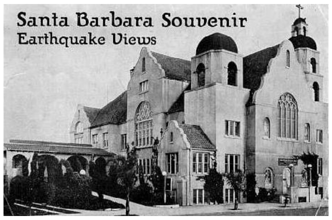

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COHERENCE VS DISTANCE AT THE GARNER VALLEY AND WILDLIFE NEES@UCSB FIELD SITES: A COMPARISON USING ACTIVE SOURCE

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ABSTRACT

Mobile shakers provide an active way to excite wave at various frequencies through the top layers of a site for characterization purposes. A temporary linear surface array of eight accelerometers at 10 meter spacing was deployed for a mobile shaker experiment at the Garner Valley Downhole Array (GVDA) and Wildlife Liquefaction Array (WLA) seismic stations, which are part of the George E. Brown Jr., Network for Earthquake Engineering Simulation (NEES) program. The mobile shaker “T-Rex”, also part of the NEES program, was positioned at three locations around the linear array and produced both Ricker and steady pulses at frequencies ranging between 3 Hz to 16 Hz in the vertical, lateral, and transverse directions. In addition to the site instrumentation and temporary accelerometer array, data channels on the mobile shaker provided the input drive signal, plate acceleration, and calculated output force acceleration for each shake. The observed attenuation of waves across the arrays suggests that energy across the sites has a directional dependence. Spectral energy and coherence analysis of the observed waveforms from the linear arrays at both sites provides information on the coupling efficiency between the shaker truck at each site. The analysis of spectral energy across the array for each input frequency shaker force suggest that the mobile shaker couples well at 12 Hz and above at GVDA and at 8Hz and above at WLA. These results suggest that the ability of a mobile shaker to effectively transfer energy to the earth is at least in part dependent on site characteristics.

INTRODUCTION

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 particular, the experimental field site facility that is part of the National Science Foundations George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) includes two permanently instrumented field sites for the study of ground response, ground failure, soil-foundation-structure interaction, and liquefaction (Steidl 2007, Youd et al., 2004, 2007). The simultaneous monitoring of geotechnical and structural components at the NEES@UCSB field sites integrates the two sub-disciplines within earthquake engineering and provides opportunities for new collaborations. The NEES@UCSB field site facilities are located in Southern California 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, earthquake monitoring to capture regional seismicity, and active testing using mobile shakers as was done for this particular study.

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 1. 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*).

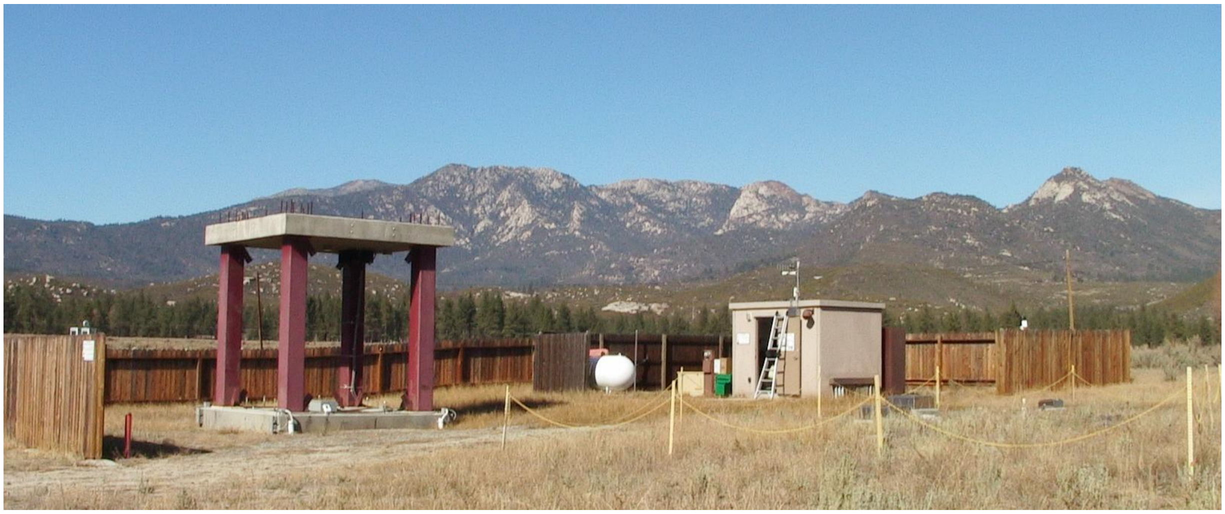

Fig. 1. Panoramic View of the NEES Garner Valley Facility in 2008.

