ENGINEERING INSIGHTS FROM DATA RECORDED ON VERTICAL ARRAYS

Ralph J ARCHULETA[1], Jamison H STEIDL[2] And Luis Fabián BONILLA[3]

SUMMARY

We show how vertical arrays of accelerometers have provided fundamental data for the interpretation and analysis of the effects of near-surface geology on seismic ground motion. We have analyzed seismic data from vertical arrays in the United States and Japan under various seismic loading conditions and various site conditions. We have used data from the Garner Valley downhole array (GVDA), 7 accelerometers in a vertical array (depths from 0 to -500 m); the Hollister earthquake observatory (HEO), with a vertical array with 6 accelerometers (depths 0 to -192 m) along with a rock array (two surface rock sites and a borehole –53 m) about 3 km from the soil array; and the Port Island, Kobe array (PI), with 4 accelerometers from 0 to –83 m. Each of these arrays have detailed geophysical, geotechnical and laboratory information about the soil properties. Largest earthquakes recorded include the 12 August 1998 Mw 5.1 earthquake at a distance of 13 km (HEO); 28 April 1992 Joshua Tree Mw 6.1 at 45 km (GVDA) and 17 January 1995 Mw 6.7 Hyogo-ken Nambu at 3 km (PI). We have successfully modeled all three components of ground motion that includes the source, path, and site effects for small earthquakes at GVDA and reproduced the surface horizontal motion in phase and amplitude up to 10 Hz using records at -220 m for the Joshua Tree earthquake. Modeling of the Mw 5.1 earthquake at HEO using the records at -192 m reproduce the observed surface motion in both the time domain and in 5% damped response spectra. HEO data shows that borehole recordings in bedrock better represent rock reference ground motion than surface rock outcrop observations. Nonlinear modeling of the PI records shows the concentration of nonlinear response at shallow depths with little effect at depths more than 16 m.

INTRODUCTION

Borehole instrumentation provides a unique opportunity to directly measure the effects of surface geology. 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 & 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]. Clearly direct evidence of the magnitude and effect of nonlinearity of the soil response, the amplification and attenuation of seismic waves, the effects of smooth versus discontinuous variation of material properties, and the effects of water saturated versus dry soil conditions all depend on *in situ* borehole measurements at varying depths within the soil column.

[1] *Institute for Crustal Studies & Dept. of Geological Sciences, Univ. of California, CA, USA (ralph@crustal.ucsb.edu;)*
[2] *Institute for Crustal Studies, Univ. of California, Santa Barbara, CA, USA (steidl@crustal.ucsb.edu;)*
[3] *Institute for Crustal Studies & Dept. of Geological Sciences, Univ. of California, CA, USA (fabian@crustal.ucsb.edu;)*

The Garner Valley downhole array

The Garner Valley downhole array (GVDA) test site is designed to improve our understanding of the effects of a shallow soil column on the recorded ground motion at the surface of the column. The GVDA test site is located in southern California in a narrow valley within the Peninsular Ranges Batholith. The near-surface structure consists of an ancestral lake-bed with soft alluvium to a depth of 18-25 meters over a layer of weathered granite, with the competent granitic bedrock interface at 88 meters depth. The *in situ* measurement of ground motion at different levels within the soil column and in the bedrock below provides the ideal data set to examine the contrasting effects of attenuation, amplification, and nonlinear soil behavior as the wave field propagates up through the soil column [Archuleta et al., 1992; Steidl et al., 1996; Steidl et al., 1998]. The upper 18-25 meters consist of soil rich in organics and alluvium. Soil types present are silty sand, sand, clayey sand, and silty gravel.

