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INSTRUMENTED FIELD SITES AND LIQUEFACTION MONITORING IN THE UNITED STATES

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Abstract

Instrumented geotechnical field sites are designed to capture the infrequent but critically important *in situ* case histories of ground response, deformation, and liquefaction during significant earthquakes that generate high intensity ground shaking and large strains. The University of California at Santa Barbara has been monitoring densely instrumented geotechnical array field sites for almost three decades. Currently these field sites include the Wildlife Liquefaction Array (WLA), the Borrego Valley Downhole Array (BVDA), the Garner Valley Downhole Array (GVDA), the Hollister Earthquake Observatory (HEO), the San Jose 101/280 Interchange Array (SJI), the Seattle Liquefaction Array (SLA), and the Delaney Park Array (DPK). The sites are geographically distributed throughout the most hazardous part of the United States, including three sites in southern California, two sites in central California, one Pacific Northwest site in Seattle, and one site in Anchorage Alaska. The design objective of these sites is to capture the penultimate earthquake in each region and instrumental observations of the earthquake effects associated with such events. The broader objective is to capture a suite of earthquakes covering a range of ground motions and strain levels at each of these sites, to enable calibration of ground motion prediction models that include the effects of the near-surface geology from linear through nonlinear behavior. The WLA, BVDA, GVDA, and HEO sites are maintained solely by UCSB, while the SJI, SLA, and DPK sites are maintained by the corresponding regional seismic network and the United States Geological Survey (USGS), with some assistance from UCSB.

UCSB provides access to the instrumental case histories generated by earthquake recordings at these field sites (as well as co-located instrumented structures at some of the sites), through a web-based data dissemination portal (http://www.nees.ucsb.edu/data-portal). Highlights of the last decade of monitoring include the newest liquefaction monitoring facility in Seattle, Washington, the recently re-instrumented San Jose 101/280 interchange array, and more than a dozen observations of excess pore pressure generation during earthquake shaking at two facilities in southern California, with PGA ranges from 0.05g to 0.33g and strains from 10^{-5} to $2x10^{-3}$. Enhancements to the facilities include long-term monitoring of an Induced Partial Saturation (IPS) test pad for liquefaction mitigation, and permanently deployed cross-hole hammer source and receivers for examining shear modulus degradation and recovery following earthquakes. Contributing these case histories for the development and validation of models that predict site response, liquefaction initiation, ground displacements and settlement, and soil-foundation-structure interaction effects, is the ultimate goal of this monitoring effort.

Keywords: Engineering Seismology; Site Effects; Borehole Arrays; Liquefaction; Nonlinear Soil Response

1. Introduction

In order to reduce the impact of earthquakes on buildings and critical facilities, the development of analytical and empirical models for accurate prediction of earthquake effects (ground shaking, liquefaction, and permanent deformation) is required. An important element to the development of these models, are well-instrumented geotechnical field sites where actual ground response and deformation, and excess pore pressure generation can be monitored during earthquake shaking both at the surface and at depth. The resulting observations provide the benchmark case histories for model verification, calibration, and further development.

An instrumented geotechnical array is defined as a site where accelerometers and pressure transducers are deployed at the surface and in multiple boreholes distributed within the soil column and if possible within the rock below. At sites where lateral spreading and ground failure is expected, additional inclinometer casings and regularly surveyed benchmarks would also be used. The University of California at Santa Barbara has been monitoring densely instrumented geotechnical array field sites for almost three decades now. Currently these field sites include the Wildlife Liquefaction Array (WLA), the Borrego Valley Downhole Array (BVDA), the Garner Valley Downhole Array (GVDA), the Hollister Earthquake Observatory (HEO), the San Jose 101/280 Interchange Array (SJI), the Seattle Liquefaction Array (SLA), and the Delaney Park Array (DPK). The sites are geographically distributed throughout the most hazardous part of the United States, including three sites in southern California, two sites in central California, one Pacific Northwest site in Seattle, and one site in Anchorage Alaska (Fig. 1). The WLA, BVDA, GVDA, and HEO sites are maintained solely by UCSB, the while the SJI, SLA, and DPK sites are maintained by the corresponding regional seismic network and the United States Geological Survey (USGS), with some assistance from UCSB. The data from all seven of these facilities flows in real-time to UCSB and is disseminated along with the relevant metadata at the UCSB geotechnical array data portal (http://www.nees.ucsb.edu/data-portal). Contributing to the development and validation of models for site response, liquefaction initiation, ground displacements and settlement, and soil-foundation-structure interaction effects, are the primary goals of this observation and analysis effort.

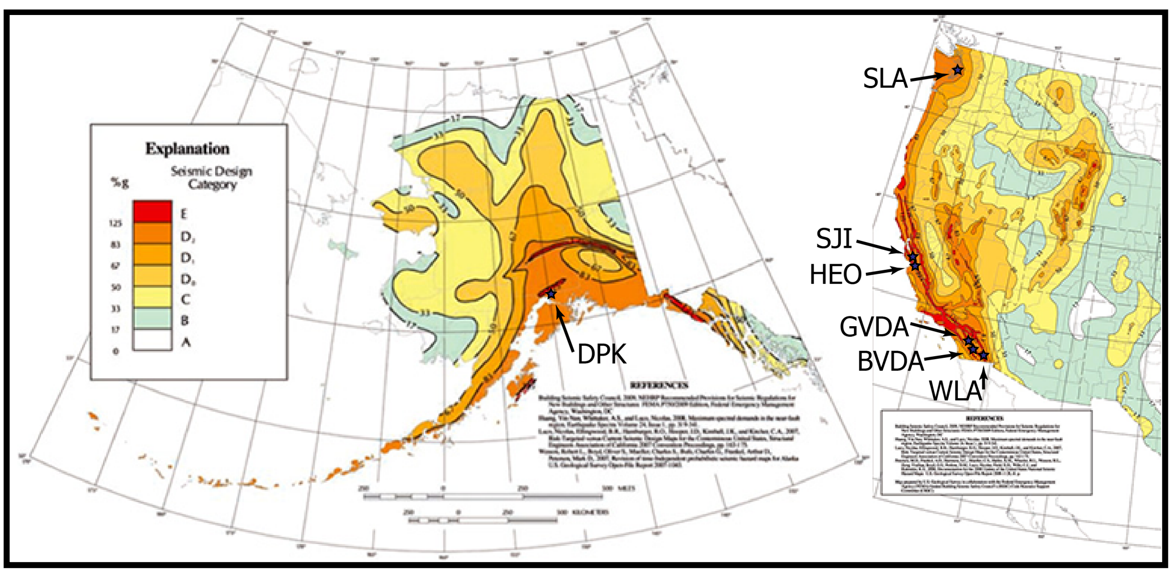

Fig. 1 - Map showing the Seismic Design Category (SDC) for the US western lower 48 and Alaska showing the location of the geotechnical array field sites. Hotter colors denote higher shaking hazard and increased earthquake resistant design standards in the building codes.

