

The Wildlife Liquefaction Array (WLA) and the Garner Valley Downhole Array (GVDA) have both boon recording earthquakes for more than two decades. These two equipment sites are now run by the Institute for Crustal Studies at UCSB, and have been in operation for more than four years under the NEES program. These sites were originally selected for their proximity to major faults and their potential for liquefaction during strong shaking. There have been many geophysical and geotechnical site characterization studies performed at these sites (*Youd et. al., 2004a*), which we briefly describe below.

The Garner Valley Site

The Garner Valley Downhole Array is located in southern California at a latitude of 33.669° north, and a longitude of 116.674° west. The instrumented site is 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 (Figure 1).

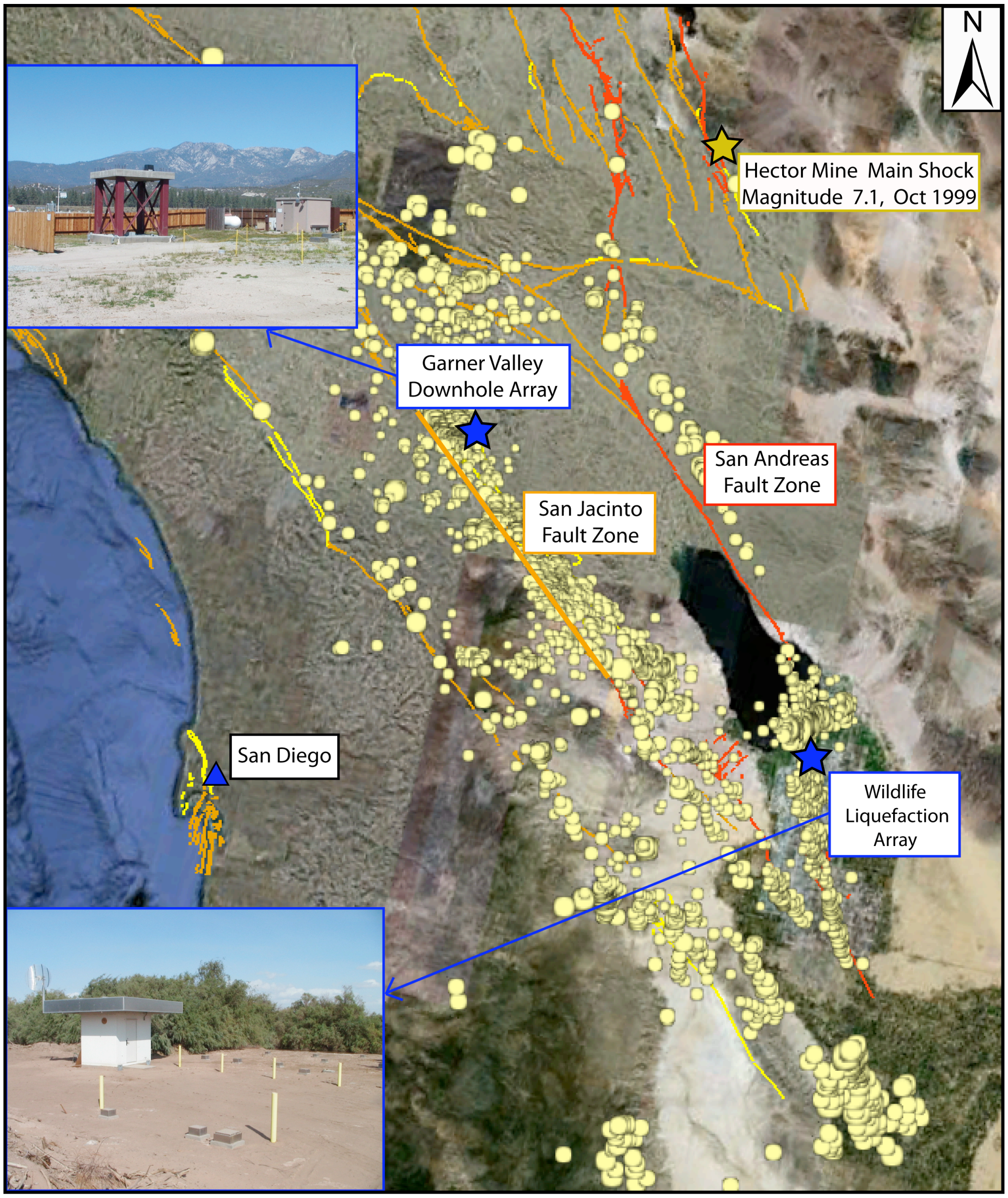

Figure 1. Location of the Garner Valley Downhole Array and the Wildlife Liquefaction Array (blue stars) shown with over 7500 recorded earthquakes representing 3-years of seismicity (yellow circles) from August 2005 through August 2008.

A geotechnical cross-section of the GVDA site is shown in Figure 2. Cone Penetrometer Testing (CPT) at the site in a line that spans a 10-meter section of the site in close proximity to the downhole pore pressure and accelerometer arrays, and a reconfigurable instrumented structure built to study soil-foundation-structure interaction (SFSI). The GVDA site conditions are soft soils with ~20 meter thickness over a 70-meter layer of weathered granite with crystalline granite (Vs=3.0 km/s) at ~90 meters depth.

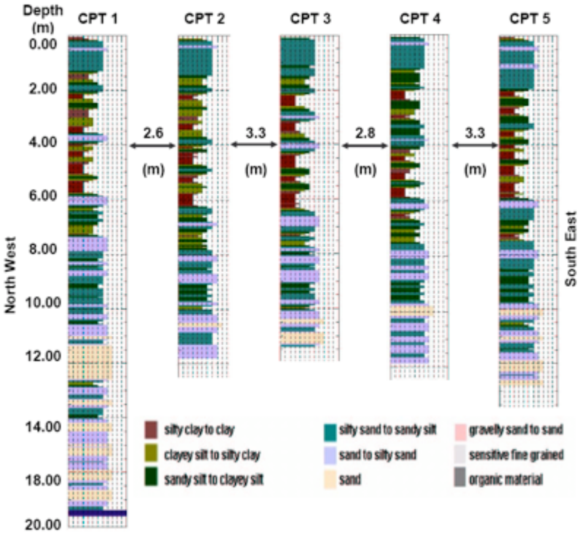

