OBSERVATIONS OF *INSITU* SOIL BEHAVIOR AND SOIL-FOUNDATION-STRUCTURE INTERACTION AT THE GEORGE E. BROWN, JR. NETWORK FOR EARTHQUAKE ENGINEERING SIMULATION (NEES) PERMANENTLY INSTRUMENTED FIELD SITES

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ABSTRACT :

The NEES@UCSB equipment site, focused on making field observations of ground motions, ground deformations, pore pressure response, and soil-foundation-structure interaction, has now been in operation for over three years. While the expected M6+ target event in the region of the NEES@UCSB permanent sites has not yet occurred, numerous earthquakes have been recorded which highlight the ability of the observation systems to record pore pressure increases associated with earthquakes in the magnitude 4-5 range. These observations, in the 10%g acceleration range, demonstrate the level of ground motion where onset of pore pressure increase and non-linear soil behavior starts. In addition to the interesting pore pressure and acceleration records from within the soil column, an instrumented experimental structure located at one of the NEES field sites has also recorded many of these same events and its response is analyzed. This structure is also excited regularly using a permanently mounted shaker located under the roof. Observations using this shaker provide insight into the affect of environmental conditions on structural response.

KEYWORDS: Instrumented Sites, Engineering Seismology, Site Response, Liquefaction

1. 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. 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. In addition, the remote sites are equipped with high performance wireless network connections that allow for real-time video and data telemetry, remote participation from geographically distributed researches during experiments, and remote control of the shaker and equipment at the sites. The ~3Gb/day continuous data stream is stored locally on site and also brought back to UCSB in real-time and archived on RAID servers for later processing and analysis.

2. GARNER VALLEY DOWNHOLE ARRAY

The NEES Garner Valley Downhole Array (GVDA) is located in southern California at a latitude of 33° 40.127' north, and a longitude of 116° 40.427' west. The instrumented site is located in a narrow valley within the peninsular ranges batholith east of Hemet and southwest of Palm Springs, California. This seismically active location is 7km from the San Jacinto Fault and 40 km from the San Andreas Fault. The valley is 4-5 km wide at its widest and about 10 km long. The valley trends northwest-southeast parallel to the major faults of southern California. The valley floor is at an elevation of 1310 m and the surrounding mountains reach heights slightly greater than 3,000 m. A panoramic view of the GVDA field site is shown in Figure 1, taken at the completion of the NEES construction in Fall of 2004. The details of the geotechnical site conditions and instrumentation at the GVDA facility can be found at the NEES@UCSB website (http://nees.ucsb.edu/), and in previous studies of the observations from this site (*Archuleta et al., 1992; Steidl et al., 1996; Bonilla et al., 2002*).

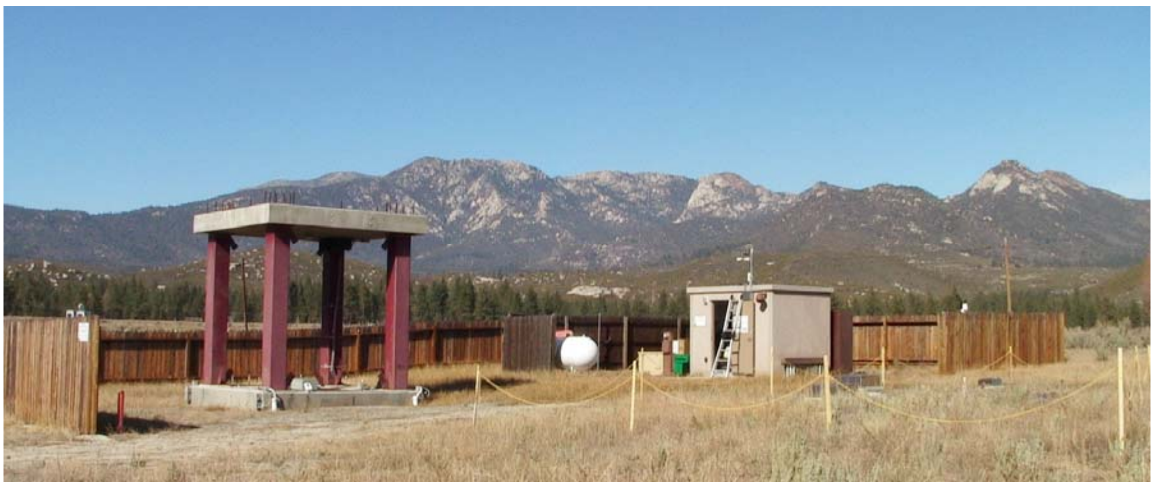

Figure 1. Panoramic View of the NEES Garner Valley Facility in 2008.