The design objective of these sites was to capture the penultimate earthquake in each region and instrumental observations of the earthquake effects associated with such events. The broader objective is to capture a suite of earthquakes covering a range of ground motions and strain levels at each of these sites, to enable calibration of ground motion prediction models that include the effects of the near-surface geology from linear through nonlinear behavior.

2. The Observation Facilities

The Geotechnical Array network consists of four sites that are operated by UCSB, and three other sites that UCSB assists with the operations, and does data processing and archival for dissemination. Each array consists of anywhere from 12 to 110 channels of data depending on the complexity of the facility, with a total of 299 channels of data, and 247 of these being the California sites maintained solely by UCSB. Extensive site characterization information is available for most of these arrays, which sample a variety of soil classes and geographic regions, providing a good cross-section of site types and a higher probability of obtaining significant data each year.

The field sites provide continuous real-time data at 200 samples per second using modern communications network technology, providing detection of earthquakes as small as magnitude one, and on-scale recording of peak ground accelerations as large as +/- 4g peak ground accelerations. The data are automatically archived locally at each field site and using multiple RAID-based database systems at UCSB. The data from these sites is also shared in real-time with the Advanced National Seismic System (ANSS) regional network operators who use this data for earthquake locations and shake map generation. The seven arrays are described in more detail below.

2.1 Wildlife Liquefaction Array (56 Channels)

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. Earthquakes have frequently shaken this region, with six in the past 85 years, generating liquefaction effects at or within 10 km of the WLA site [1]. Based on this history, there is high expectation that additional liquefaction-producing earthquakes will shake the WLA site in the future, which led to the selection of this location for development of a permanently instrumented facility in 1982 by the USGS, and a major upgrade of the site in 2002-2004 by the National Science Foundation (NSF).

Details of the geotechnical site conditions and instrumentation at the WLA facility can be found at the UCSB website (http://nees.ucsb.edu/facilities/wla), and in previous studies of the observations from this site [2, 3, 4, 5, 6, 7, 8]. The water table is between 1-2 meters and the V_s30 is ~170 m/s. The WLA site is representative of a saturated liquefiable soil site in NEHRP Site Class E/F. The 2004 NEES WLA site upgrade includes 9 pressure transducers within the liquefiable layer and a surface barometer, 3 surface accelerometers and 6 borehole accelerometers (all three-component) above, within, and below the liquefiable layer.

In 2005 after the NEES upgrade, additional funds were provided to re-instrument the old USGS site (NP.5210), ~70m up-river from the newly upgraded NEES site (SB.WLA). In addition to the accelerometer below the liquefiable layer and at the surface that was part of the original USGS instrumentation plan [2], an additional sensor was installed at the top of the liquefiable layer at 3 meters depth. Three pore pressure transducers were installed at the top, middle, and bottom of the liquefiable layer. In 2014, five additional pore pressure transducers were installed near the NP.5210 site and are now recording continuously, all located within the upper half of the liquefiable layer. These were part of a U.S. National Science Foundation (NSF) funded research experiment to monitor an induced partial saturation liquefaction mitigation method.

Continuous observations from the WLA facility are providing unique data on the evolution of site response and excess pore pressure generation during earthquakes at an unprecedented level of spatial and temporal detail. Between the "NEES" WLA and "USGS" WLA sites, there are now a total of 56 channels of continuous real-time data. Since 2004, over 9,500 M1+ events have been recorded and made available via the UCSB data dissemination portal (http://www.nees.ucsb.edu/data-portal), including 35 M5+ events and 1 M7.2 event (2010 El Mayor-Cucapah). The maximum PGA is 0.33g from a M4.9 at ~10 km, and a maximum excess pore pressure ratio of 60% from that same event. Over 25 events have produced measurable excess pore pressure generation since 2004.

In addition to the real-time sensor technology, the site has inclinometer casings and an array of benchmarks that are typically surveyed once every 2-3 years, to provide a regularly surveyed baseline at the site prior to any future significant event that might cause lateral spreading or settlement.

2.2 Garner Valley Downhole Array (110 Channels)

The Garner Valley Downhole Array (GVDA) was also part of the 2002-2004 NSF Upgrade Program, and has been operated by UCSB from 1989 to the present. The GVDA test site is situated in a narrow valley within the Peninsular Ranges batholith, 23km east of Hemet and 20km south-west of Palm Springs, California. It is located 7km and 35km from the San Jacinto Fault (SJF) and the San Andreas Fault (SAF), respectively. The SJF is historically the most active strike-slip fault in the SAF system, with a slip rate of ~10 mm/year, and the southern SAF is an active fault with a slip rate of ~25 mm/year.

The GVDA near-surface geological conditions consist of soft alluvial lake deposits to a depth of 18-25 meters overlaying weathered granite, with crystalline bedrock at ~90 meters depth. Multiple impedance contrasts at several depths exist at this site, resulting in a complex amplification of ground motion. The fundamental frequency is found to be around 1.7Hz [9, 10, 11, 12] and several higher resonance frequencies exist at 3, 6, 8 and 12Hz.

In-situ surveys have been performed, providing an extensive description of the site in terms of geotechnical and geophysical characteristics [9, 13, 14, 15, 16, 17]. The shear-wave velocity ranges from 90m/s in the uppermost layer to 3,500m/s at the bottom (500m depth). Stokoe and Darendeli [18] performed laboratory tests to extract the *G-γ* curve of the surficial sediments on *insitu* samples taken from the site at various depths. The *in situ* details of the geotechnical site conditions and instrumentation at the GVDA facility can be found at the UCSB website (http://nees.ucsb.edu/facilities/gvda).