Figure 2. Geotechnical cross-section for GVDA developed from CPT data.

The vertical array of accelerometers consists of 3-component sensors placed at the surface and at depths of 6, 15, 22, 50, 150 and 501 meters below ground level. In addition, five pore pressure transducers are located within the soft saturated alluvium at depths of 3.5, 6.2, 8.8, 9.9, and 12.4 meters below ground level (Figure 3). Data is collected continuously from all sensor channels at a 200 Hz sampling rate (~1Gb per day total) and is stored both locally on site, and brought back to UCSB in real-time via high performance wireless telemetry. At UCSB the continuous data is archived on RAID storage servers for processing, where earthquake data is segmented out of the continuous data stream, and eventually made available via a web-based data dissemination portal. The continuous data is migrated to tape archive for long-term storage, once the event processing has been completed.

In addition to the CPT testing above, the GVDA site has been the subject of multiple site characterization studies in the past, including SPT (*Youd et. al., 2004a*), SASW (*Brown et. al., 2002, Stokoe et. al., 2004*), downhole logging (Gibbs, 1989), suspension logging (*Steller, 1996*), and Pitcher and Shelby sampling with laboratory evaluation of the dynamic properties of intact soil specimens using resonant column and torsional shear testing (*Stokoe and Darendeli, 1998*). Spectral array analysis of ambient noise has also been done at the GVDA site (*Liu et. al., 2000*). Many of these studies have been compiled and made available at the NEES@UCSB website [http://nees.ucsb.edu].