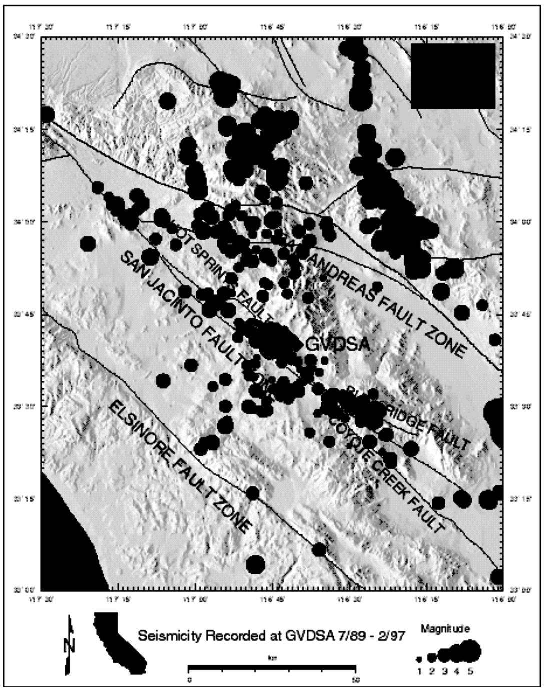

Figure 1. Map showing the location of GVDSA (diamond). Also shown is the recorded seismicity (circles), shaded relief, and faults (black lines).

There is a gradual transition from alluvium to decomposed granite from 18 to 25 meters. Decomposed granite consisting of gravely sand exists between 25 and 88 meters. At 88 meters the contact with hard competent bedrock is reached.

GVDA is located in a seismically active region 7 km from the main trace of the San Jacinto fault system, and 35 km from the San Andreas fault (Figure 1). The San Jacinto fault system is historically the most active strike-slip fault system in Southern California. The slip rate of 10 mm/y [*Sharp*, 1967; *Rockwell et al.*, 1990] and the absence of a large earthquake since at least 1890 on a 40 km zone of the Anza segment leads to a relatively high probability for a magnitude 6.0 or larger event in the near future. The GVDSA location is in an area where there is good local control on the location of earthquakes. The USGS/Caltech Southern California Seismic Network (SCSN) of high-gain velocity transducers and the UC San Diego ten-station array of velocity transducers in the Anza region provide excellent coverage of the local and regional seismicity.

Ground motion at GVDA is recorded at the surface and depths of 6, 15, 22, 50, 220, 500, and 501 meters below the surface on Kinematics dual-gain FBA 23 accelerometers. The geotechnical soil properties of the site are well defined and include: measured shear-wave velocities (downhole and suspension), gamma logs; guard and point resistivity; short and long normal resistivity; split spoon samples to 30 m; SPT blow to 30 m; Cone tip force, resistivity, sleeve friction, and seismic cone; soil behavior classification; moisture content; dry density;

and dynamic testing of Pitcher and Shelby samples. The geotechnical properties of the GVDA test site are described in detail in Steidl et al., 1998.

One of the simplest, yet demanding, tests for the accuracy of our knowledge of the subsurface structure is to compare theoretical accelerograms with records from small earthquakes. In Figure 2 we compare synthetic accelerograms to the observed surface, GL-50 m, and GL-501 m recordings of an M 3.2 earthquake located 18 km from the array. The data and synthetics are bandpassed from 0-10 Hz. We are able to predict the ground motion in the bedrock quite well using a 1-D model and a point source and reflectivity code called Axitra [modified from Coutant, 1989]. The weathered granite (GL-50 m) and the surface alluvium are not quite as well matched with the reflectivity code. Notice that there is a strong S-to-P conversion that arrives on the vertical component just before the S-wave arrival, which comes from the alluvium/weathered granite interface, and is matched by the 1-D model. The P-to-S conversions that are observed on the horizontal components are not modeled as well. Late arriving energy from scattering and 3-D effects are also not modeled well with the 1-D model. Using the recordings at different levels within the soil column, we model the waveforms to determine the best fitting layered velocity & attenuation model. Figure 3 shows the resulting model for GVDA, which is consistent with both the velocity logging and the waveform modeling.