The borehole array at Garner Valley consists of seven 3-component accelerometers located at GL-0m (GL: ground level) and at GL-6m, GL-15m, GL-22m, GL-50m, GL-150m and GL-501m. Additionally, there are five other surface 3-component accelerometers and a 3-component rotational sensor. Approximately 3km from the main station at GVDA, a remote rock outcrop site is deployed at the Lake Hemet dam abutment, with 3-component surface and GL-30m borehole accelerometers.

At GVDA, a deep bedrock borehole was drilled in 1994 to a depth of 520 meters. This unique well is artesian, and sealed off at the surface. Six stainless steel sampling lines extend into the borehole to various depths. Five of the lines extend to just below each of the top five packers (all except the accelerometer packer at the bottom). The sixth line extends just below the wellhead at the top of the borehole. Each sampling line is connected to a pressure transducer at the surface, where pressure measurements are made of each zone. These transducers were installed to measure *in situ* the response of the local bedrock and the ambient hydrostatic pressure to seismic waves and tectonic strains. Two fracture zones that produce water based on flow-meter logs are sealed off above and below with packers, and the pressure is monitored above, within, and below these fracture zones via the stainless sampling lines and transducers at the surface. The GL-501m accelerometer is installed at the bottom of this borehole in a zone of intact granitic bedrock with no fractures (V_s = 3.5 km/s).

Observations from the 520-meter borehole instruments to date include dynamic changes during the passage of seismic waves from local, regional, and teleseismic earthquakes, static pressure changes from local earthquakes, and daily changes in pressure induced by earth tides. In general, the dynamic pressure response to earthquakes is proportional to the amplitude of motion. These deep instruments continue to be monitored at 200 sps along with all the other channels at GVDA, as understanding the effect of static and dynamic earthquake ground deformation on the hydraulic conductivity of groundwater systems has relevance to any proposed deep storage of high-level nuclear waste and potential carbon sequestration reservoirs.

At GVDA, an instrumented structure for the study of soil-foundation-structure interaction (SFSI) is monitored with 36-channels of structural data. These include displacement strain gauges and vertical accelerometers on the 4 corners, 3-component accelerometers on the base and roof slabs, 3-component rotation on the base slab, load cells under the 4 corners of the base slab, and pore pressure and 3-component acceleration under the structure. A permanent remotely operable shaker is mounted to the roof slab, and remotely operable cross-hole hammer source with geophone array is also installed under the structure [19]. In addition to the earthquake sources, the cross-hole source and roof mounted shaker allow daily observation of structural and ground response showing seasonal variations related to changes in the water table height. The cross-hole source is programmed run more frequently following significant earthquakes. The combination of structural, ground motion, pore pressure, cross-hole, and remote outcrop arrays at GVDA make up a total of 110 channels of 200 sps continuous data that are streamed 24/7 to UCSB and archived.

Since 2004, over 6,500 M1+ events have been recorded at GVDA and made available via the UCSB data dissemination portal, including 37 M4+ events within 100 km, and 1 M7.2 (El Mayor-Cucapah). The maximum PGA is 0.17g from a M5.2 at ~18 km, and a maximum excess pore pressure ratio, $R_{u,}$ of ~20% from that same event. Four events have produced measurable excess pore pressure generation since 2004 at the Garner Valley site, and also the 1999 Hector Mine M7.1 earthquake. Given the level of seismicity in this region, the likelihood of the "Anza" event on the San Jacinto Fault zone, and the likelihood of a significant event on southern San Andreas Fault or Elsinore Fault, the GVDA site remains in a position to provide unique observations from these potential earthquakes. While there has been numerous publications and interesting results to date using the GVDA data, the events that this facility was designed to capture have yet to occur, providing the large-strain case histories, potentially including liquefaction, to help calibrate nonlinear soil models.

2.3 Borrego Valley Downhole Array (45 Channels)

In 1993, Kajima Engineering and Construction Corp. of Japan contracted with Agbabian Associates to construct the Borrego Valley downhole array (BVDA) near Borrego Springs, in Southern California. In this array there are four borehole instruments extending to depths of GL-9, GL-19, GL-139 and GL-238 meters. In addition, BVDA has 8 surface instruments extending in two directions across the Borrego Valley, with a remote rock site at the edge of the valley that includes surface and borehole sensor. The BVDA facility was donated to UCSB in 2000, and continuous data transmission began in 2008 with borehole sensor upgrades in 2012. Since 2008, over 6,500 M1+ events have been made available for download from the UCSB data dissemination portal, including 70 M4+ events within 100 km, and 1 M7.2 (2010 El Mayor-Cucapah) at over 100 km distance. The maximum ground motion recorded is 0.16g from a M5.4 at 15 ~km distance. At BVDA, 29 channels are real-time, with some of the more distant surface and the remote rock stations in triggered mode using the older Kinemetrics K2 technology.

The details of the geotechnical site conditions and instrumentation at the BVDA facility can be found at the UCSB website (http://nees.ucsb.edu/facilities/bvda). At the main station the shear wave velocity gently increases from about 300 m/s at the surface to 750 m/s at 230 m depth—the granite interface—where it jumps to 2500 m/s. The water table is at ~100 m; BVDA is representative of a deep alluvial dry site with a V_s30 of ~395 m/s just above the NEHRP site class D/C boundary (stiff soil). The 3-D basin structure of the upper Borrego Valley is compliceted [20] and has been studied using data from the borehole and surface arrays [21]. Spatial variability and ground motion coherence has also been studied using data from the BVDA facility [22, 23].

2.4 Hollister Earthquake Observatory (27 Channels)

In 1991, Kajima Engineering and Construction Corp. of Japan contracted with Agbabian Associates to construct the Hollister Earthquake Observatory (HEO), located at the northern end of the Salinas Valley between the cities of Hollister and Salinas, in central California, ~10 km from the San Andreas Fault. At the HEO main soil station accelerometers are located at 192, 110, 50, 20, 10, and 0 meters depth, going from crystalline rock at the bottom, up through consolidated and unconsolidated alluvium to the surface. The water table is approximately 30 meters. Three sensor locations, surface Tertiary sandstone, surface Granite, and GL-53 meter borehole Granite are instrumented at the HEO remote rock outcrop station. All sensors are 3-component accelerometers.

Measured velocity profiles at both the main soil station and the remote rock station are available, as well as geotechnical lab testing results. The main station has a V_s30 of ~355 m/s making it a stiff soil site. The remote rock station has a V_s30 of ~590 m/s (soft rock) with a velocity of 2.5 km/s at 40 meters depth. The location of HEO along the San Andreas Fault in Central/Northern California makes it an important addition to the UCSB geotechnical array monitoring program, providing expanded geographic coverage and a basin/rock-outcrop pair within 3km. The HEO facility was donated to UCSB in 2000, and continuous data transmission of 15 channels (6 at main station, 9 at remote station) began in 2005 with over 3,600 M1+ events available for download at the UCSB data dissemination portal.

