Ground Motion, Pore Water Pressure and SFSI Monitoring at NEES Permanently Instrumented Field Sites

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Abstract---**As part of the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES), two permanently instrumented field sites for monitoring ground motion, pore water pressure generation, ground deformation, and soil-foundation-structure interaction (SFSI), were added to the NEES equipment portfolio. The sites are the Wildlife Liquefaction Array (WLA) and the Garner Valley Downhole Array (GVDA); both are located in highly seismic areas of the southern California; both have histories of monitored earthquake responses; both are underlain by liquefiable layers; and both have been well characterized. To engender ground deformation, the WLA site is adjacent to a 3-m high bank of the Alamo River. A reconfigurable, steel-framed structure has been constructed at the GVDA site and instrumented with sensors in the structure, foundation, and underlying soil. These field sites will monitor responses generated by earthquakes and by active experiments using shakers. These sites will provide beds for testing of new in-situ characterization techniques and for development of new sensor technologies. Telepresence and teleparticipation capabilities will provide opportunities for collaborative research and educational interaction. The continuous streaming of data to the NEES data repository, ANSS, and local networks will provide ready access to the collected data.**

Keywords---**Earthquakes, structures, foundations, interaction, instrumentation, liquefaction**

INTRODUCTION

Records from field sites during actual earthquake shaking provide essential information for development and validation of analytical and empirical models of ground response, pore water pressure generation, ground deformation and soil-foundation-structure interaction (SFSI). The purpose of this project is to provide such data by instrumenting two field sites, the Wildlife liquefaction array (WLA) and the Garner Valley downhole array (GVDA). Both sites are located in highly seismic areas of southern California (Fig. 1). Each site is equipped with surface and downhole accelerometers, pore pressure transducers, and inclinometers to monitor ground response and ground deformation during earthquake shaking. In addition, GVDA will be equipped with a single-degree-of-freedom structure to monitor SFSI response. When completed, the sites will become part of the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES).

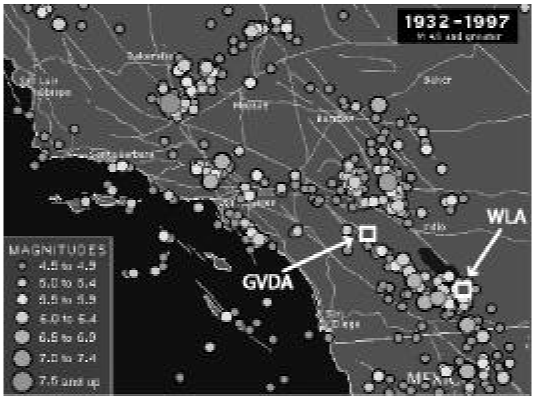

Fig. 1: Map of southern California showing locations of WLA and GVDA and epicenters of earthquakes with magnitudes greater than 4.5 between 1932 and 1997.

The WLA and GVDA sites can also be artificially excited with shakers either on the ground or on the SFSI structure. Demonstration projects at GVDA using shakers are being developed in cooperation with NEES projects at the University of Texas and the University of California at Los Angeles. These demonstration projects, scheduled for August 2004, will test the response of the instrumentation and demonstrate the capability of the electronic systems to stream data in real time to the NEES-grid network.

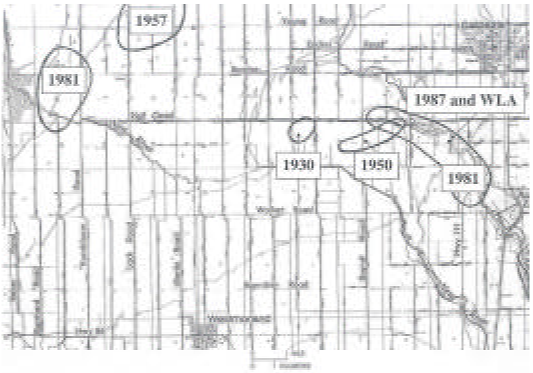

Fig. 2: Area surrounding WLA site showing localities where liquefaction effects have occurred during earthquakes in the past 75 years

Fig.3: 1950 Sand boil deposit near house about 1.5 km northwest of WLA site

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 area has been frequently shaken by earthquakes with six events in the past 75 years generating liquefaction effects within 10 km of the WLA site (Fig. 2). Fig. 3 is a photograph of one of those effects, a sand boil that erupted during an earthquake in 1950 at a locality about 1.5 km northwest of WLA. 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.