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 (Youd et al., 2004). Based on this history, there is high expectation that additional liquefaction-producing earthquakes will shake the WLA site in the future. Figure 4 is a view of the WLA site after construction was completed in Fall 2004.

Fig. 2. The NEES WLA facility just after construction was completed in 2004

THE DATA

An active source experiment was carried out using the tri-axial mobile shaker "T-Rex" at the Wildlife Liquefaction Array (WLA) on May 26th 2010 and at the Garner Valley Downhole Array (GVDA) on June 3rd 2010. The GVDA and WLA equipment site facilities are part of the George E. Brown Jr., Network for Earthquake Engineering Simulation (NEES) program (Youd et. al., 2004, 2007). For each site, a linear array consisting of eight accelerometers was arranged at 10 meter spacing, recording continuously for the duration of the experiment. Sinusoidal transient shakes of 10 cycles in duration corresponding to input frequencies of 3, 4, 5, 8, 12, and 16 Hz were carried out in the transverse, longitudinal, and vertical directions. The mobile shaker was arranged facing perpendicular to the linear array. Thus the truck transverse (ST) shaking direction was parallel to the array while the truck longitudinal (SL) shaking direction was perpendicular to the array (Fig. 3). The sensors were oriented in line with the array, i.e., the north component of each sensor is parallel to the array while the east component is perpendicular to the array. Only the mobile shaker location between sensors 01 and 02 has been analyzed for this paper. The peak force output of the shaker, corresponding to a 5 volt input motion, is 30,000 lbs for horizontal motion and 60,000 lbs for vertical motion (Stokoe et al., 2004). The full force shakes were preceded by tests of identical frequencies and motions with a weaker input force of 1.5 volts. The temporary array used for this experiment was composed of eight 5 volt/g Episensor accelerometers, +/-4g full scale, recording at 200 samples per second (Fig. 3). The geologic conditions at GVDA and WLA are very different. The surface layer at GVDA is composed of lake-bed alluvium transitioning to weathered granite at depths of 18-25 meters, in a narrow intermountain valley, while WLA has a silty clay surface layer over a liquefiable sand layer, and sits in the middle of the larger scale Imperial Valley.