2.5 Seattle Liquefaction Array (19 channels)

The Seattle Liquefaction Array (SLA) was installed in February of 2012 as a joint effort between the University of Washington (UW), the USGS ANSS program, and UCSB. The site is located in the Duwamish river valley in the "SoDo" or south of downtown industrial district of Seattle, with very soft Holocene sediments that are highly susceptible to liquefaction. The V_s30 at this site is ~135 m/s which puts it in Site Class E/F. The site instrumentation consists of a surface and three downhole 3-component accelerometers. Six pressure transducers are also installed between 6 and 52 meters depth.

UCSB was involved in the design, and deployment of the SLA facility, and has partnered with the University of Washington and USGS since deployment, acquiring continuous data in real-time through data exchange with the PNSN. A total of 126 M1.0 to M4.0 events within 75 km of SLA have been segmented from the continuous data and are available for download at the UCSB data dissemination portal. Given the urban location of this array, and the fact that the site is located directly adjacent to a large train yard that serves both commuter and freight train traffic, the background noise at this site is relatively high, and thus most of the segmented events are buried within the noise. The surface layout of the SLA facility adjacent to the train yard provides an excellent periodic source that serves as a functional test for all the instruments. The trains provide small excess pore pressure generation across the array of pressure transducers, with the magnitude being proportional to the length and weight of the trains. After the first 4 years of monitoring, the trains and a few local and larger regional (M6's at 450-7500km) earthquakes have provided the largest recorded ground motions to date, all less than 1%g.

2.6 Delaney Park Geotechnical Array (21 Channels)

Instrumented buildings are a significant component of the USGS Advanced National Seismic System (ANSS). In order to examine structural response as well as soil-structure interaction, and the effects of surface geology on the input motions to structural arrays, the ANSS program has deployed borehole instrumentation at some instrumented structures in the United States.

Downtown Anchorage Alaska sits on top of the great Alaskan subduction zone and has been subjected to large damaging earthquakes in the past. The March 27th, 1964 (Good Friday), magnitude 9.2 great Alaska earthquake shook the ground for more than 4 minutes over a 50,000-square-mile region and caused 131 deaths. One of the first buildings to be fully instrumented under the ANSS program is the Robert Atwood Government Building in downtown Anchorage Alaska, a 20-story steel-frame structure with a single story basement and a reinforced-concrete foundation. The building instrumentation is complemented by an array of 3-component accelerometers in six boreholes ranging in depth from 15 to 200 feet (5-60 meters), with a seventh sensor at the surface. These sensors were installed and UCSB began recording the geotehnical array continuously in 2005, and the structural array in 2014. The borehole array is located a city block from the building in an open park (Delaney Park Array – DPK), sufficiently removed from the building that the records are considered to be "free-field" observations. The borehole data thus record the input signal of the seismic waves impinging on the building.

The current data set at DPK consists of observations below 0.1g, where linear site response modeling provides the control data for the low-strain range of the constitutive soil model at this site. The future strong shaking events that will inevitably be recorded at this site are critical for extending the shear modulus degradation and damping curves out to the large strain regime in order to validate models that incorporate the nonlinear dynamic soil behavior during prolonged duration subduction zone events. Data from over 1,900 $M \geq 1.0$ events recorded in the last decade have been segmented out of the continuous data stream and are available for viewing and download at the UCSB data dissemination portal. This data set includes 103 $M \geq 4.0$ events, 24 $M \geq 5.0$ events, and 8 $M \geq 6.0$ events. The largest motions are from the recent 2016 M7.1 Iniskin earthquake (261 km distance), with surface PGA of 7.5%g. The majority of events are ≥ 40 km in depth, and many are quite distant, thus the lack of data above 0.1g so far for this site. In August of 2014, UCSB began to combine the continuous data from the Atwood building along with the geotechnical array, and now includes this structural data in the data dissemination portal.

2.7 The San Jose 101/280 Interchange Array (12 Channels)

The most recent addition to the geotechnical array data available at the UCSB data dissemination portal is from a USGS array that was re-instrumented in March of 2016. The array consists of three downhole and one surface 3-component accelerometer (12 Channels). The borehole sensors are located at depths of 17, 42, and 91 meters below the suface. The shear-wave velocity was determined back in 2003 when the 91 meter casing was installed using downhole logging, providing a V_s30 of ~215 m/s. We are still in the process of trying to locate additional site characterization information that might have been collected when the initial array was installed.

With only the first 3 months of continuous observations from the new array, 24 earthquakes with M ≥ 1.0 have been segmented out and are available at the UCSB data portal. The largest motions so far come from a M3.1 ~14km away, with a surfae PGA of 1.8 cm/s^2, less than 1%g. The location of this array inside a large freeway interchange overpass, in the middle of a large urban basin south of the San Francisco Bay, means that the data are inherently noisy. The penultimate earthquake for this array is a Hayward/Calavares fault rupture, which has a moderate probability of occurance, and should provide useful input ground motion data for modeling and understanding the structural response of this freeway interchange, as well as the nonlinear response of low velocity basin sediments.

3.0 Observations and Analysis Examples

In order to reduce the impact of earthquakes on buildings and critical facilities, a goal of earthquake engineering research is to generate analytical and empirical models for accurate prediction of earthquake effects (ground shaking, liquefaction, and permanent deformation) and to understand how these predictions affect the built environment. A required element for the development of these models, are well-instrumented test sites where actual ground response and deformation, and excess pore pressure generation, can be monitored during earthquake shaking. The resulting observations provide the benchmark case histories for model verification, calibration, and further development. These instrumented field sites are beginning to provide these case histories. Below are some examples of the observations and analysis of this data.

3.1 WLA Example

An example of these benchmark case histories discussed above is given by the data recorded at the WLA site during the 2012 Brawley swarm. This swarm provided an unprecedented data set of pore pressure and acceleration recorded within, and surrounding, the liquefiable layer at WLA, with six events producing significant ground motions (>1 m/s^2). This data has provided extremely interesting insights into the details of site response, excess pore pressure generation, and the liquefaction process. This includes examples of nonlinear soil behavior as seen through the reduction of high frequency amplification and also through the decrease in shear-wave velocity with increasing excitation levels [24].