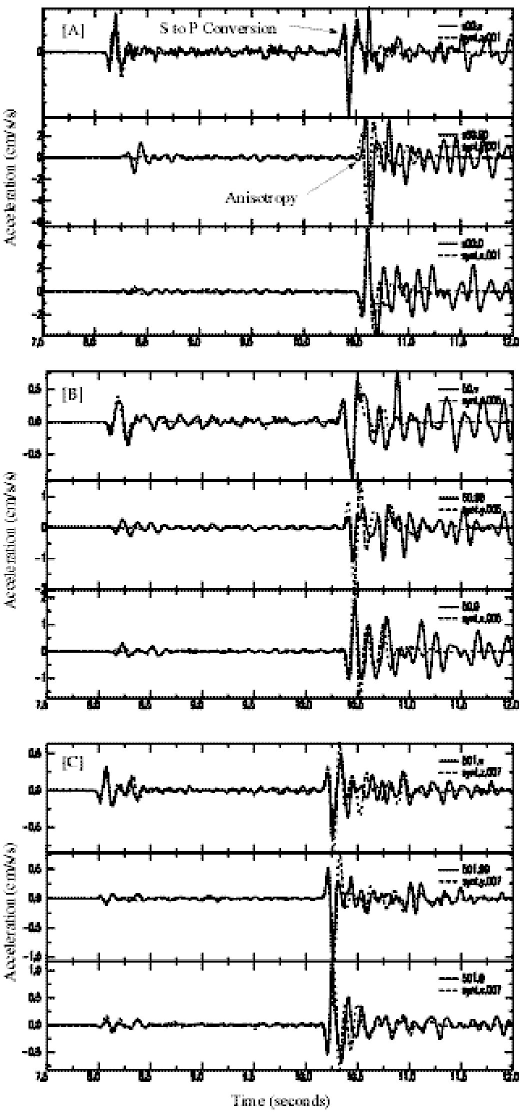

Figure 2. Observed (solid) and synthetic (dashed) ground motions at the surface [A], at 50 m [B], and at 501 m [C], from point source modeling in an damped linear-elastic layered medium.

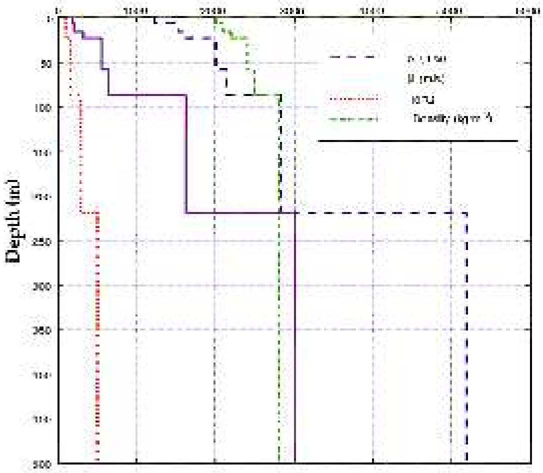

Figure 3. Geotechnical parameters used in modeling ground motion at GVDA.

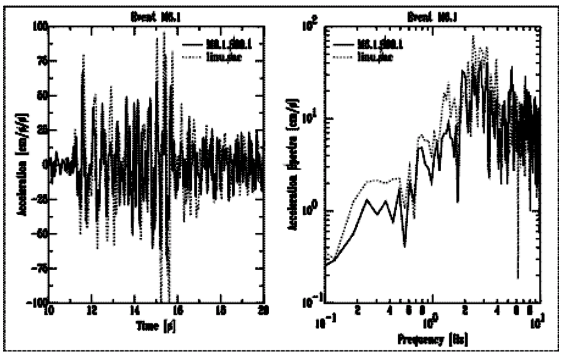

Figure 4. GVDA surface ground motion prediction of the 1992 M6.1 Joshua Tree earthquake by SH propagation of bedrock borehole up to surface. Left and right show time and frequency domain respectively

When we use the bedrock borehole motion from the M6.1 Joshua Tree Mainshock as the input to a linear wave propagation model we do a better job at matching the late arriving energy. Numerical propagation of the 220 meter bedrock borehole recording of the 1992 M6.1 Joshua Tree earthquake up through the soil structure shown in Figure 3 is presented in Figure 4. The first 10 seconds of the SH-wave observed (solid) and predicted (dashed) acceleration time time-history is shown on the left, for frequencies up to 10 Hz. The corresponding observed (solid) and predicted (dashed) Fourier spectrum is shown on the right. Using the bedrock borehole motion as the input to a soil profile with parameters shown in Figure 3, we are able to match the observed ground motion almost wiggle for wiggle up to 10 Hz.