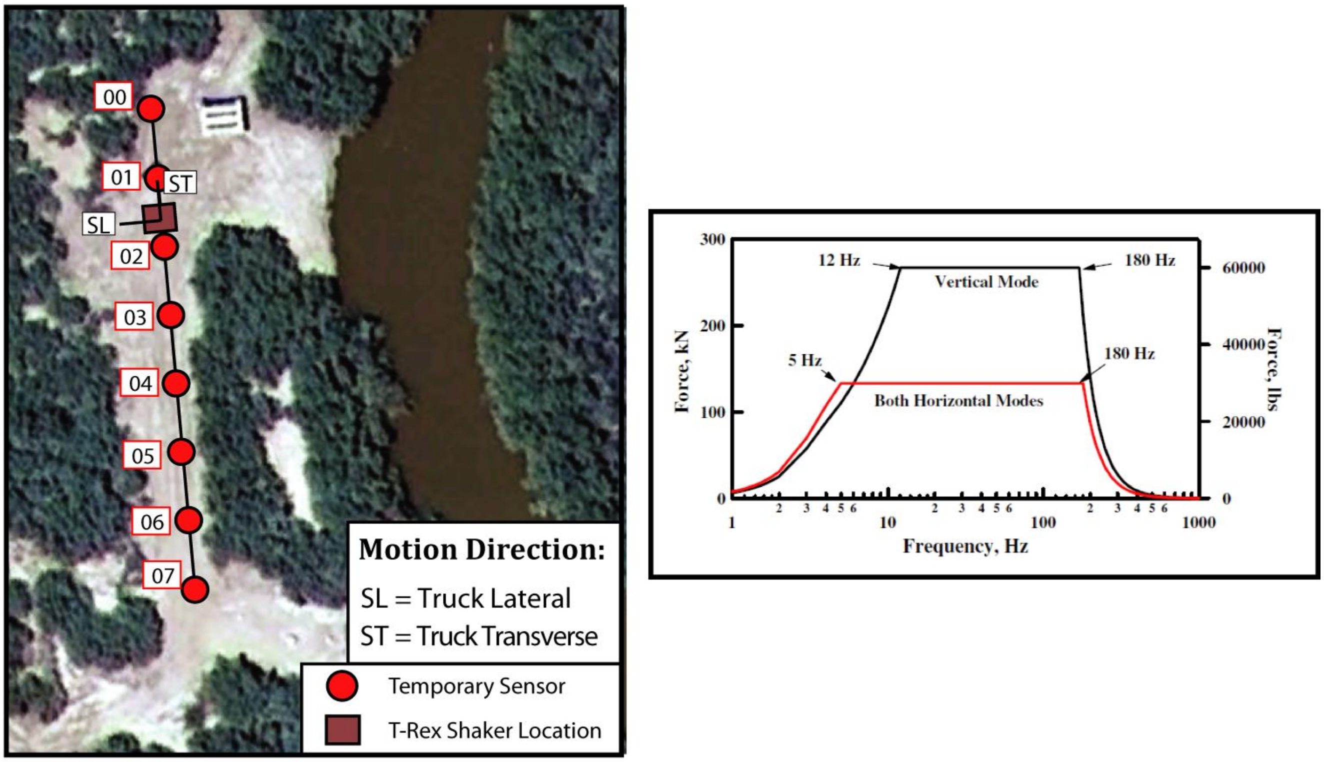

Fig. 3. Temporary linear array at the Wildlife Liquefaction array (left) and the theoretical force output of the shaker "T-Rex" (right). Theoretical force output function from Stokoe et al., (2004).

An important caveat regarding the theoretical force output of the "T-Rex" shaker is its inaccuracy below certain frequencies. The minimum frequency for maximum force output is 12 Hz in vertical mode and 5 Hz in horizontal mode (Figure 3. (right), Stokoe et al., 2004). This means that the force output of T-Rex is unstable for lower frequencies. In other words, two tests at the same frequency might yield different force outputs if the frequency is unstable. Although shake results from unstable frequencies can still be used to analyze site behavior, comparisons with similar frequencies at other sites should be done with caution.

SIGNIFICANCE OF PLATE MOTION

An accelerometer connected to the mobile shaker plate provides a record of the movement of the plate motion for each test. Besides providing a useful reference frame to observe the travel time of the waves, it is also used to observe how the plate is interacting with the ground. Ideally, the plate motion should be a transient sinusoidal shake consisting of ten wavelengths matching the frequency of the input motion, each representing a single up-down or left-right motion of the shaker truck plate. This behavior was observed to be inconsistent between sites at certain frequencies. The plate motion corresponding to a 5 volt, 4 Hz, transverse shear motion appears sinusoidal when observed at the wildlife site, but is non-sinusoidal at GVDA (Fig. 4). This is most likely a function of the coupling of the base plate to the earth and higher mode harmonic vibrations of the plate. The waveforms observed at a distance of 35 meters from the plate, corresponding to sensor 05 in the array shown in figure 1 for WLA, are also included in figure 4.