The NEES GVDA facility was constructed through a multi-disciplinary collaboration between seismologists, geotechnical, and structural engineers. The reconfigurable structure (Figure 1) built at the GVDA site is instrumented with pressure cells under the four corners of the foundation, vertical displacement transducers on the four corners, accelerometers on the corners, bottom slab, and top slab, and a rotational sensor on the bottom slab. In addition, a downhole accelerometer and pore pressure transducer are installed below the foundation. The structure is intended for improving our understanding of soil-foundation-structure interaction (SFSI). Figure 2 is a schematic of the structure and the different input forces that can be used in response testing.

The SFSI test structure instrumentation is designed to easily capture both rocking and torsional modes of the structure. It was also designed to be re-configurable, so that the stiffness could be modified by adding or removing bracing on any of the 4 sides. The mass of the structure can also be modified through the addition of weight on the roof slab, or even the addition of a second story. A permanent shaker is mounted under the roof slab, and can be operated remotely, providing an excellent tool for teaching SFSI and structural dynamics concepts. The shaker is also used in research by exciting the structure on a regular basis and comparing the response with environmental factors like soil saturation and temperature. A weather station is installed at the GVDA site to provide rainfall and temperature data, and soil moisture probes are installed below the foundation of the structure. In figure 3, the locations of the various sensors installed on and beneath the SFSI test structure are shown. In addition to the instrumented structure, the soil column at GVDA is heavily instrumented with 6 additional downhole accelerometers (6, 15, 22, 50, 150, and 501 meter depths) and 4 additional pore pressure transducers (6.1, 8.8, 10.1, and 12.4 meter depths). The combination of the geotechnical and structural instrumentation combined with the remote telepresence and teleopertational network capabilities make the Garner Valley site a unique earthquake engineering research facility.

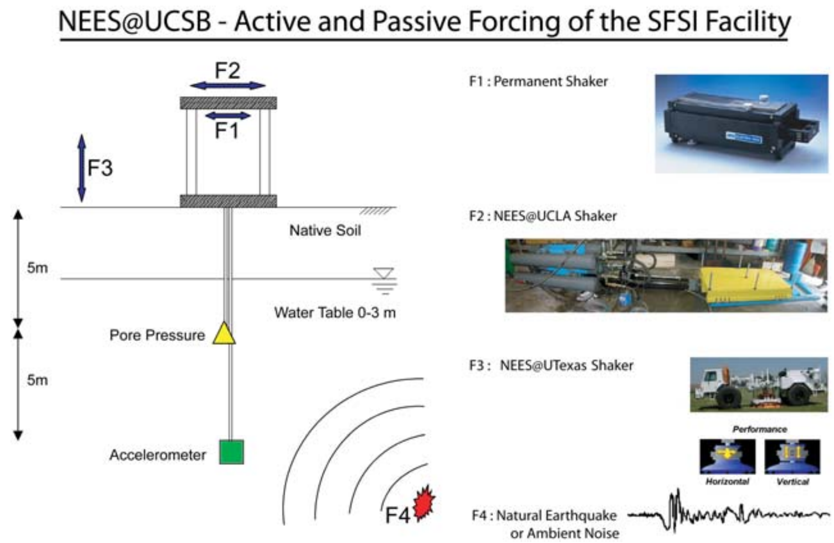

Figure 2. The various input forces used to study soil-foundation-structure interaction at GVDA