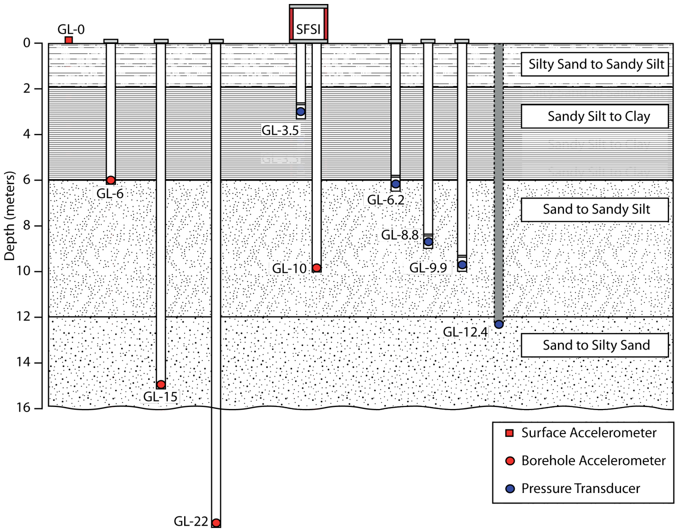

Figure 3. Cross-section showing shallow pore pressure and accelerometer vertical array instrumentation at GVDA.

The Wildlife Liquefaction Array Site

The Wildlife Liquefaction Array (WLA) is located on the west bank of the Alamo River, 13 km north of Brawley, California and 160 km east of San Diego, at a latitude of 33.098° north, and a longitude of 115.531° west (Figure 1). This location, within the Imperial Valley, just south of the Salton Sea and the southern terminus of the San Andreas Fault system, provides a natural laboratory for monitoring earthquake ground motions, liquefaction, and permanent deformations.

The facility is located within the Brawley Seismic Zone, a region of very active seismicity along the Pacifc - North American plate boundary between the Imperial and San Andreas Fault zones (Figure 1). The location was selected because of the six events in the past 75 years generating liquefaction effects within 10 km of the WLA site (*Youd et al., 2004b*). Based on this history, there is high expectation that additional liquefaction-inducing earthquakes will shake the WLA site during the 10-year operational phase (2004-2014) of the NEES program.

The near-surface geology of the WLA site consists of a layer of saturated silty sand, from approximately 2 – 7 m, with silty clay above and below the layer. A geotechnical cross section of the site based on the extensive CPT work done at the site is shown in Figure 3. Details of the site characterization work performed at the site can be found in the geotechnical testing report of Youd et. al. (2004a). Additional information, including suspension logging results, SPT logs, and survey data can be found at the NEES@UCSB project website [http://nees.ucsb.edu].

The NEES@UCSB WLA facility is a combination of the newly instrumented 2004 location and the older 1982 USGS facility that was re-instrumented in 2005. These two sets of instrumentation are located approximately 80 meters apart along the bank of the Alamo River. The combined sites provide extensive instrumentation for monitoring ground motion with tri-axial accelerometers, 4 located at the surface and 8 at various depths within the soil column down to 100 meters depth. Pore pressure monitoring includes a total of 11 sub-surface pressure transducers (Figure 5). Numerous benchmarks and inclinometer casings have been installed and surveyed repeatedly for monitoring lateral ground displacements.

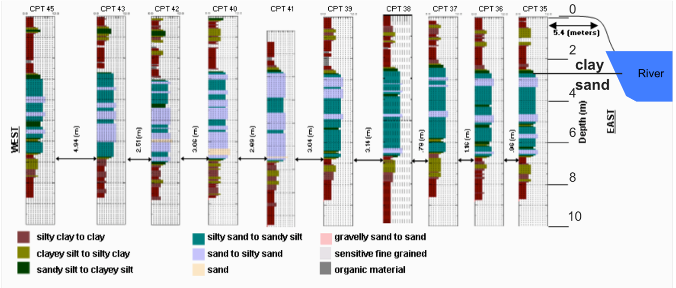

Figure 4. Geotechnical cross-section for WLA developed from CPT data.

Similar to GVDA, the WLA site has state-of-the-art wireless communications systems, which bring the continuous data recorded at the site at 200 Hz back to UCSB. Unlike the GVDA site, due to the remote location the WLA site also operates exclusively on solar power. The continuous data recorded at the WLA facility is also segmented into individual events, and eventually made available via the same web-based data dissemination portal as the GVDA data. [http://nees.ucsb.edu/facilities/data].