Because sand boils erupted pervasively in the floodplain of the Alamo River during the 1981 Westmorland earthquake, an instrumented site was established at that locality in 1882 by the US Geological Survey (USGS), with T.L. Youd as project leader. That site, noted as the “Existing USGS Station” on Fig. 4, was equipped with surface and downhole force-balance accelerometers (FBA) and six electrically transduced piezometers. The downhole FBA was placed at a depth of 7 m, immediately below the liquefiable layer, and five of the six piezometers were placed within the liquefiable layer. Fig. 5(a) is a plan view of the 1982 instrumentation and Fig. 5(b) is a cross section showing the soil stratigraphy and the positions of the six piezometers and the FBA (Bennett et al, 1984). In November of 1987 WLA was struck by two earthquakes, the Elmore Ranch event (M = 6.2) at 5:54 pm PST November 23 and the Superstition Hills event (M = 6.6) 11 hours later at 5:15 am PST November 24. Ground motions and pore water pressures were recorded during

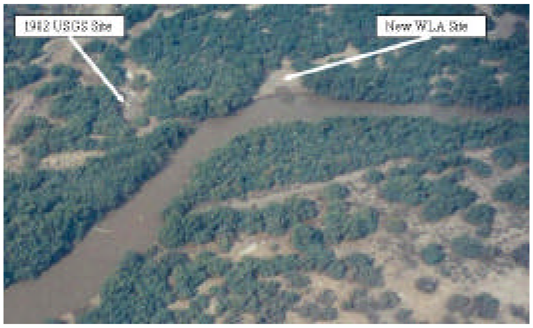

Fig. 4: Aerial view of WLS showing localities of old and new sites

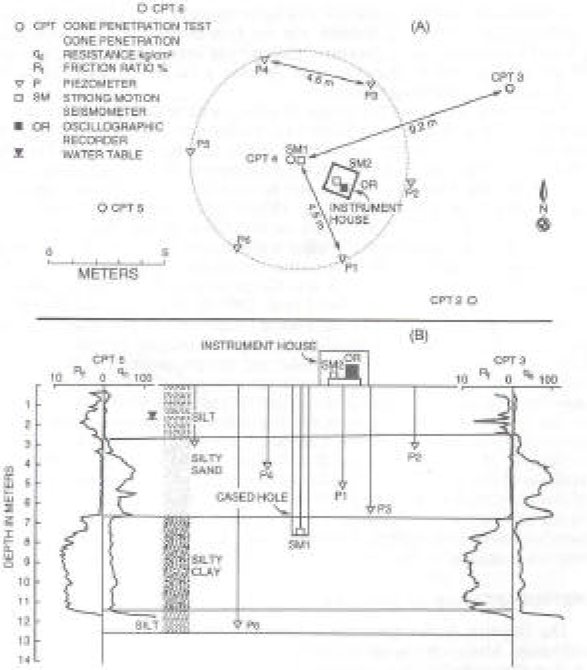

Fig. 5: Plan and cross sectional views of instrumentation placed at Wildlife site in 1982 (Bennett et al., 1984)

the Elmore Ranch event, but the pore pressures did not rise significantly. During the Superstition Hills event, however, pore pressures rose to a pore pressure ratio of 100 % and numerous sand boils erupted within and near the instrumented site (Holzer et al., 1989; Youd and Holzer, 1994). Lateral spread displacements as great as 300 mm were also measured during the Superstition hills event (Dobry et al., 1992). Many researchers have used the data collected from the 1987 earthquakes to analyze the response of the site and to develop or verify models for predicting ground response and ground deformation.

Since 1987, the piezometers installed in 1982 have failed and the site has been disturbed by additional investigations. Because of the deterioration of the 1982 site, we proposed and developed a new NEES equipment site to reestablish WLA, but at a locality 65 m down river (northward) from the 1982 USGS site. The localities of both the old and new sites are marked on Fig. 4, and a scaled map of the sites is reproduced in Fig. 6. Also noted on the map are localities of 24 CPT soundings we installed in April 2003 to define the sediment stratigraphy beneath the new site. Fig. 7 is a stratigraphic cross section beneath line A-A' developed from the CPT data. Fig. 7 also indicates the position of the free face at the river bank. Fig. 8 is a view of the steep river bank and the USGS CPT rig working at the site.