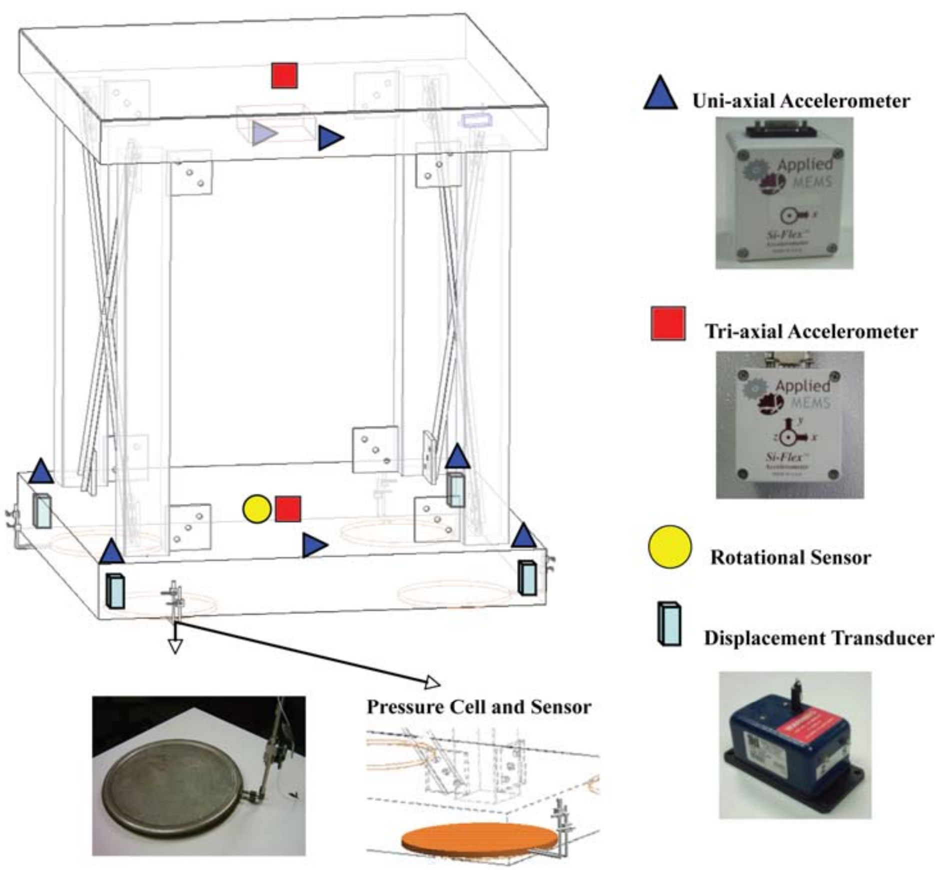

Figure 3. Instrumentation at the GVDA SFSI Facility

3. WILDLIFE LIQUEFACTION ARRAY

The Wildlife Liquefaction Array (WLA) is located on the west bank of the Alamo River 13 km due north of Brawley, California and 160 km due east of San Diego. The site is located in the Imperial Wildlife Area, a California State game refuge. This region has been frequently shaken by earthquakes with six earthquakes in the past 75 years generating liquefaction effects at or within 10 km of the WLA site. Based on this history, there is high expectation that additional liquefaction-producing earthquakes will shake the WLA site during the 10-year operational phase (2004-2014) of the NEES program. Figure 4 is a view of the WLA site after construction was completed in Fall 2004.

Figure 4. The NEES WLA facility just after construction was completed in 2004

The extensive instrumentation at this site includes 4 surface accelerometers, 6 downhole accelerometers, 11 sub-surface pore pressure transducers, and numerous benchmarks and inclinometer casings for monitoring lateral ground displacements. \Detailed information on the instrumentation and geotechnical properties of the site can be found in previous publications (*Youd et. al., 2004; Youd et. al., 2007*). Like the Garner Valley facility, the WLA site also has a state-of-the-art wireless communications system that allow for both video and data telemetry in real-time back to UCSB, and for remote participation of researchers or the public during active experimentation at the facility. Unlike the Garner Valley site, the WLA site operates completely on solar power.

3. LIQUEFACTION MONITORING AT GVDA AND WLA

Both earthquakes and active testing using the NEES@UTA "T-Rex" mobile shaker have been used to examine the response of the NEES@UCSB sites to ground shaking. In the late summer of 2005 the "T-Rex" shaker excited the WLA site and provided a useful test of the system, as well as some provocative observations of pore pressure during local shaking. The active shaking from the NEES@UTA shaker during this experiment lasts for approximately 10 seconds, however the pore pressure signals that are generated by the active source have still not dissipated back to the pre-shake levels, even 10 minutes after the source has stopped (*Steidl, 2007*).

These active source observations of pore pressure generation and slow dissipation are also seen when earthquakes shake the sites. The largest ground motions observed to date at the WLA site are from a local magnitude 5.1 event located approximately 10 km from the site. In addition to the M5.1 event, numerous M3 and M4 level earthquakes that followed also generated very interesting observations at the site. The largest ground accelerations from this swarm of events was only about 10% g, however even these modest levels of shaking, the pore pressure response can clearly be seen in the observations. The observations from the eight pore pressure transducers for a 1-hour period during this swarm of earthquakes is plotted in Figure 5 from shallowest to deepest (top to bottom). Similar to the active source testing (*Steidl,2007*), all of the transducers show a clear response to the earthquake activity.