An example of the unique excess pore pressure generation observations from this swarm are shown in Fig. 2. These measurements are typically expressed in kilo-Pascal (kPa), or pore pressure ratio R_u, a value between 0% and 100%, in which an R_u of 0% represents the normal hydrostatic pressure level, and 100% represents a pressure level equal to the total effective lithostatic load, a level at which the site would be considered liquefied. Fig. 2 is an example where the excess pore pressure is more than 20 kPa near the surface of the liquefiable layer, reaching an R_u of greater than 60%. These observations also show that the pore pressure at WLA tends to increase the most in the top part of the liquefiable sand layer, just below the impermeable clay cap, and occurs coincident with the S-wave arrival. The continuous data shows that the dissipation of excess pressure tends to be downward through the layer. As the pressure near the top of the layer begins to dissipate, the pressure is increasing towards the middle and bottom of the layer, showing the migration of the pressure pulse away from the base of the clay cap layer. Close examination of the pressure observations in Fig. 2 show sensor 67 is still increasing at 60 seconds after the event, while the sensors near the top of the layer (60, 62, 63) are dissipating. These *insitu* details augment the data from laboratory and centrifuge tests, and can enable our theoretical simulation capabilities and constitutive models to be validated against field-based case history data.

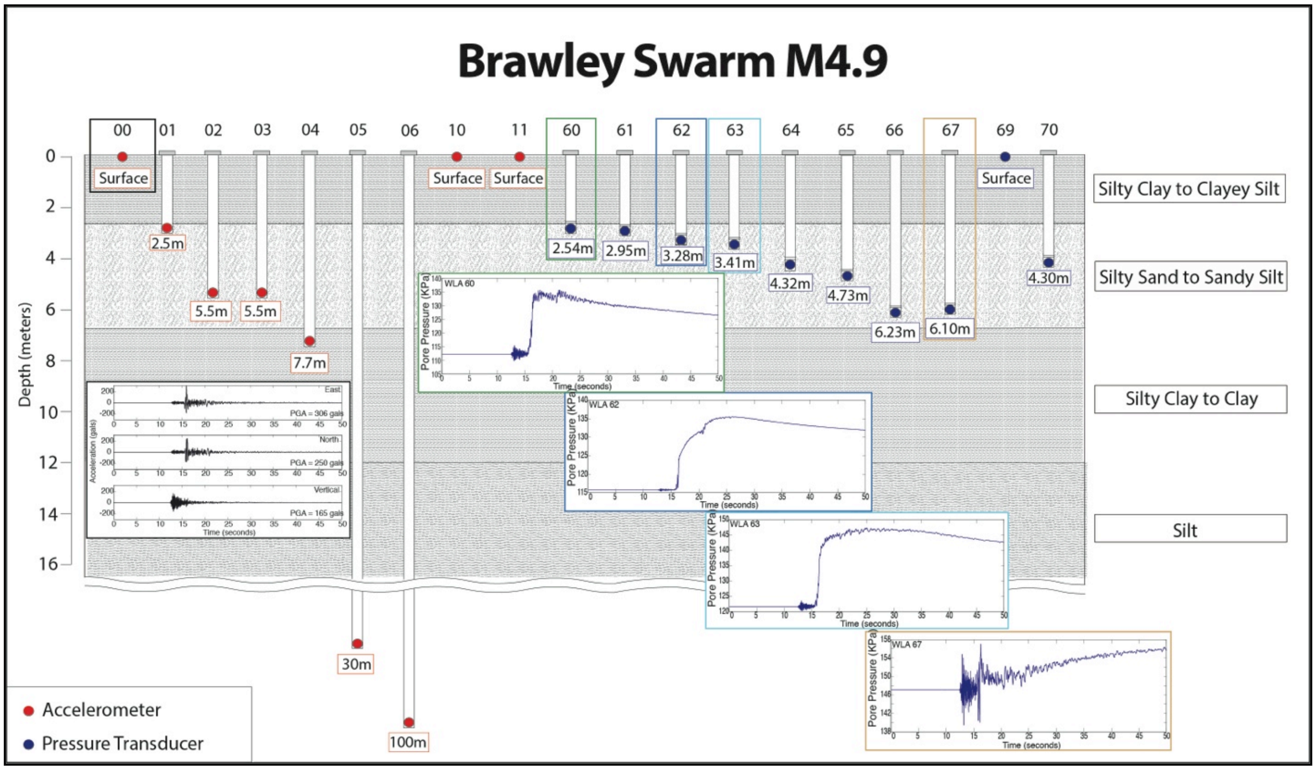

Fig. 2 Cross-section of acceleration (red) and pore pressure (blue) instrumentation at the WLA site, with sensor location codes listed above each instrument. Inset images show selected data from the 27 August 2012 M4.9 earthquake and image borders are color-coded to the box surrounding the sensor they correspond to.

As seen above, the benefit of having the field sites in regions of high seismic activity ensures that even without the "Big One" happening in the short term, the sites are still providing very useful observations. Another example of this is the ability to examine the evolution of shear modulus, *G,* with both strain level, γ, and in time during and between earthquakes. As the stress level increases during shaking (higher accelerations), the strains increase, and shear modulus decreases. Using surface observations, nonlinear response is observed by examining changes in the fundamental site frequency, f_0 [24, 25, 26], the variation of mode shape [27], or reduction of amplification of the sediment response [25, 28]. For geotechnical earthquake engineering applications involving soil nonlinearity, the site is generally characterized by establishing the G-γ curve (shear modulus degradation), using data from cyclic laboratory tests that are performed on collected samples form the field.

The field sites are now beginning to provide *in situ* G-γ curves covering a wide range of strain levels. An effective solution for observing *in situ* nonlinear response consists of measuring the shear wave velocity variation under different levels of excitation [29, 30, 31]. Using the vertical propagation of shear waves across sensors in the geotechnical arrays, we can calculate the material velocity using classical methods such as cross-correlation techniques [7, 32, 33] and more recently using seismic interferometry by deconvolution [8, 34, 35].