To test the liquefaction susceptibility of sediments in the granular layer beneath WLA, we applied the CPT procedure for evaluating liquefaction resistance published by Youd et al. (2001) to the data collected from CPT 35 for a magnitude 6.5 earthquake and peak ground acceleration (Amax) levels ranging from 0.2 g to 0.4 g. The results of that analysis, noted on Fig. 9, indicate that for a peak acceleration of 0.3 g to 0.4 g, a likely occurrence, much of the granular layer would liquefy. With the nearness of the incised river, liquefaction to this extent would likely lead to ground deformation and lateral spread toward the river.

Fig. 10 shows the approximate locations of instruments placed at the site. The purposes of the downhole and horizontal FBA arrays are to monitor ground response during future earthquakes. The piezometers are to monitor pore water pressure changes generated in response to ground shaking and ground deformation. The piezometers are field-proven ParoScientific devices that were carefully saturated prior to installation. The positioning casings are flexible pipes that were surveyed with a positioning sensor after installation and will be resurveyed after significant earthquakes. The intent of these casings is to detect the depths and amounts of ground deformation after an earthquake, including the thickness and nature of the failure zone.

A Kinemetrics/BRTT Antelope data acquisition system, installed in a small instrumentation structure erected at the site, records data from all of the instruments. The recorded data is streamed from the site by radio link in near real-time to the NEES grid data

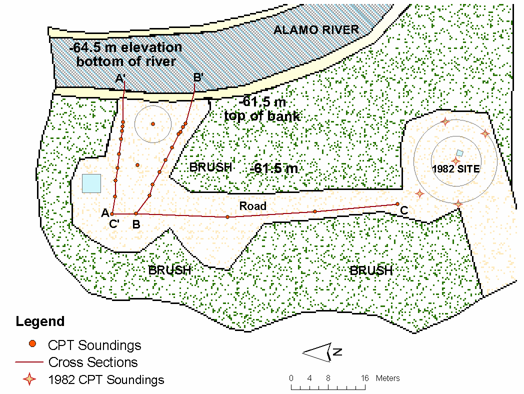

Fig. 6: Map of 1982 and new WLA site with localities of CPT soundings

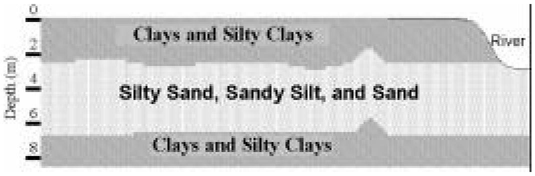

Fig. 7: Cross section A-A' at WLA showing continuity of granular layer between 2.4 m and 7.0 m depth and intersection of those layer with the 3-m deep Alamo river channel

Fig. 8: Steep bank of Alamo River with USGS CPT rig conducting a sounding at WLA site

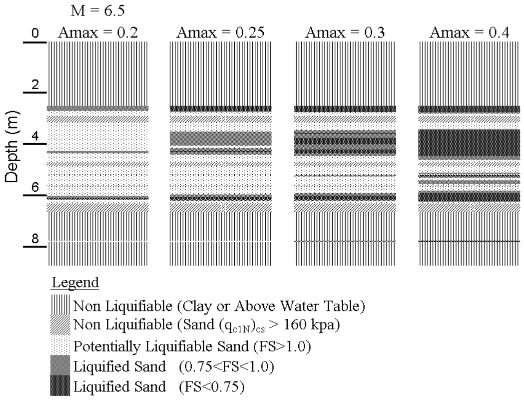

Fig. 9: Liquefaction resistance of sediments penetrated by CPT 35 at WLA for a magnitude 6.5 earthquake and various level of PGA

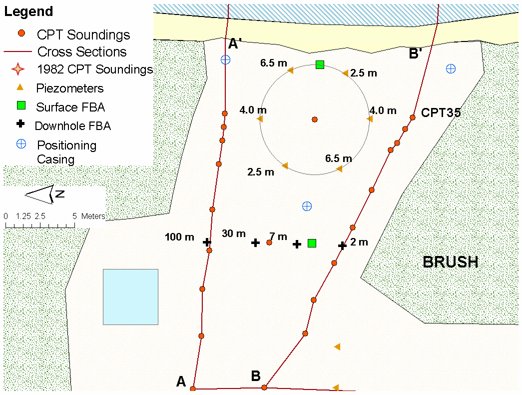

Fig. 10: Map showing approximate locations of FBA's, piezometers, inclinometer casings installed at WLA

archive, making the data available to interested individuals shortly after future earthquakes.