The Hollister earthquake observatory

Agbabian Associates installed the Hollister Earthquake Observatory (HEO), in 1991 with funding from the Kajima Engineering and Construction Corp. Kajima Corp donated this array to the University of California, Santa Barbara in January 1998. It is located in the Salinas Valley where alluvium overlies Tertiary sandstone overlying granitic basement. HEO has been operating since early 1992, and is located about 10 kilometers from the San Andreas fault near the cities of Hollister and Salinas in central California (Figure 5). The ground motion array consists of a vertical array of six accelerometers in Quaternary alluvium, and three accelerometers installed at a remote rock station, 3 km to the Northeast. 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. Three sensor locations, surface Sandstone, surface Granite, and GL-53 meter borehole Granite are instrumented at the remote rock. The location of HEO along the San Andreas Fault in Central/Northern California makes it an important addition to the engineering seismology test site program at UCSB. It is complementary to GVDA, and increases our chances of recording a moderate to large earthquake by having state-of-the-art vertical test site observatories in two seismically active places instead of one.
On 12 August 1998, an M_W 5.1 earthquake occurred 13 km almost due east of HEO (Figure 12). All accelerometers recorded the event. In addition to the mainshock the array recorded one foreshock and at least three aftershocks. The acceleration time histories for the 180˚ horizontal component are shown in Figure 6. The largest acceleration occurs on the granite outcrop. Note the similarity between the two borehole recordings in rock: GL-192m and Gl-53m. 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.

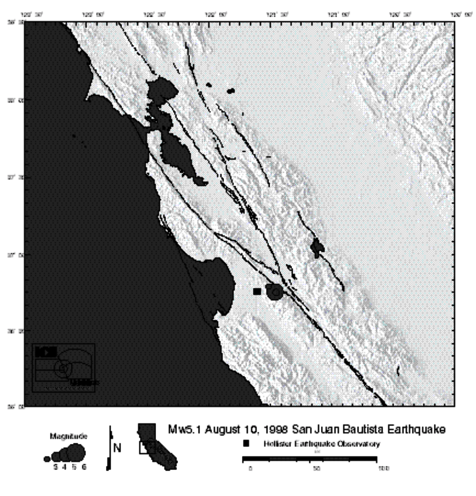

Figure 5. Map showing the location of HEO (square). Also shown is recorded seismicity from the M5.1 sequence (circles), shaded relief, and faults (black

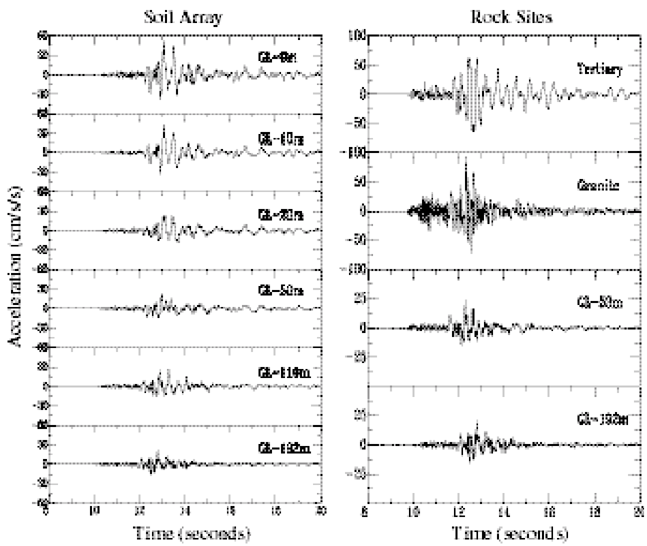

Figure 6. Acceleration time histories for the M5.1 mainshock recorded at HEO.