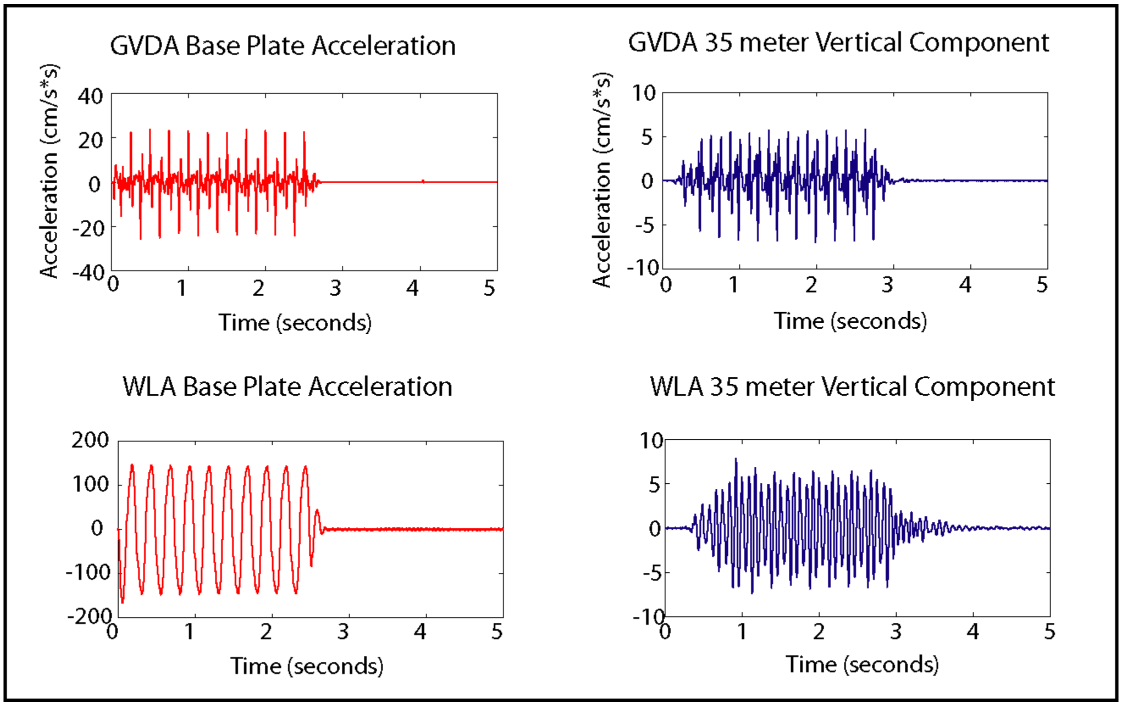

Fig. 4. Accelerations of mobile shaker base plate and a temporary array sensor 35 meters away for a 5 volt, 4 Hz, truck transverse shake at GVDA and WLA stations.

ATTENUATION OF ENERGY

An objective of this mobile shaker experiment was to understand how the sites respond to various frequencies of excitation and to test the hypothesis that the plate coupling, and thus output force, is a function of site stiffness as well as the mechanics of the truck itself. To analyze this, Fourier transforms of waveforms from temporary array sensors 03 through 07 (Fig. 3) were calculated for all frequencies of excitation. The attenuation was observed by superposing the Fourier transform of each accelerometer waveform along the array. The highest force possible would be desired to observe attenuation over distances, and for this experiment that corresponds to T-Rex shaking in the vertical direction (60,000 lbs of force). However, the lower frequency shaking in the vertical direction cannot be compared between sites because the vertical theoretical force output function of T-Rex is unstable for frequencies lower than 12 Hz (Fig 3. (right), Stokoe et al., 2004). Because of this, shaking in the horizontal direction (30,000 lbs of force) was used.

The 12 Hz shakes at each site behave similarly, with the largest Fourier amplitude corresponding to the input frequency. The main difference between these two records is the strength of each component: for GVDA, the greatest energy is in the transverse component, while in WLA, the greatest energy is in the vertical component (Fig. 5). However, the 5 Hz “T-Rex” shakes look drastically different between the two sites. At GVDA, the 5 Hz drive signal input frequency has the smallest Fourier amplitude for all components while the higher harmonic resonances dominate the spectrum (Figure 6). In particular, the 15 Hz and 30 Hz resonances are especially strong. At WLA, the Fourier amplitude of the 5 Hz frequency shakes is greater at the 30 Hz resonance in the transverse and vertical component, but is the dominant frequency in the parallel component spectrum (Figure 6). Similar to the 12 Hz input frequency in figure 5, the greatest energy is in the transverse component for GVDA and in the vertical component for WLA.

It is clear that while the “T-Rex” drive signal is trying to input energy to both sites at 5 Hz (Figure 6), higher harmonics are what make it into the soil, with the exception of the the parallel component at WLA. If we examine the 8 Hz “T-Rex” shakes, intermediate between the 5 and 12 Hz input signal, we can now see that the plate motion couples the input drive signals to the WLA site, but is still no able to couple this frequency to the stiffer GVDA site where harmonics dominate (Figure 7). As seen in both 12 and 5 Hz drive inputs, the vertical component at WLA is still the largest, while at GVDA the parallel component in the harmonics is now the largest for this input frequency.