An example of the cross-correlation approach is shown in Fig. 3 for "old" USGS site (5210) and "new" NEES site at WLA [7]. The time lag calculated by cross-correlation between the accelerometer just below the liquefiable layer (~7.7 meter depth) and the accelerometer at the surface is plotted vs. peak surface ground acceleration. The smaller events (PGA's $\leq$ 40 cm/s^2), which occur both before and after the larger events, tend to show some variability around a nominal correlation lag, which when dividing the 7.7 meter distance by this time lag provides an estimate of the low strain velocity at the sites between these sensors. As the surface ground shaking increases, the correlation lag increases. This increase in time lag of the S-wave pulse traveling from below the liquefiable sand layer to the surface, as ground motion level increases, indicates that shear-wave velocity has decreased, caused by a reduction in stiffness at the site. Shear modulus degradation has occurred and decreased the S-wave velocity, somewhere in the upper 7.7 meters.

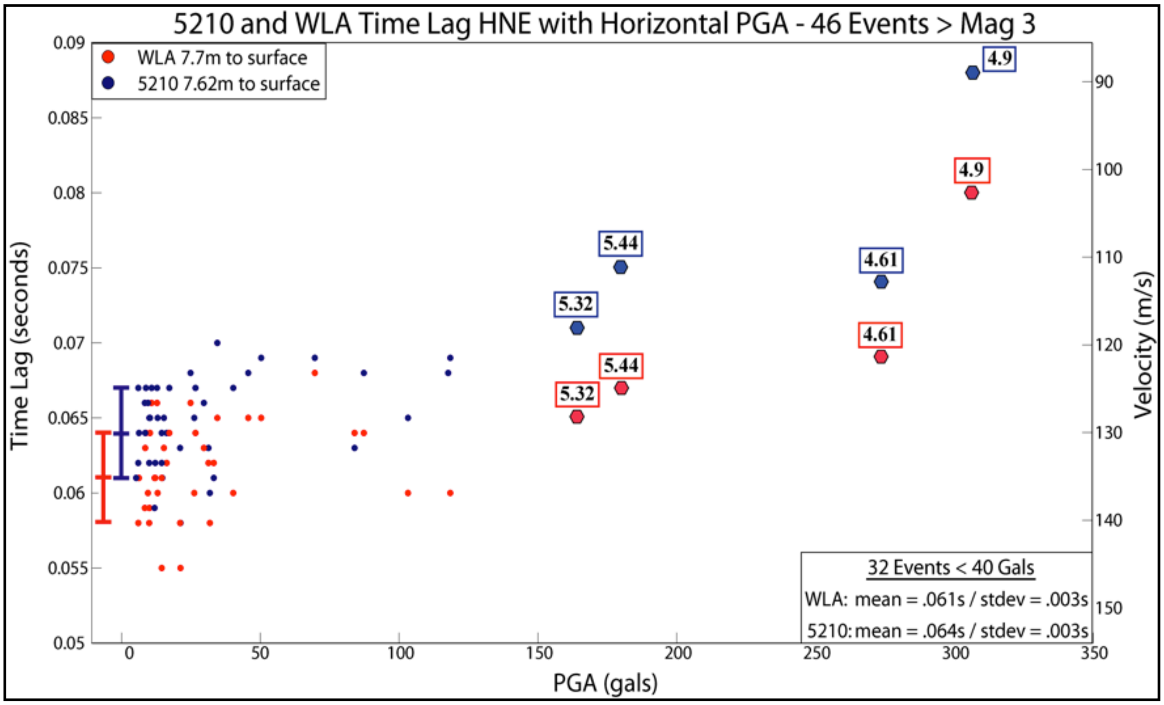

Fig. 3. Cross-correlation time lag plotted vs. surface PGA at the old (blue) and new (red) arrays at the WLA field site for events within the 2012 Brawley swarm.

The analysis of this type of velocity change can be repeated, using events that span a range of strain levels, to define the *in situ* shear modulus degradation curve (Fig. 3). The average strain between two accelerometers can be computed by double integration of the acceleration traces into displacement, and dividing the difference in displacement by the distance between the two sensors. Assuming the material density remains constant, the ratio of G^*/G_{max} for each event can be estimated by the ratio of the shear-wave velocity squared for each event $(V_s^*)^2$ to the square of the average low strain shear-wave velocity V_s^2, as shown in Figure 4.

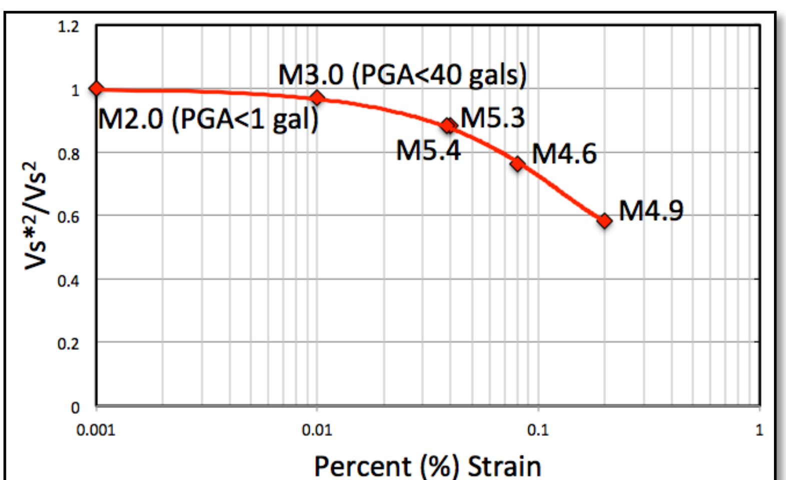

Fig. 4. *In Situ* shear modulus degradation represented by the decrease in shear-wave velocity plotted vs. increasing strain calculated using the vertical array at the WLA field site.

Consistent with laboratory testing [36] at strain levels of 10^{-5} to 10^{-4}, the results shown in Fig. 4 show that the soil stiffness remains in the region where linear elastic models can still be used to model the constitutive behavior at WLA. As we get to the range between 10^{-4} and $2x10^{-3}$, the site is now in the medium to large strain regime as defined by Ishihara [36; Table 3.1] and the site is now demonstrating clear nonlinear constitutive behavior, with the G/G_{max} proxy reduced to 0.6 for the M4.9 earthquake that had over 0.3g PGA and strains at $2x10^{-3}$.