The largest motions recorded so far at the GVDA site are also just at the level where the onset of nonlinear soil behavior might be expected, around 10%g peak ground acceleration. Observations from the liquefaction array sensors are beginning to show the build up of pore pressure at this level, and also show the slow decay back to the background level. A recent M5.1 earthquake near Anza, CA produced a quality set of observations showing this behavior at GVDA (*Steidl, 2007*). Interestingly, the shallow transducers show increases in pore pressure during the strongest shaking, while the deeper transducer seems to show an opposite effect. It is expected that these observations will be used for many years to come as simulation techniques are tested and new physics based models are proposed to model dynamic soil behavior that include pore pressure and liquefaction effects.

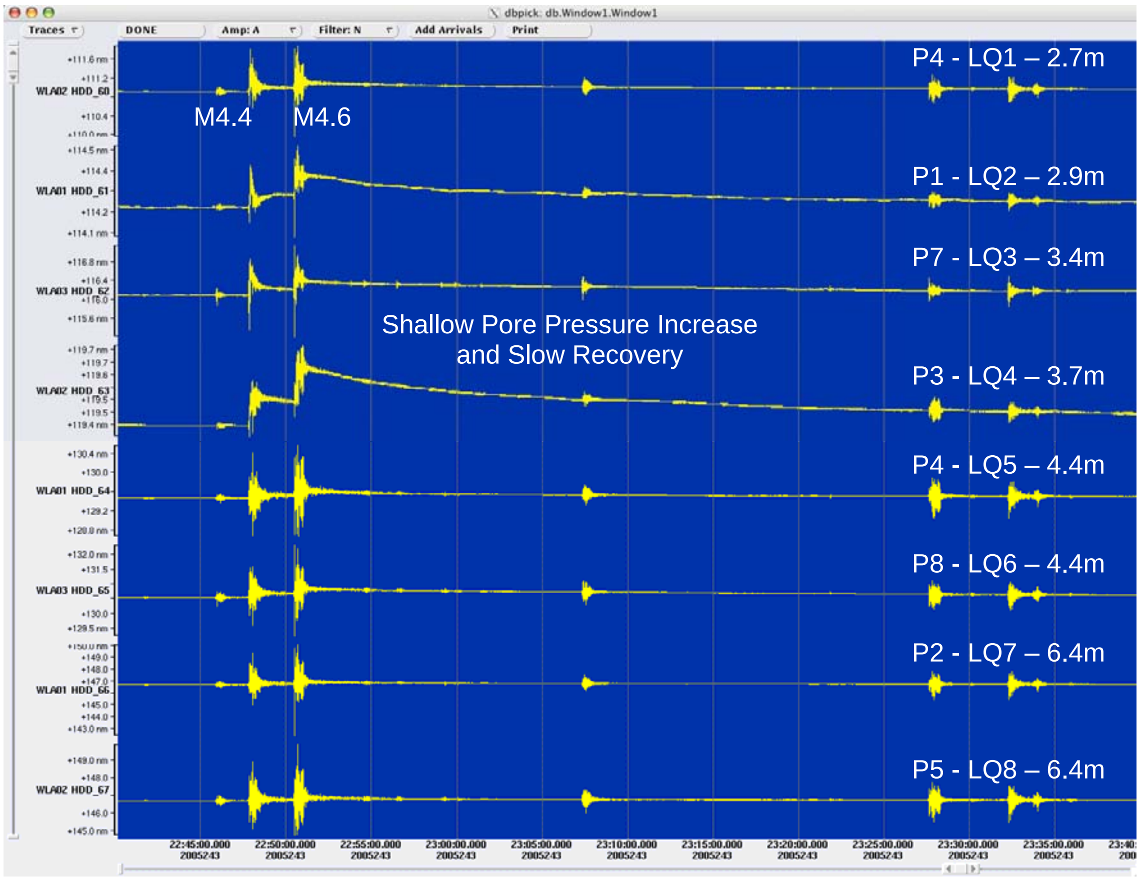

Figure 5. Sixty minutes of WLA data showing both dynamic response of the pore pressure sensors and static pressure increase, with slow dissipation when excited by the 2005 Obsidian Buttes earthquake swarm.