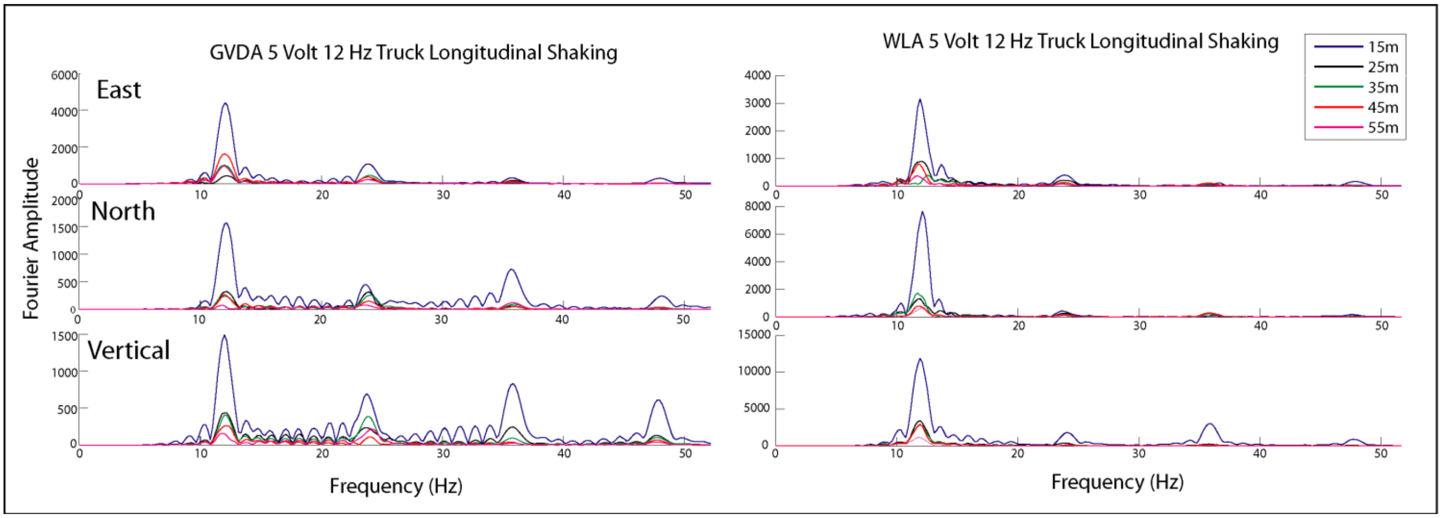

Fig. 5. Fourier spectrum of 5 volt, 12 Hz, longitudinal shaking (SL) at GVDA and WLA for temporary array sensors 03 through 07 with distances 15-55 meters away from the "T-Rex" shaker truck.

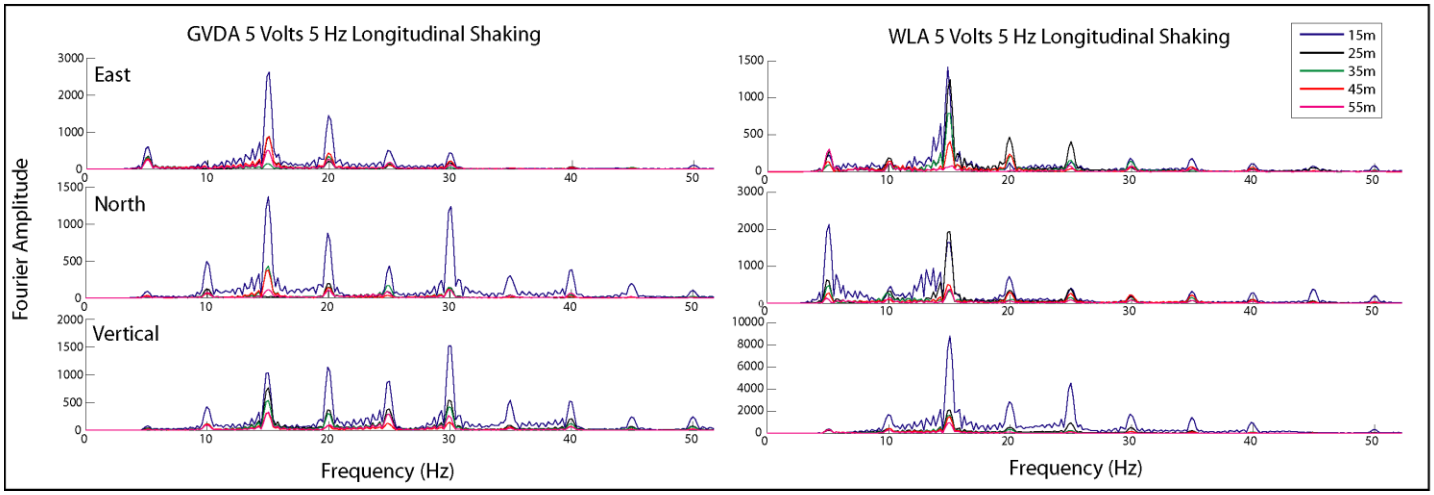

Fig. 6. Fourier spectrum of 5 volt, 5 Hz, longitudinal shaking at GVDA and WLA for temporary array sensors 03 through 07 with distances 15-55 meters away from the "T-Rex" shaker truck.