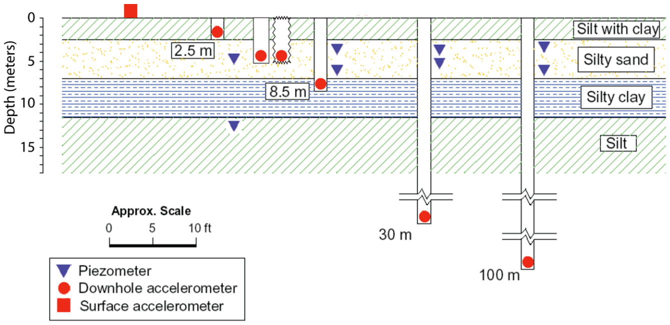

Figure 5. Cross-section showing shallow pore pressure and accelerometer vertical array instrumentation at WLA.

RECORDED EVENTS

The NEES@UCSB field sites are recording hundreds of earthquakes every month (Figure 1). The majority of these are small events and they provide the control data that represent the linear behavior of the site. The larges motions recorded to date, on the order of 0.1g, with moderate strain levels at the onset of nonlinear soil response. All events recorded at the two sites from August 2005 to August 2008 are shown in Figure 1.

WLA Events

The largest ground motions observed since the NEES operations began at WLA were recorded during the Obsidian Buttes swarm in 2005 with the largest earthquake being a magnitude 5.1 event located 10 km from the site. The swarm contained numerous events in the M = 3 to M = 5 range. The largest ground accelerations from this swarm were around 0.1g from the 5.1 and some of the larger magnitude 4 events. At this level of acceleration, pore pressure response is easily seen at all depths within the liquefaction array. The data from the five pore pressure transducers over a 1-hour period during this swarm of earthquakes is plotted below in Figure 6, from shallowest to deepest (top to bottom).

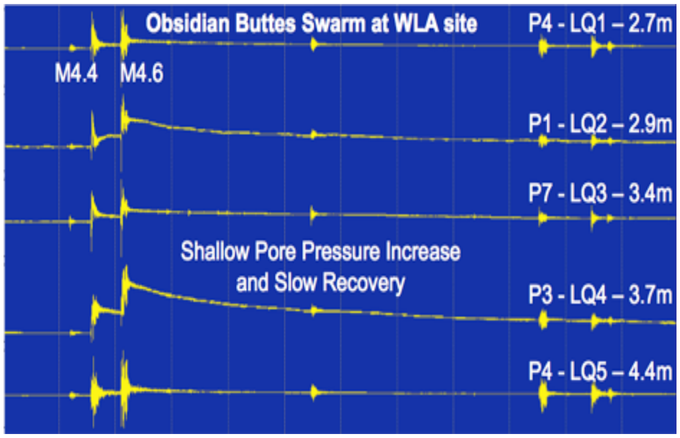

Figure 6. Sixty minutes of WLA data from the 2005 Obsidian Buttes swarm. The data show both the dynamic response of the pore pressure sensors and the static pressure increase, with slow dissipation.

A smaller event recorded at WLA (23 February 2006, M = 3.6) is plotted below in Figure 7. Here the pore pressure response continues long after the accelerations have died off. The pore pressure response appears to be correlated to the displacements from surface waves in the Imperial Valley.

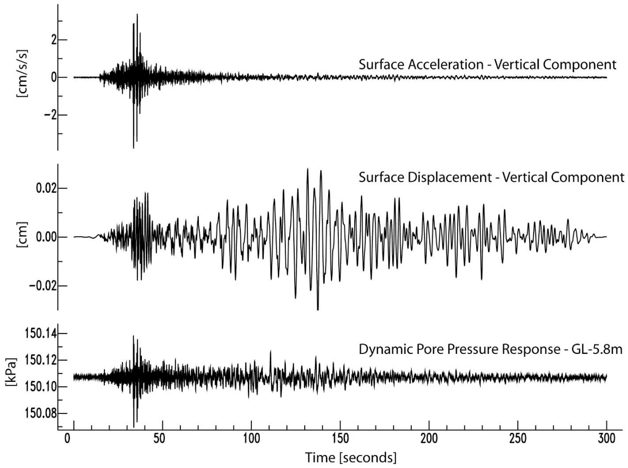

Figure 7. Acceleration, displacement and pore pressure recorded at WLA from M3.6 event.