GARNER VALLEY DOWNHOLE ARRAY

The 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 instrument site is located in a narrow valley within the Peninsular Ranges Batholith east of Hemet and southwest of Palm Springs, California. The valley is 4 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.

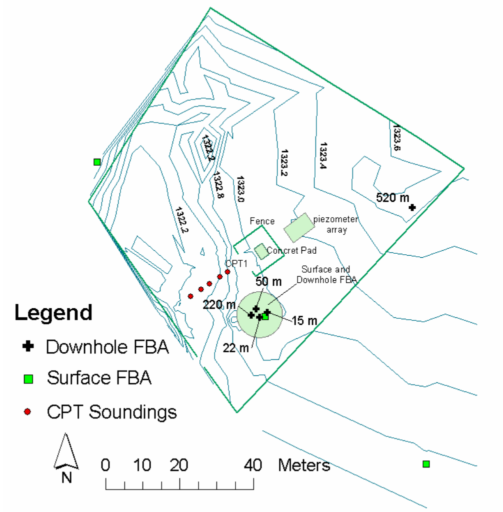

Fig. 11: Topographic map of GVDA showing boundaries of site, instrument locations, and CPT soundings

Fig. 11 is a topographic map of GVDA showing the boundaries of the site, installed instruments, and CPT soundings placed as part of the NEES project.

GVDA is in a seismically active region and lies only 7 km from the main trace of the San Jacinto fault and 35 km from the San Andreas fault (Fig. 12). Historically, the San Jacinto is the most active strike-slip fault system in southern California. A fault slip rate of 10 mm/yr and an absence of large earthquakes since at least 1890 lead to a relatively high probability for magnitude 6.0 or larger earthquake on the San Jacinto fault near the site in the near future. 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 local and regional seismicity (Steidl et al., 1998).

The near-surface stratigraphy beneath the site consists of 18-25 m of lake-bed alluvium overlying weathered granite to a depth of 88 m. Sediments in the upper 18-25 m consist of alternating layers of sand, silty sand, clayey sand, and silty gravel. The alluvium gradually transitions into decomposed granite in the depth interval between 18 m to 25m. The decomposed granite classifies as gravely sand (Steidl et al., 1998). The ground water levels beneath the site ranges from near surface in wet seasons to several meters depth during dry seasons.

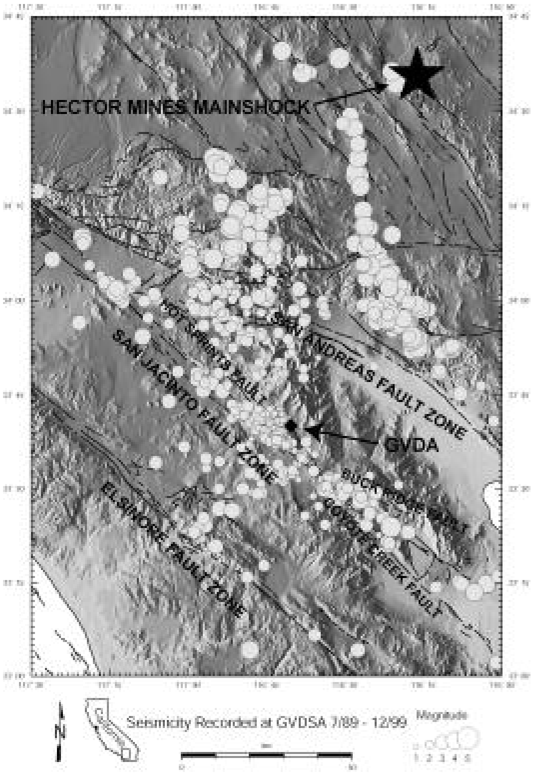

Fig 12: Map showing location of GVDA (diamond), nearby faults (lines) and epicenters of recently recorded earthquakes (circles) (after Steidl et al., 1998)

Geotechnical properties of the site have been defined with samples from SPT borings and data from CPT soundings. Grain size and other index tests have bee conducted on the retrieved split-spoon samples. SPT have been conducted to a depth of 30 m and CPT to a depth of 18 m as part of the NEES and previous investigations. Fig. 13 is cross section of sediment layers to a depth of 18 m compiled from CPT data.