3.2 HEO Example

An example of data from HEO is shown in Fig. 5 below for an M_W 5.1 earthquake that occurred 13 km east of the site with the acceleration time histories for the 180˚ horizontal component plotted. The largest acceleration occurs on the granite outcrop at the remote site. Note the similarity between the two borehole recordings in rock: GL-192m (bedrock borehole at main station) and Gl-53m (bedrock borehole at remote site). Notice the difference between the two outcrop observations at the remote site (Tertiary and granite), both which could be classified as rock in many attenuation models and used as the rock input motion for driving a nearby soil column. The Tertiary and granite recordings are located approximately 325 meters apart, while the GL-53 and GL-192 recordings are an order of magnitude further apart (3 km), yet are a much more consistent, and a better representation of the true input. Even while remaining in the linear strain regime PGA ≤ 0.1g), these records still emphasize the importance of the geotechnical array data.

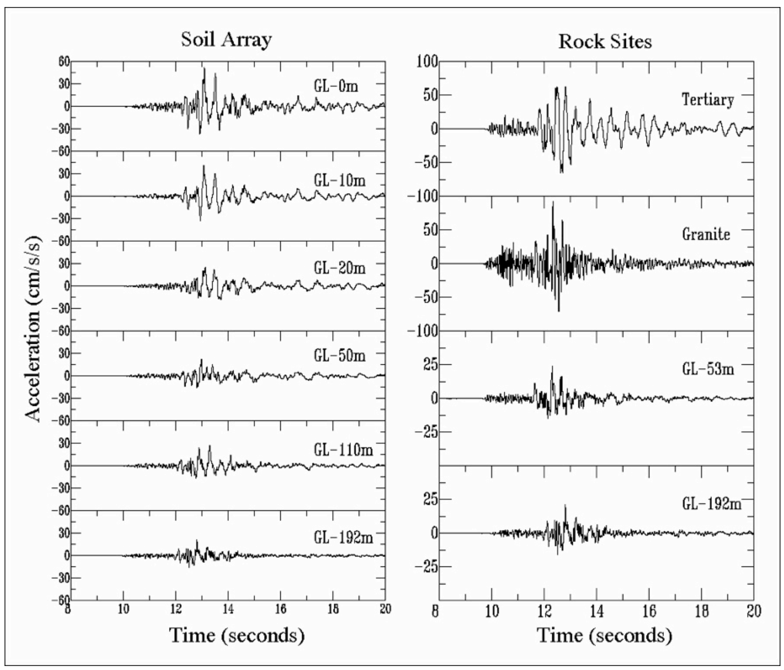

Fig. 5. Acceleration time history for an M5.1 earthquake recorded at HEO. Note the scale on left- and right-side are different. The main station GL-192 record is repeated on the right for comparison with remote rock site.

4. Conclusions

In over 25 years of UCSB field site monitoring, local and regional seismic activity has produced a valuable data set providing a unique opportunity to observe site response and the evolution of pore pressure generation with time throughout the liquefiable layer, at an unprecedented level of detail. These observations are providing *in situ* empirical evidence documenting the range of ground motion levels at which the onset of nonlinear behavior and excess pore pressure begins, augmenting previous case history data, and laboratory data from cyclic tri-axial and centrifuge testing. The ability to collect continuous data is extremely important in order to capture the long-term behavior of pore pressure evolution and dissipation with time. Continuous vs. triggered recording also provides important awareness of sensor and systems state-of-health, and assists in making sure as many sensors are functioning as possible when the significant events occurs.

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6. References

[1] Youd, T.L., J. H. Steidl, and R. L. Nigbor (2004): Lessons learned and need for instrumented liquefaction sites, *Soil Dynamics and Earthquake Engineering*, vol. **24**, Issues 9-10, p 639-646.

[2] Holzer, T. L., T. L. Youd, and T. C. Hanks (1989): Dynamics of Liquefaction during the 1987 Superstition Hills, California, Earthquake, Science, **244**, no. 4900, p. 56-59.

[3] Zeghal, M. & Elgamal, A. W. (1994): “Analysis of Site Liquefaction Using Earthquake Records”, *Journal of Geotechnical Engineering*, **120**(6), 996–1017.

[4] Holzer, T. L. and T. L. Youd, (2007): Liquefaction, Ground Oscillation, and Soil Deformation at the Wildlife Array, California, *Bull. Seism. Soc. Am.* 2007; **97** (3), 961 – 976.

[5] Steidl, J. H., R. L. Nigbor and T. L. Youd, (2008). Observations of *in situ* Soil Behavior and Soil-Foundation-Structure Interaction at the George E. Brown, Jr., Network for Earthquake Engineering Simulation (NEES) Permanently Instrumented Field Sites, *Proc. Fourteenth World Conf. Earthquake Engineering*, October 12-17, 2008; Paper S16-01-14, Beijing, China.

[6] Steidl, J. H., and S. Seale (2010): Observations and analysis of ground motion and pore pressure at the NEES instrumented geotechnical field sites, *Proceedings of the 5th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, May 24-29, San Diego, CA, paper No. 133b, ISBN-887009-15-9*

[7] Steidl, J. H., F. Civilini, and S. Seale (2014): What have we learned after a decade of experiments and monitoring at the NEES@UCSB permanently instrumented field sites?, *Proceedings of the 10th National Conference on Earthquake Engineering,* July 21-25, Anchorage Alaska.

[8] Chandra, J., P. Gueguen, J. H. Steidl, and L. F. Bonilla (2015): In-situ assessment of the G-g curve for characterizing the nonlinear response of soil: application to the Garner Valley Downhole Array and the Wildlife Liquefaction Array, *Bulletin of the Seismological Society of America*, 105, p. 993-1010.

[9] Archuleta, R. J., S. H. Seale, P. V. Sangas, L. M. Baker, and S. T. Swain (1992): Garner Valley downhole array of accelerometers: instrumentation and preliminary data analysis, *Bull. Seism. Soc. Am.,* **82**, 1592-1621 (Correction, *Bull. Seism. Soc. Am.,* **83**, 2039).

[10] Theodulidis, N., Bard, P.-Y. and R. J. Archuleta (1996): Horizontal to vertical spectral ratio and geological conditions: the case of Garner Valley downhole array in Southern California, Bull. Seism. Soc. Am., **86**, 306-319.

[11] Steidl, J. H., Tumarkin, A. G. & Archuleta, R. J. (1996): “What is a reference site?”, *Bulletin of the Seismological Society of America*, **86,** 1733–1748.

[12] Bonilla, L. F., J. H. Steidl, J-C. Gariel, and R. J. Archuleta (2002): Borehole response studies at the Garner Valley downhole array, southern California, *Bulletin of the Seismological Society of America*, **92**, p. 3165-3179.