4. WEB-BASED DATA ACCESS

The NEES@UCSB field sites are producing very interesting observations from a large data set that includes 100's of earthquake observations each month. While the majority of these are very small events, they provide the control data that represents the linear behavior of the site. The largest motions recorded to date, ~10%g, are only just getting to the regime where nonlinear effects become important. In order to make these data more accessible to the earthquake engineering research community, software development has taken place under the NEES program to facilitate data access. This development includes web-based data dissemination and analysis tools available through the NEES@UCSB web portal and the NEES central data repository. These tools include state-of-health monitoring which is extremely useful in the maintenance and operations of the facility in order to provide data quality control. An example of these tools is shown in Figure 6 where an interactive map-based search tool is used to select one of the instrumented sites, then select the information needed (in this case vault parameters such as battery voltage, current use, and temperature), and finally plot the information for viewing at hourly, daily, weekly, monthly, or yearly time scales (see http://nees.ucsb.edu).

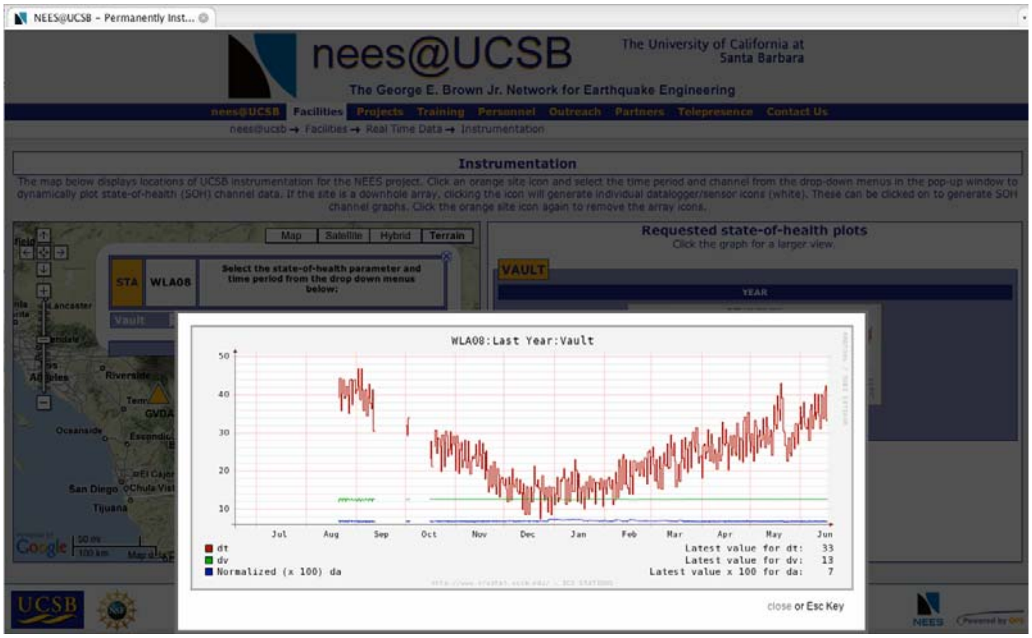

Figure 6. Web-based state-of-health monitoring software tools for NEES@UCSB sites.

Similarly, researchers interested in obtaining data records from the NEES@UCSB field sites can use the map-based event search tool to select a particular station and instrument, and show the records available at the site. These records can then be downloaded and viewed in the real-time data viewer (RDV) tool, a platform independent JAVA program that can display both real-time streaming data, or playback data that has been downloaded through the web-based event search tool. Figure 7 shows a screen capture of the map-based event search tool where events of M4.0 or larger have been selected.