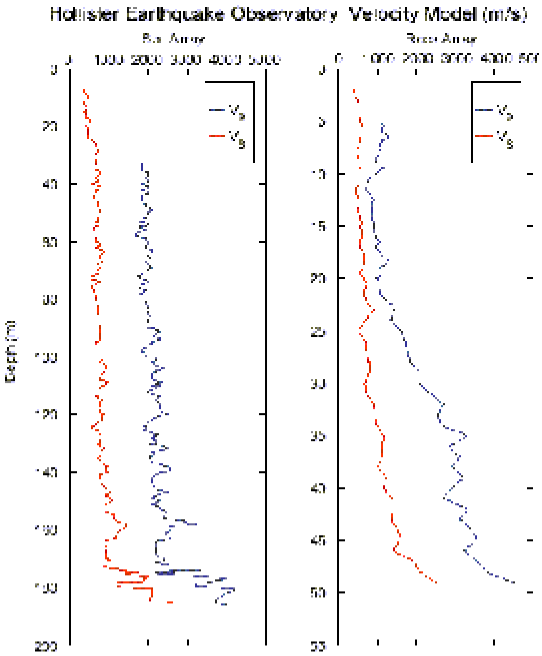

Figure 7. Measured velocity profiles from the HEO main soil station and remote rock station.

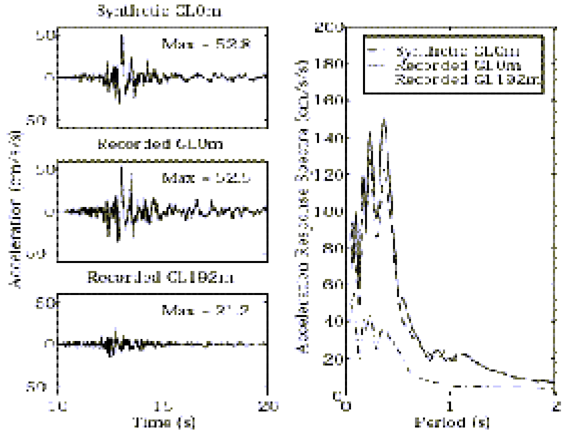

Figure 8. Ground motion prediction at HEO. The M5.1 mainshock surface soil ground motion (north-south component) is modeled using the observed GL-192 as the input motion. Comparison of the time history (left) and 5% damped response spectra (right) is shown.

Similar to the GVDA test site, HEO has extensive geotechnical site characterization data. Measured velocity profiles at both the main soil station and the remote rock station are shown in Figure 7. We model the M5.1 earthquake using a 7 layer 1-D model approximated from the shear wave velocity from 7 m to 186 m using the same linear code as in the previous GVDA example (Figure 4). The north-south component GL-192 observed acceleration time history is used as the input to the model and the synthetic surface motions are computed and compared to the observed. In order to match the amplitudes and frequency content, the damping parameter was held between 2 and 8% (Q =25 to 6) for the entire soil column. This high degree of attenuation in the soil is one of the reasons that the soil array peak ground accelerations are lower than the nearby rock outcrop motions.

The predicted (Figure 8-top) and observed (Figure 8-middle) ground acceleration at the surface of the main soil station and the observed GL-192 m record (Figure 8-bottom) used as the input motion for the modeling, are shown for the M5.1 event. In the time domain, the amplitude and duration of the observed surface ground motion are well predicted by the synthetic time history. In addition, the observed surface 5% damped response spectrum is well predicted by the synthetic response spectrum.

The Port island, kobe array

The recorded motions at the two previously discussed California vertical array sites only just reach the strain levels where the onset of nonlinear behavior begins, and linear models do a good job of predicting those ground motions. We thus turn to observations from a vertical array site in Japan to show an example of modeling larger motions where we can develop and validate our numerical codes that take into account nonlinear soil behavior.

The Port Island (PI) borehole accelerograms from the 1995 Hyogo-ken Nanbu earthquake clearly demonstrated that a non-linear process took place between the deeper sensors and the surface (Figure 1). These records have been extensively studied [e.g., Sato et al. 1996; Iwasaki and Tai, 1996; and Aguirre and Irikura, 1997, Mohammadioun, 1997]. The borehole observations make it very clear that as the waves proceed from depth to the surface the peak acceleration is significantly reduced by the behavior in the near surface soil, especially between -16 m and 0 m.