[13] Pecker, A., and Mohammadioun, B. (1991): “Downhole instrumentation for the evaluation of non-linear soil response on ground surface motion.” *Trans. 11th SMIRT Conf.* K: 1991, Tokyo, Japan, pp.33-38

[14] Gariel, J. C., Mohammadioun, B., and Mohammadioun, G. (1993): “L’experimentation sismique de Garner Valley: Resultats Preliminaires” *Proc. of the 3eme Colloque National AFPS,* Saint-Remy-les-Chevreuse, France. ES p.18-27.

[15] Pecker, A. (1995): “Validation of small strain properties from recorded weak seismic motions.” *Soil Dynamics and Earthquake Engineering*., Vol.14, pp. 399-408.

[16] Steidl, J. H., Archuleta, R.J., Tumarkin, A.G., and Bonilla, L.-F. (1998): Observations and Modeling of Ground Motion and Pore Pressure at the Garner Valley, California, Test Site, in The Effects of Surface Geology on Seismic Motion (K. Irikura, K. Kudo, H. Okada, and T. Sasatani, Eds.), A. A. Balkema, Rotterdam, The Netherlands, Vol. 1, 225–232.

[17] Youd, T. L., Bartholomew, H. A. J., and Proctor, J. S. (2004): "Geotechnical logs and data from permanently instrumented fields sites: Garner Valley Downhole Array (GVDA) and Wildlife Liquefaction Array (WLA)." NEES@UCSB *internal report.*

[18] Stokoe, K. H., and Darendeli, M. B. (1998): "Laboratory evaluation of the dynamic properties of intact soil specimens: Garner Valley, California." *Geotechnical Engineering Report GR98-3,* Civil Engineering Department, University of Texas at Austin.

[19] Steidl, J.H., R. Gee, S. Seale, and P. Hegarty (2012): Recent enhancements to the NEES@UCSB permanently instrumented field sites, Proceedings of the 15th World Conference on Earthquake Engineering, September 24-28, 2012, Lisbon, Portugal, paper No. 4275.

[20] Martin, A. (1999): Geophysical Characterization of the Upper Borrego Valley, M.S. Thesis, Department of Geological Sciences, California State University, Long Beach, 259 pgs.

[21] Olsen, K.B., Nigbor, R., and Konno, T. (2000): 3D viscoelastic wave propagation in the upper Borrego Valley, California, constrained by borehole and surface data, *Bulletin of the Seismological Society of America*, **90,** 134-150.

[22] Ancheta, T.D., J.P. Stewart, N. A. Abrahamson, R. L. Nigbor (2008): "Preliminary estimation of seismically induced ground strains from spatially variably ground motions", in Geotechnical Engineering and Soil Dynamics IV,, May 18-22, 2008, Sacramento, CA, ASCE Geotechnical Special Publication No. 181, D. Zeng, M.T. Manzari, and D.R. Hiltunen (eds.), 10 pages (electronic file).

[23] Ancheta, T. D., J. P. Stewart, and N. A. Abrahamson (2011): Engineering characterization of earthquake ground motion coherency and amplitude variation, *Proceedings of the 4th IASPEI/IAEE International Symposium on The Effects of Surface Geology on Seismic Motion*, University of California, Santa Barbara.

[24] Beresnev, I.A., and Wen, K.-L. (1996): "Nonlinear Soil Response-A Reality?" *Bulletin of the Seismological Society of America.*, Vol.86, No.6, pp. 1964-1978.

[25] Tsuda, K., and J. H. Steidl (2006): Nonlinear site response from the 2003 and 2005 Miyagi-Oki earthquakes, *Earth, Planets, and Space*, **58**, 1593-1597.

[26] Wu, C., Peng, Z., and Assimaki, D. (2009): Temporal Changes in Site Response Associated with the Strong Ground Motion of the 2004 Mw 6.6 Mid-Niigata Earthquake Sequences in Japan. *Bulletin of the Seismological Society of America*. 99(6): 3487-3495.

[27] Guéguen P., Langlais M., Foray P., Rousseau C., and Maury J. (2011): "A natural seismic isolating system: the buried mangrove effects." *Bulletin of the Seismological Society of America*., Vol. 101, Issue 3, pp. 1073-1080. doi: 10.1785/0120100129

[28] Assimaki, D., Steidl, J. H., and Peng, C. L. (2006): "Attenuation and Velocity Structure for Site Response Analyses via Downhole Seismogram Inversion." *Pure appl. Geophys.* 163: 81-118.

[29] Haskell, N.A. (1953): "The dispersion of surface waves on multilayered media." *Bulletin of the Seismological Society of America.* Vol.43, No. 1, pp. 17-34.

[30] Ohmachi, T., Inoue, S., Mizuno, K.-I., and Yamada, M. (2011): "Estimated cause of extreme acceleration records at the KiK-net IWTH25 station during the 2008 Iwate-Miyage Nairiku earthquake, Japan." *Journal of Japan Association for Earthquake Engineering*. Vol.11. Issue. 1, pp. 1_32-1_47.

[31] Dobry, R. (2013): "Radiation damping in the context of one-dimensional wave propagation: A teaching perspective." *Soil Dynamics and Earthquake Engineering*., Vol.47, pp. 51-61.

[32] Rubinstein, J.L, and Beroza, G.C. (2004): "Evidence for Widespread Nonlinear Strong Ground Motion in the Mw 6,9 Loma Prieta Earthquake." *Bulletin of the Seismological Society of America.*, Vol.94, No. 5, pp. 1595-1608.

[33] Rubinstein, J.L, and Beroza, G.C. (2005): "Depth Constraints on Nonlinear Strong Ground Motion from the 2004 Parkfield Earthquake." *Geophysical Research Letters*., Vol.32, L14313.

[34] Mehta, K., Snieder, R., and Graizer, V. (2007). "Downhole Receiver Gunction: a Case Study." *Bulletin of the Seismological Society of America*, Vol. 97, No. 5, pp. 1396-1403.

[35] Nakata, N., and Snieder, R. (2012). "Estimating near-surface wave velocities in Japan by applying seismic interferometry to KiK-net data." *Journal of Geophysical Research.,* Vol. 117, B01308.

[36] Ishihara, K. (1996). *Soil Behaviour in Earthquake Geotechnics*. Oxford Engineering Science Series. Oxford University Press.