To test liquefaction susceptibility of granular layers beneath GVDA, we applied the standard CPT procedure for evaluating liquefaction resistance as published by Youd et al. (2001). Results from this analysis using data from CPT 1, a magnitude 7.0 earthquake and PGA levels ranging from 0.2 g to 0.4 g are plotted on Fig. 14. For a peak acceleration of 0.3 g to 0.4 g, a likely occurrence in the next 10 years, liquefaction would likely occur beneath the site.

Compression and shear wave velocities were measured to depths as great as 500 m using downhole and suspension logging techniques. Gamma radiation and electrical resistivity logs have also been compiled from geophysical tests in open boreholes. Logs of some of these measurements are plotted on Fig. 15.

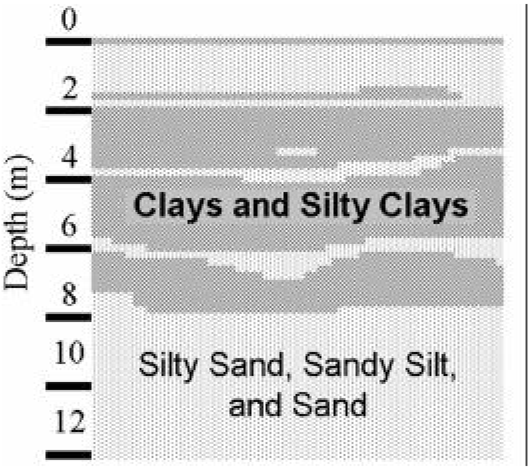

Fig. 13: Cross section of sediments beneath GVDA interpreted from CPT data

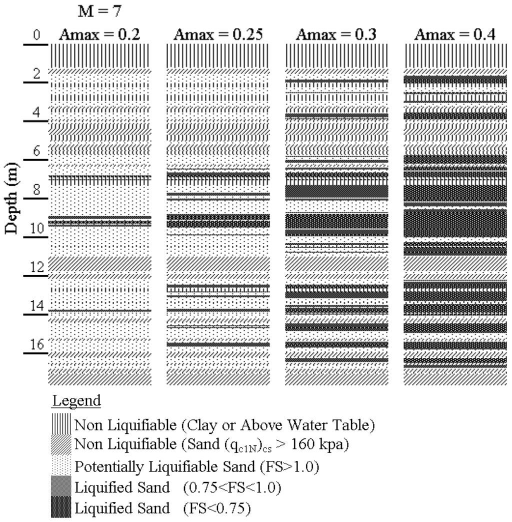

Fig. 14: Liquefaction susceptibility of sediments beneath GVDA calculated from CPT 1 data

At GVDA, seismic motions are monitored by arrays of five surface and six downhole FBA's. The map position of the various FBA's is noted on Fig. 16. Fig.17 is a cross section of the site with plotted depths of the downhole FBA's. All of the FBA's noted on Fig. 16 were placed prior to the NEES project, except for the FBA at 150 m, with support from previous projects and supporting agencies.

In addition to the FBA arrays noted above, a remote station has been set on a bedrock outcrop 3 km east of the main site. This station contains an FBA set into the rock surface and a second FBA set at a depth of 30 m. Data from this remote site is telemetered back to the main station via a radio link.

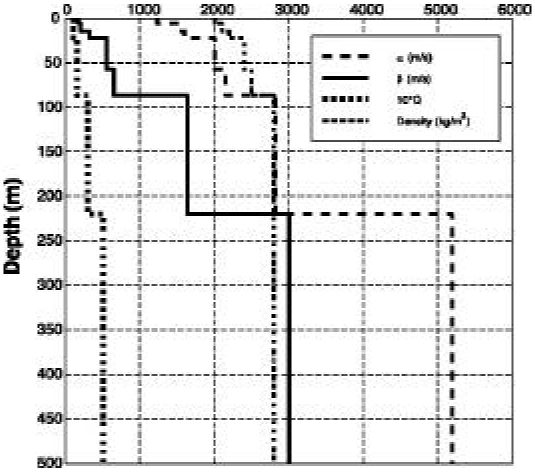

Fig. 15: Compression-wave (a) and shear-wave (ß) velocities and other geophysical measures beneath GVDA site (after Steidl et al., 1998))