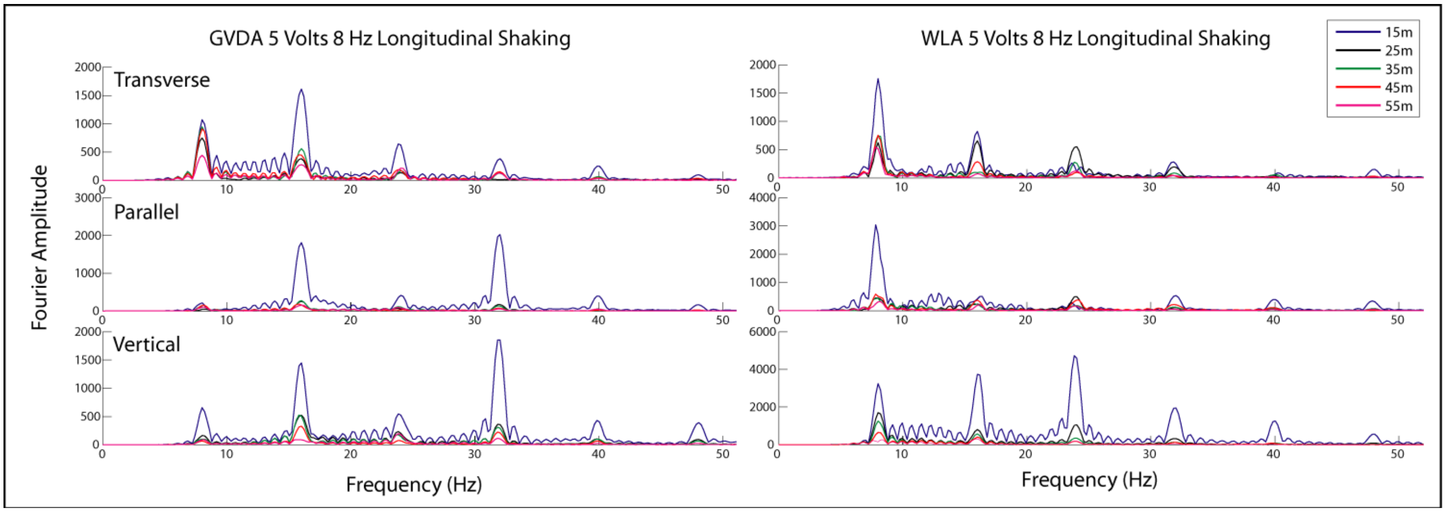

Fig. 7. Fourier spectrum of 5 volt, 8 Hz, longitudinal shaking at GVDA and WLA for temporary array sensors 03 through 07 with distances 15-55 meters away from the "T-Rex" shaker truck.

COHERENCE ACROSS TEMPORARY ARRAY

Coherence is used to quantify the similarity of waves to one another across the frequency domain of observation. Magnitude square coherence uses estimates of power spectral densities to quantify the similarity of two signals on a scale from 0 to 1 for all frequencies (Marple, 1987) is used in this analysis. This coherence function was calculated for sensors 04 through 07 as compared to sensor 03, thus providing coherence values corresponding to distances of 10 meters through 40 meters away from T-Rex at 10 meter intervals. Two main frequency bands were analyzed: one band ranging from the source frequency to 30 Hz and another from 30 Hz to 60 Hz. The value from these two bands was then averaged and plotted for each distance, and for each source drive frequency. This average coherence value is shown for the vertical component of the accelerometers and is plotted in both these average frequency bands, for 5 volt vertical T-Rex shaking (Figs. 5 and 6).

Coherence decays with distance away from the 03 sensor (and T-Rex source) as would be expected intuitively. There are differences in the rate of decay and absolute value of coherence between the two sites that are interesting. While the T-Rex has a harder time coupling at lower frequencies at the GVDA site, the trucks drive energy that does make it into the site is in general more coherent in an absolute sense.