In this last modeling example, the surface motions at the PI array will be predicted using the GL-83 m observed ground acceleration as the input to the nonlinear model. We use extended Masing rules incorporated into a visco-elastic finite difference code to propagate the observed borehole ground motion up through the soil column. The details of the nonlinear method are given in Archuleta et al. (these proceedings).

The predicted (Figure 9-top) and observed (Figure 9-middle) ground acceleration at the surface of the PI array and the observed GL-83 m record (Figure 9-bottom) used as the input motion for the modeling, are shown for the Hyogo-ken Nambu (Kobe) earthquake. The general character of the observed surface ground motion is reproduced in the synthetic time history. As seen from both the 5% damped response spectra and the time domain amplitudes, the predicted ground motion still contains high frequency amplitudes in excess of the observed surface motion. We are continuing to develop the nonlinear model to improve our predictions. It is only with these critical direct observations from vertical array sites that we can continue to test and calibrate our numerical techniques for modeling nonlinear soil behavior.

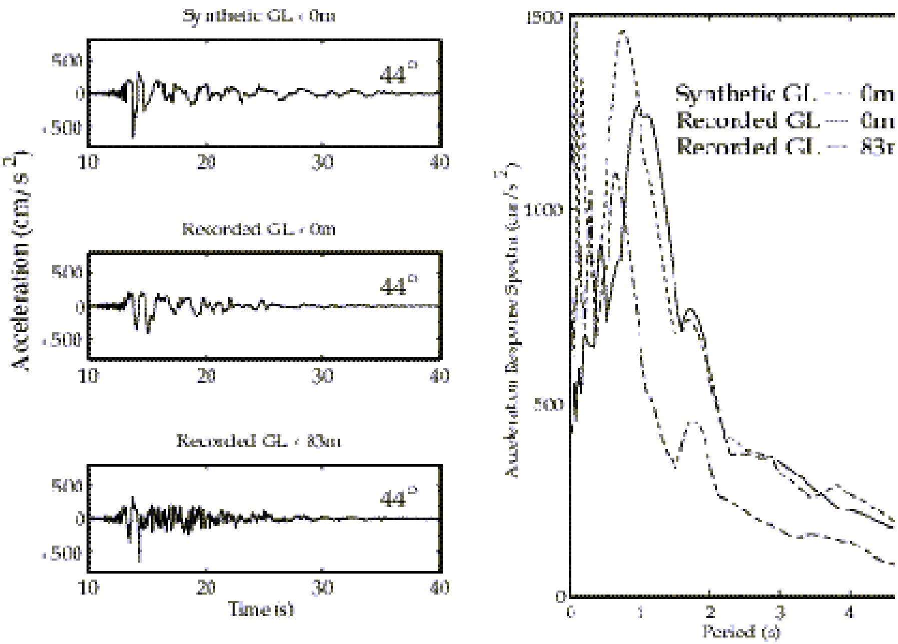

Figure 9. Ground motion prediction at PI. The Hyogo-ken Nambu (Kobe) earthquake surface soil ground motion (44° component) is modeled using the observed GL-83 as the input motion. Comparison of the time history (left) and 5% damped response spectra (right) is shown.

CONCLUSIONS

The direct observation of ground motion in vertical arrays has provided fundamental data for the interpretation and analysis of the effects of near-surface geology on seismic ground motion. At the GVDA and HEO arrays the effects of amplification and attenuation are modeled using ground motion from small to moderate earthquakes. The observed surface ground motion is reproduced using the geotechnical site characterization data, the observed borehole motions, and a linear wave propagation technique due to the relatively low ground motion amplitudes. Observations at both the GVDA and HEO vertical test arrays with nearby rock outcrop and borehole stations show the need to be cautious when using surface rock motion as the input motion in site response analysis due to the site effects present at rock outcrop. At the PI array the observed surface ground motion is modeled using the site characterization data and laboratory dynamic testing results, the observed borehole motions, and a nonlinear wave propagation technique due to the relatively large ground motion amplitudes. In both the linear and nonlinear modeling techniques we are able to reproduce the observed surface ground motion. The vertical array data are the only way to directly study the effects of the near-surface site conditions on ground motion and as shown in this study are critical to the development and validation of numerical techniques to correctly reproduce site response effects at all strain levels.

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