GVDA Events

The largest motions recorded at the GVDA site are also at the level where the onset of nonlinear soil behavior is expected, around 0.1g peak ground acceleration. Observations from the liquefaction array sensors to this level of excitation show the build up of pore pressure and the slow decay back to the background level similar to the response seen at the WLA site. A magnitude 5.1 earthquake near Anza, California, produced a quality set of observations showing this behavior at GVDA (Figure 8). Interestingly, the shallow transducers show increases in pore pressure during the strongest shaking, while the deeper transducers seem to show the opposite effect. One possible explanation for this could be dense dilatant soils that are exhibiting negative pore pressures due to shear strain.

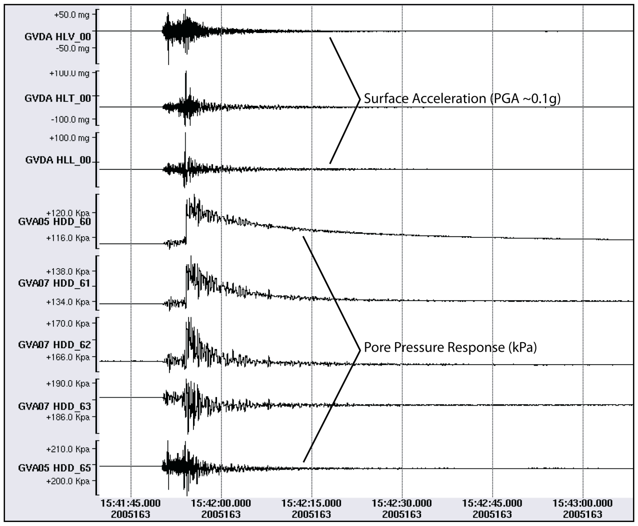

Figure 8. Pore pressure and accelerations recorded over ~90 seconds at GVDA from the M = 5.1 Anza event.

The 1999 M7.1 Hector Mine Earthquake

The 1999 Magnitude 7.1 Hector Mine earthquake occurred at a distance of approximately 110km from GVDA (Figure 1). The unique *in situ* observations of both ground motion and pore pressure in saturated alluvium during the Hector Mine earthquake provided the ideal data set for examination of the dynamic soil behavior properties during ground shaking. These observations included ground motions on the order of 10%g, generally considered to be at about the range where nonlinear soil behavior, and excess pore pressure generation might be considered a factor in site response estimation. The pore pressure observations from this event include a steady increase in pore pressure with time, and then a slow steady decrease back to the pre-event pore pressure level (Figure 9). Riding on top of this longer period trend are higher frequency dynamic oscillations.

These observations are used as the control motions for calibration of nonlinear computational models of the dynamic soil behavior. The Hector Mine event was the first recorded earthquake at Garner Valley that generated an observed pore pressure increase in the near-surface alluvium. Evidence of the onset of nonlinear soil response is seen in the acceleration and pore pressure records of the Garner Valley vertical array in the upper 10 – 20 meters. This build-up of pore pressure correlates with a breakdown in the linear behavior of the stress-strain time histories (*Steidl et al., 2001*).

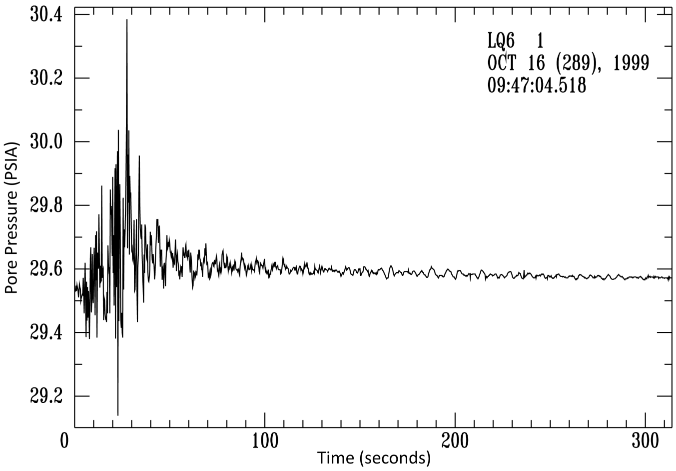

Figure 9. A five-minute record of pore pressure response observed at GVDA during the Hector Mine M7.1 event.