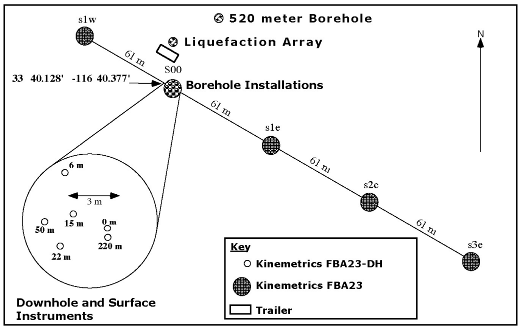

Fig. 16: Horizontal distribution of FBA's and relative location of liquefaction array at GVDA (after Steidl et al., 1998)

Two piezometers have been set at GVDA within the deeper crystalline bedrock in sealed off fracture zones at depths of 335 m and 419 m. These piezometers monitor the ambient hydrostatic pressure in the bedrock and dynamic pore pressures generated by seismic waves.

Pore-pressure response within the alluvial sand and decomposed granite layers are monitored by an array of seven piezometers set at depths between 3 m to 13 m (Fig. 18). These piezometers are set in gravel packs placed at the bottoms of uncased boreholes. Bentonite chips were placed above the gravel packs to seal the boreholes. These piezometers are ParoScientific and PSA models that were set in February 2000 to replace a previous set of piezometers that had failed. The piezometers set in 2000 have functioned without further failures.

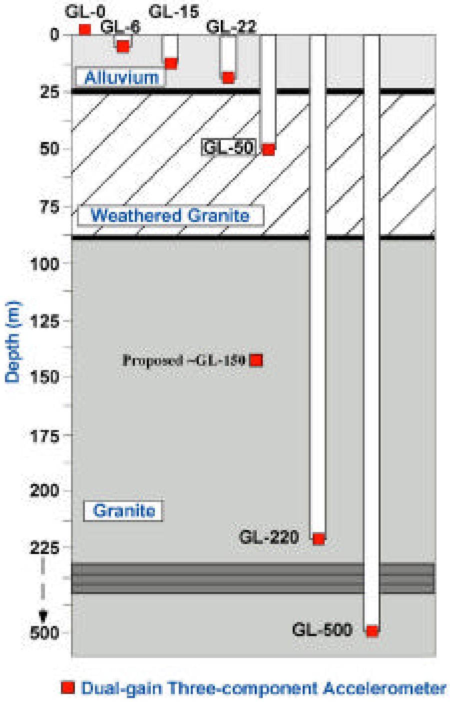

Fig. 17: Cross section of GVDA site with depths of installed FBA's (after Steidl et al., 1998)

An additional piezometer was set at a depth of 6.5 m in an open slotted casing to monitor depths and fluctuations of the shallow ground water table. As with the WLA site, data from GVDA will be streamed between the site, the southern California HP WREN system, and the NEES grid via radio links.

GVDA TEST STRUCTURE

A major addition to the GVDA site for the NEES project was the construction of a test structure for monitoring of soil-foundation-structure-interaction (SFSI) during earthquake shaking. This structure can also be excited by shakers mounted on the structure or nearby on the ground surface. The general purpose for the SFSI test structure is to provide a medium-scale reconfigurable steel-frame structure founded on a rigid, massive concrete slab on grade. The superstructure is of a size appropriate for testing on a large NEES shake table. Provisions are made for mounting shakers on the roof for active experiments to complement the primary purpose of passive response to earthquake monitoring.

The design criteria for the GVDA SFSI Test Structure are defined as follows:

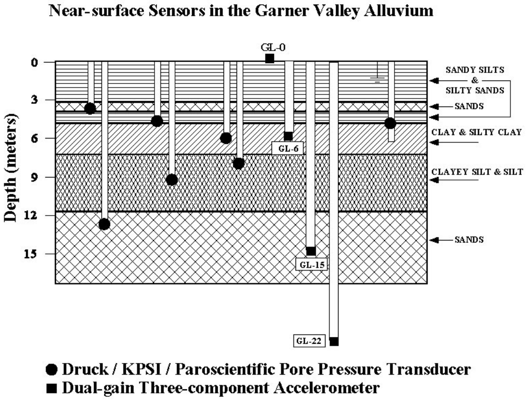

Fig. 18: Cross section of GVDA site showing depths of electrically transduced piezometers

Fig. 19: GVDA site with superimposed approximate drawing of the test structure.