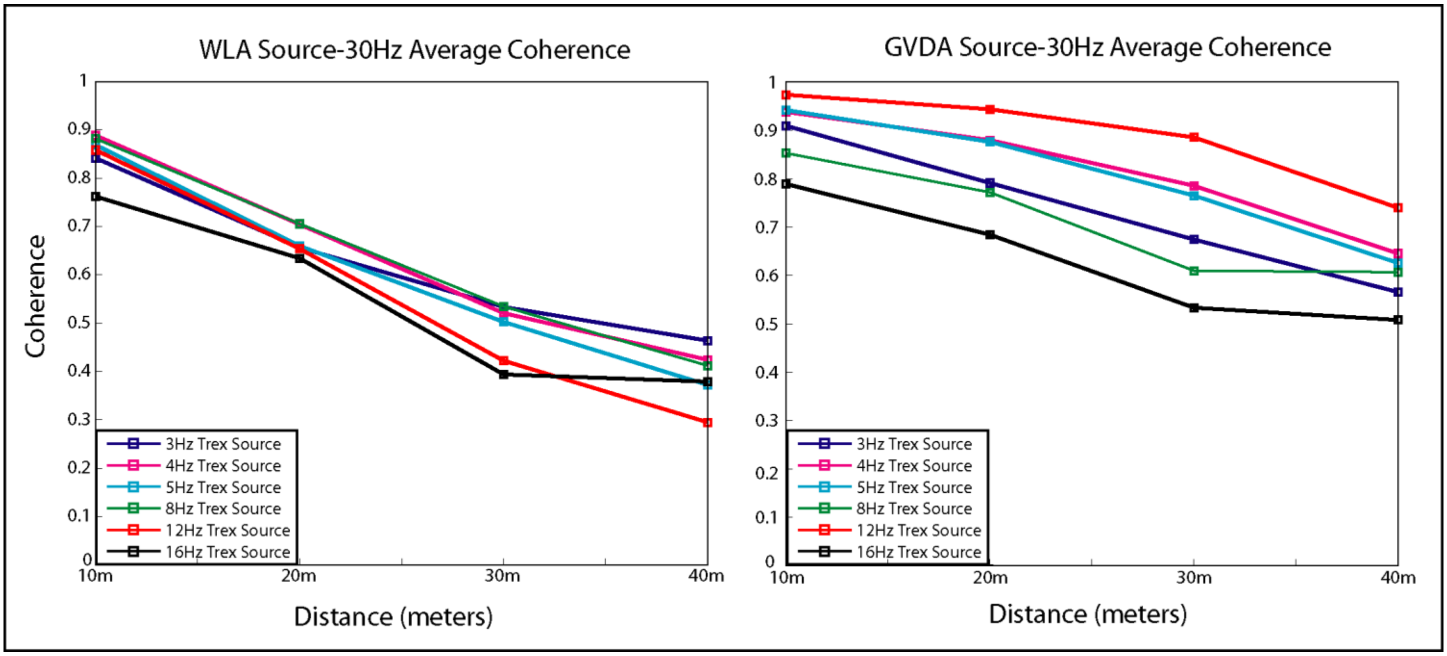

Fig. 8 Average coherence between the 15 meter sensor (03) and the rest of the linear array for WLA and GVDA between the T-Rex input frequency and 30 Hz. The T-Rex input motion is 5 volts in the vertical direction, observed on the vertical component.

CONCLUSIONS

The comparisons detailed above suggest that the ability of the T-Rex shaker to effectively transfer energy into the ground is highly dependent on the site. This can be observed by comparing the acceleration of the plate at each site for the same input motion (Fig. 4). The difference in the observed plate motion is most likely a result of a lack of physical coupling with the ground and the excitation of higher modes of vibration in the plate and truck. There is a significant difference in the stiffness of the GVDA and WLA sites, with the GVDA site having a higher Vs30 as well as higher shallower and deeper velocities. It is important to consider the target site of interest when planning an experiment using the T-Rex shaker and trying to determine what drive frequencies will couple well to the site. The softer WLA site couples the lower frequency drive energy down to 8 Hz while at GVDA, the 8 Hz energy does not couple well.

Analysis of the attenuation of frequencies by comparison of the spectral energy across the temporary array (Figs. 5 thru 7) reveal a site-specific change in the partition of energy. For both 12 Hz and 5 Hz signals the directional component with the maximum energy observed on the array is site dependant: for the same truck longitudinal motion the energy was higher in the transverse component for

GVDA and in the vertical component for WLA. The varying directions of maximum energy output suggest that the site response is not one-dimensional.