ANALYSIS RESULTS

The Hector Mine data set was used to perform full nonlinear modeling of ground response, including the effects of the pore pressure. The numerical model NOAH is a Nonlinear Anelastic Hysteretic finite difference code that computes the nonlinear wave propagation in saturated soil deposits subjected to vertically incident SH ground motion (Bonilla, 2000; Bonilla *et al.*, 2005). This model applies generalized Masing rules for maximum stress and damping constraints. It also takes into account the cyclic mobility and dilatancy of sands. The model is based on the strain space multi-shear mechanism (Towhata and Ishihara, 1985; Iai *et al.*, 1990), where pore pressure build-up depends on the cumulative shear work done during the shaking.

A model of horizontal layers of the Garner Valley site was developed for use with NOAH based on an approximation of the site characterization data at the site. Figure 10 shows the input layered model to the finite difference code, which requires values of P-wave velocity α, S-wave velocity β, damping Q and material density ρ.

The simulation using NOAH predicts excess pore pressure generation with time (Figure 11, red line) during the strong shaking of the earthquake. Note that the model assumes an undrained condition so there is no pore pressure decay over time. Clearly this is not the case for the GVDA site as the observed pore pressure response includes a slow decay with time after the strong shaking has subsided (Figure 9 & 11).

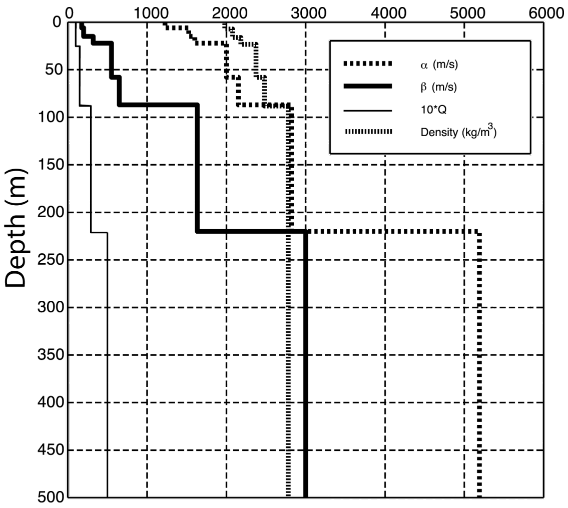

Figure 10. Material properties and input accelerations to the finite difference model of GVDA.

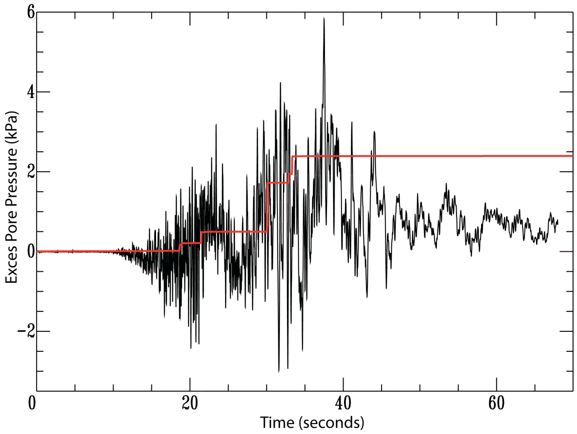

Figure 11. Observed excess pore pressure recorded at GVDA during the Hector Mine earthquake (black line) and simulated pore pressure generation (red line) using NOAH.

Synthetic accelerations, computed at the surface by NOAH, are plotted along with the recorded surface accelerations for the Hector Mine earthquake in Figure 12. The input motion to the model is the motion observed at 50 meters below the surface where the material behavior could be considered linear. The comparison of the 5% damped response spectral acceleration between the simulation and observed compare well with one another except out at longer periods where the simulation tends to over predict the observed motions.