- The structure is founded on a simple spread footing at grade.
- The foundation bearing pressure is 33-48 kPa footing to insure high stresses.
- Approximately 50% of the mass is in the foundation to insure significant SFSI.
- The superstructure size is appropriate for mounting on NEES shake tables (4 m x 4 m, 50 ton maxima).
- The steel frame is reconfigurable to allow flexibility.
- The bracing system is adjustable to allow adjustment of stiffness and damping.
- A strong RC rigid roof slab was placed to provide additional mass and a platform for shaker mounting.
- The 7-10 Hz fixed-base natural frequency of superstructure can be adjusted from approximately 5 to 15 Hz with adjustments to stiffness and mass.
- The stiffness of the foundation soils changes with ground water level. These soils are softer during wet seasons with high water table and stiffer during dry seasons with a deeper water table.
- Instruments in the foundation soils include accelerometers, stress cells, piezometers, and displacement transducers.
- Instruments in the structure include accelerometers, strain gages, and load cells.
- Cased holes were installed on each side of the structure for cross-hole seismic velocity tests before, during and after experiments.
- The structure is covered with architectural cladding attached with flexible connections.

From preliminary analyses of the stiffness of the structure relative to the site, we calculate a dimensionless site parameter, s, equal to 1.6 as illustrated in Fig. 20. For this calculation, the frequency ratio, W/Ws, was set at 0.7, which yielded an approximately 30 % reduction in the frequency of the soil-foundation-structure system compared to the stricture on a rigid fixed base. In this calculation, W is the natural frequency of whole system, Ws is the natural frequency of the structure on a rigid base, s is a dimensionless parameter hWs/Cs, where Cs the shear wave velocity of the soil.

A web-based simulation tool is being developed to assist the design of SFSI experiments at GVDA. The primary purpose of the simulation tool is to provide users with a simple JAVA-based interface to perform finite element analyses of the SFSI structure. The simulation tool will be a web-based application with the finite element analyses performed on the server side by implementing the JAVA SERVLET technology. The results will be displayed for the remote user via a TCP/IP protocol through a web browser. This simulation tool eventually will be used to verify the structural configurations and the shaker parameters for experiments to be conducted at this NEES-sponsored test facility.

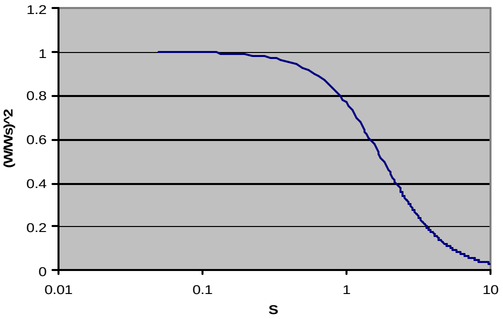

Fig. 20: Property of equivalent one degree of freedom system of v = 0.33, Cs = 150 m/sec and h = 4 m

SUMMARY

The purpose of NEES is to provide a national, networked, simulation resource that includes geographically-distributed, shared-use, next-generation experimental research Equipment Sites built and operated to advance earthquake engineering research and education through collaborative and integrated experimentation, theory, data archiving, and model-based simulation. The goal is to accelerate progress in earthquake engineering research and to improve the seismic design and performance of civil and mechanical infrastructure systems through the integration of people, ideas, and tools in a collaboratory environment. Open access to and use of NEES research facilities and data by all elements of the earthquake engineering community, including researchers, educators, students, practitioners, and IT experts, is a key element of this goal (http://www.NEES.org/NCI/purpose.html).

The WLA and GVDA instrumented sites are key elements in the NEES system to meet this purpose and goal**.** These field sites will provide data from monitored responses generated by earthquakes and by active experiments using shakers. These sites will also provide beds for testing of new in-situ characterization techniques and for development of new sensor technologies. The telepresence and teleparticipation capabilities of the sites will provide opportunities for collaborative research and educational interaction. The continuous streaming of data to the NEES data repository, ANSS, and local networks will provide ready access to the collected data.

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