A few hypotheses can be made from observations of the average coherence at each of the sites (Figures 8 and 9). The first is that coherence tends to decrease with increasing distance as intuitively expected. Another observation is the comparison of the absolute value and rate of decay of coherence with distance between the two sites. At GVDA, the decrease of coherence over 40 meters is less steep and the overall coherence higher, while at WLA the coherence value decays faster and the overall level is lower. Although the energy output of T-Rex at WLA is higher than that of GVDA as observed in the absolute level of observed ground motions, the rate at which the original waveform degrades is more rapid, suggesting higher attenuation at WLA.

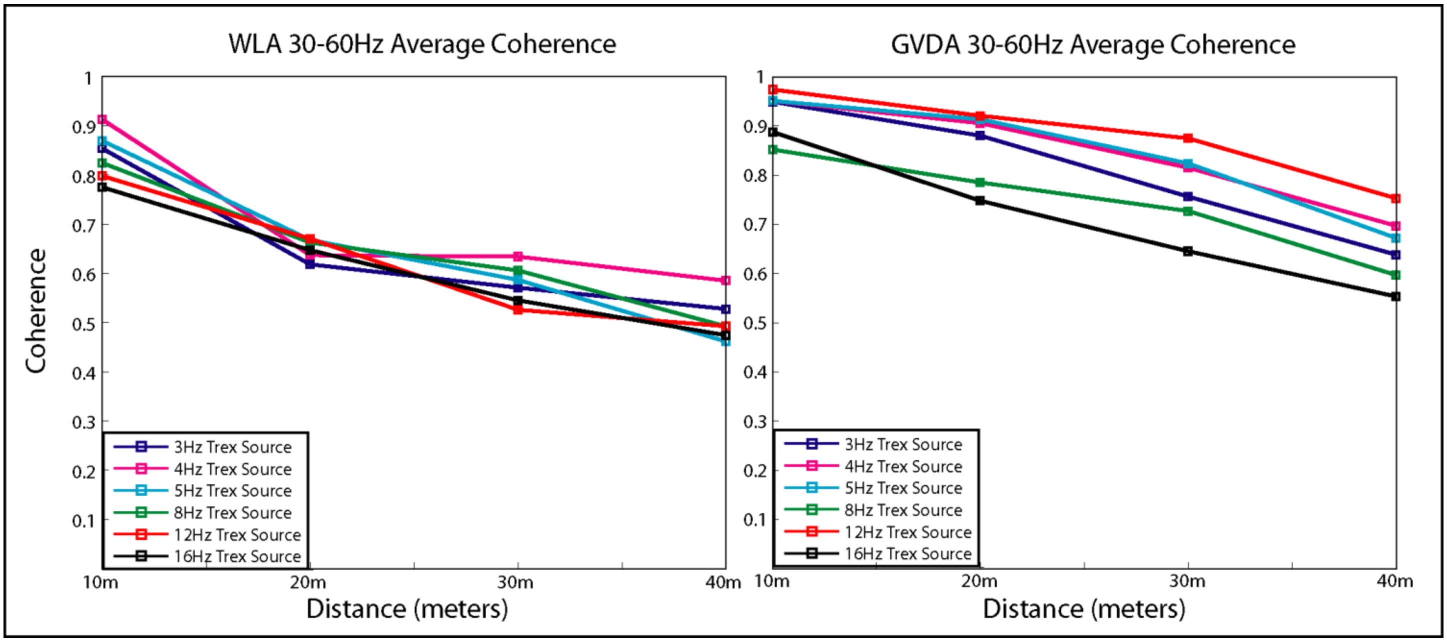

Fig. 9 Average coherence between the 15 meter sensor (03) and the rest of the linear array for WLA (left) and GVDA (right) between the frequency band of 30 Hz to 60 Hz. The T-Rex input motion is 5 volts in the vertical direction, observed on the vertical component.

FUTURE CONSIDERATIONS

The greatest restriction for this experiment was the instability of low frequencies produced by T-Rex. A more accurate methodology to understand the effect of low frequencies on each site will be to use the low frequencies generated by earthquakes. Although the temporary array is no longer deployed at either station, GVDA has a permanent linear array consisting of five accelerometers with spacing of 65 meters that could be augmented with a longer term temporary array. Data from the linear array in this experiment can also be used to model a Q value of the surface layer. Similarly, the permanent borehole instruments at each site can be used to determine Q within each subsurface layer using the T-Rex source.

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