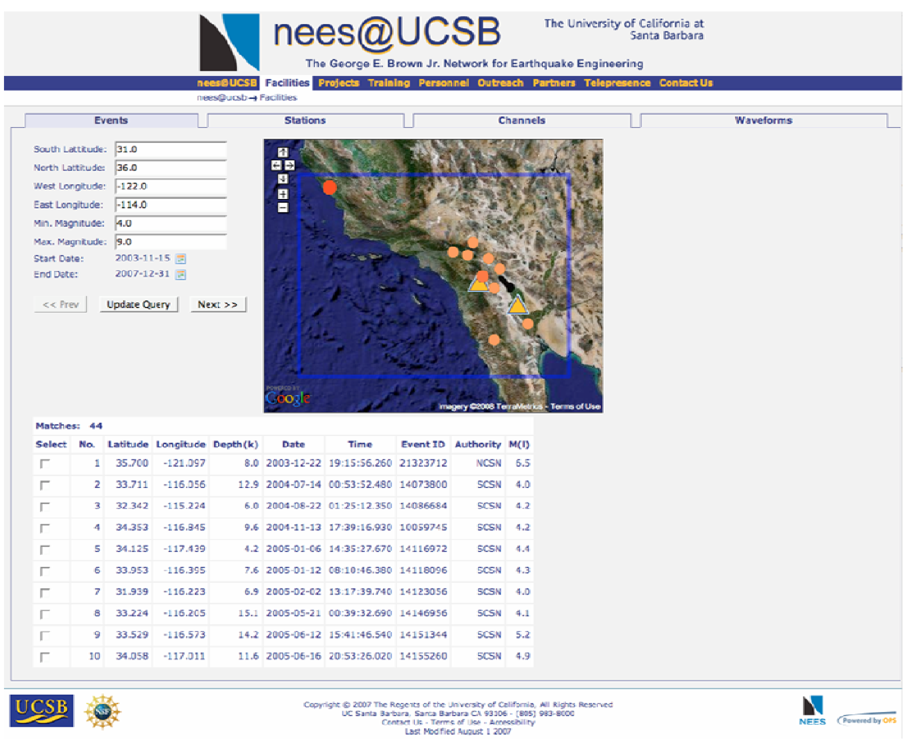

Figure 7. Map-based event search tool for access to data records at the NEES@UCSB sites.

In figure 8, the RDV tool is shown plotting an M4.9 event that has been downloaded from the search tool shown in figure 7. In addition to this play back feature, both data channels and video streams can be accessed through the RDV tool. These tools allow remote participants in research experiments the ability to watch the experiments as they happen. This collaborative research environment represents the new NEES paradigm for shared-use access to experimental facilities.

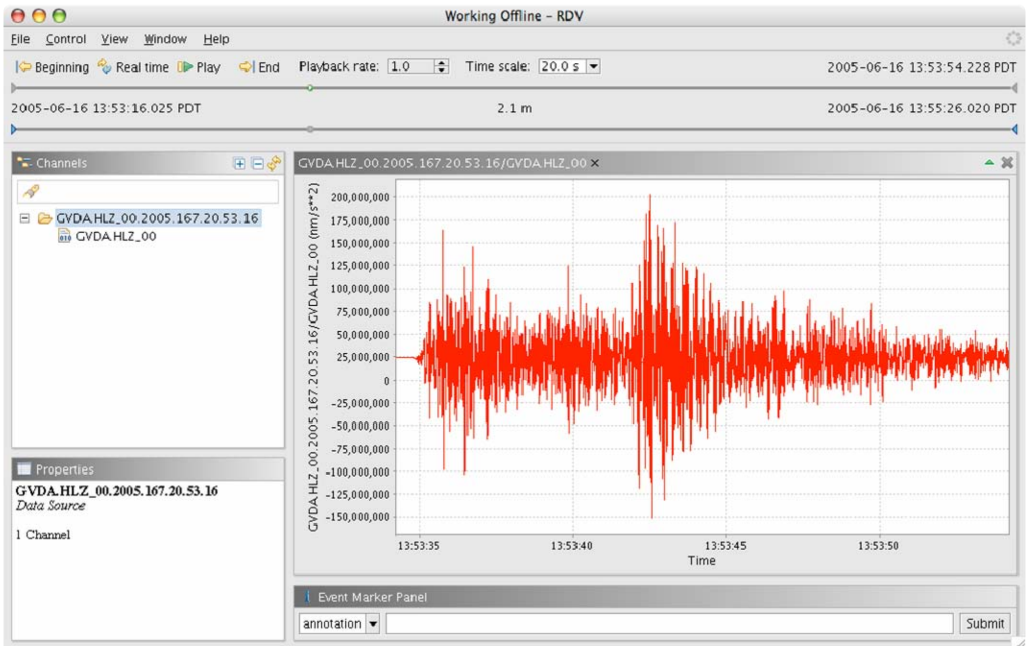

Figure 8. The RDV tool displays a M4.9 event downloaded using the map-based search tool.

4. CONCLUSIONS

The performance analysis of instrumented structures incorporating both geotechnical and structural aspects should provide advances in our ability to predict the effects of earthquakes on the built environment. This combined with the new collaborative shared-use research environment facilitated through the NEES program will help to advance the pace at which discovery is made and new results are put into practice.

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