CONCLUSIONS AND FUTURE WORK

It is well established that the build up of pore pressure during earthquake shaking correlates with a breakdown in the linear behavior of the stress-strain relationship in the material. The numerical model NOAH, which computes the nonlinear wave propagation in saturated soil deposits, is able to reproduce the build up of pore pressure and the observed surface ground motions, using records from the GVDA site.

Research using earthquake data has traditionally focused on liquefaction in hindsight: identifying the point in time at which the pore pressure ratio exceeds one, the soil liquefies, and then studying the subsequent ground response. Additional work to be completed for this conference includes the development of an empirical model to enable the prediction of pore pressure generation before the large earthquake occurs based on expected ground motions within a saturated soil column. The new prediction model will be based in large part on the observed data from the GVDA and WLA field sites.

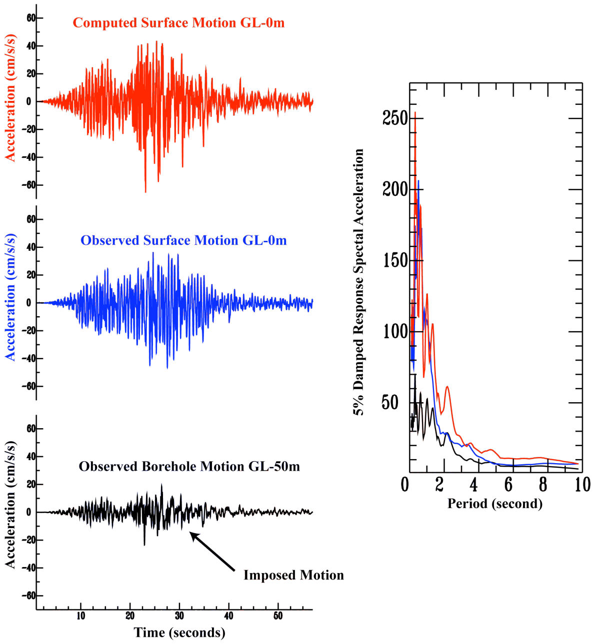

Figure 12. Synthetic surface accelerations(red) computed by NOAH compared to observed.(blue) for the Hector Mines earthquake at GVDA and their spectra. The motion input to the model at 50 m is shown in black.

The current study is intended to go beyond just an empirical correlation between ground motion and pore pressure response, but to also develop a physical basis for the liquefaction process based on the characteristics of the ground motion excitation. In this way, it is similar to previous work done by Zeghal and Elgamal (1994) and Holzer and Youd (2007) using the 1987 Superstition Hills data recorded at the previous WLA site. Holzer and Youd (2007) found that, during the P-wave arrivals, the pore pressure response tracked the vertical accelerations and thus was responding to volumetric strains. Zeghal and Elgamal showed that shear strain, as recorded by pore pressure, continued after the strong shaking had ceased. Holzer and Youd (2007) proposed that surface waves are the source of this phenomenon, and the data from the new WLA site shown in Figure 7 seem to support this.

The goal of the current work is to continue to examine the underlying properties of the ground motion that drive the liquefaction process by studying both the time domain and frequency domain characteristics of the excitation. This includes looking at windows on the P-wave, S-wave, and surface wave trains, the particle motions in both vertical and horizontal planes, and the spectral content of these time windows as well as the full record spectral content and strong shaking duration effects.

Analysis of these new sets of data from the GVDA and WLA field sites will continue to improve our understanding of the physical process that drives liquefaction and nonlinear soil response.

ACKNOWLEDGMENTS

The authors acknowledge the contributions of Hank Ratzesberger, Paul Hegarty, Les Youd, Rob Steller, and Rod Merril in the construction, maintenance, and operations of the field sites. The authors wish to thank Francesco Civilini for his assistance in preparing this manuscript. The GVDA and WLA sites are currently operated under contract with the National Science Foundation as part of the George E. Brown Jr., Network for Earthquake engineering Simulation, award number CMS-0402490. The UC San Diego High Performance Research and Education Network (HPWREN), NSF award number 0426879, make real-time data telemetry possible. Without the support and cooperation of the Lake Hemet Municipal Water District and the California Department of Fish and Game, the monitoring at the GVDA and WLA sites would not be possible.

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