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DEVELOPMENT OF THE NEES LARGE-SCALE MOBILE SHAKERS AND ASSOCIATED INSTRUMENTATION FOR IN SITU EVALUATION OF NONLINEAR CHARACTERISTICS AND LIQUEFACTION RESISTANCE OF SOILS

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SUMMARY

The U.S. National Science Foundation is developing the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). As part of the NEES program, a network of fifteen advanced testing facilities, called Equipment Sites, is being developed that will be distributed across the United States. The Equipment Site specializing in mobile, geotechnical, field equipment is being developed at the University of Texas at Austin. This Equipment Site is called nees@UTexas and encompasses: (1) three mobile shakers that have diverse force and frequency capabilities and a tractor-trailer rig to move the two largest shakers to and from field sites, (2) an instrumentation van that houses state-of-the-art data acquisition systems and a satellite link-up, (3) a large collection of field instrumentation that includes wired and wireless sensors that measure vibrational motion and pore water pressure, and (4) telepresence capabilities. As an example, some characteristics of one large shaker are: buggy-mounted shaker, weight = 29,000 kg (64,000 lb), peak vertical force = 267 kN (60,000 lb), capable of shaking in the x, y and z directions, optimal frequency range of 4 to 180 Hz, programmable forcing functions, and variable hold-down force. The nees@UTexas equipment, which is presently undergoing field trials, is described. Examples of using the equipment to evaluate nonlinear soil characteristics and liquefaction resistance are presented. This large-scale field equipment: (1) represents a significant advance over current field capabilities, (2) offers geotechnical earthquake engineers opportunities for direct field testing that have previously been possible only in the laboratory, and (3) most importantly, is intended for shared use by all engineers in the United States for national and international projects. The shared-use aspect of the NEES program is a critical component that will be overseen by a community-based, not-for-profit organization called the NEES Consortium, Inc. The NEES Consortium will also oversee an advanced information

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technology infrastructure that will link all fifteen Equipment Sites, making them accessible from remote locations and fostering research collaborations, data sharing, and research dissemination.

INTRODUCTION

The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) is funded by the U.S. National Science Foundation. NEES is a collection of fifteen, next-generation, shared-use experimental facilities for earthquake engineering that are geographically-distributed throughout the United States (Figure 1). The fifteen experimental facilities, called Equipment Sites, cover a wide range of large-scale testing capabilities. The experimental facilities can be divided into the following five general categories: (1) geotechnical centrifuges, (2) mobile and permanent field testing facilities, (3) structural laboratories, (4) shaking tables, and (5) a tsunami wave basin. The shared-use aspect of all equipment sites will be overseen by a community-based, not-for-profit organization called the NEES Consortium, Inc. The NEES Consortium will also oversee an advanced information technology (IT) infrastructure that will link all fifteen equipment sites, making them accessible from remote locations and fostering research collaborations, data sharing, and research dissemination.

The NEES Equipment Site that specializes in mobile, geotechnical, field, equipment is being developed at the University of Texas at Austin. This Equipment Site is called nees@UTexas. The primary goal of nees@UTexas is to develop large mobile shakers that can dynamically load geotechnical and structural systems in the field and simultaneously monitor their response with wired and wireless sensors. The nees@UTexas equipment is discussed below. Additional information can be found on the Internet (http://nees.utexas.edu). Two examples of how this equipment can be used in the future to advance our understanding of nonlinear soil behavior and liquefaction resistance are then presented.

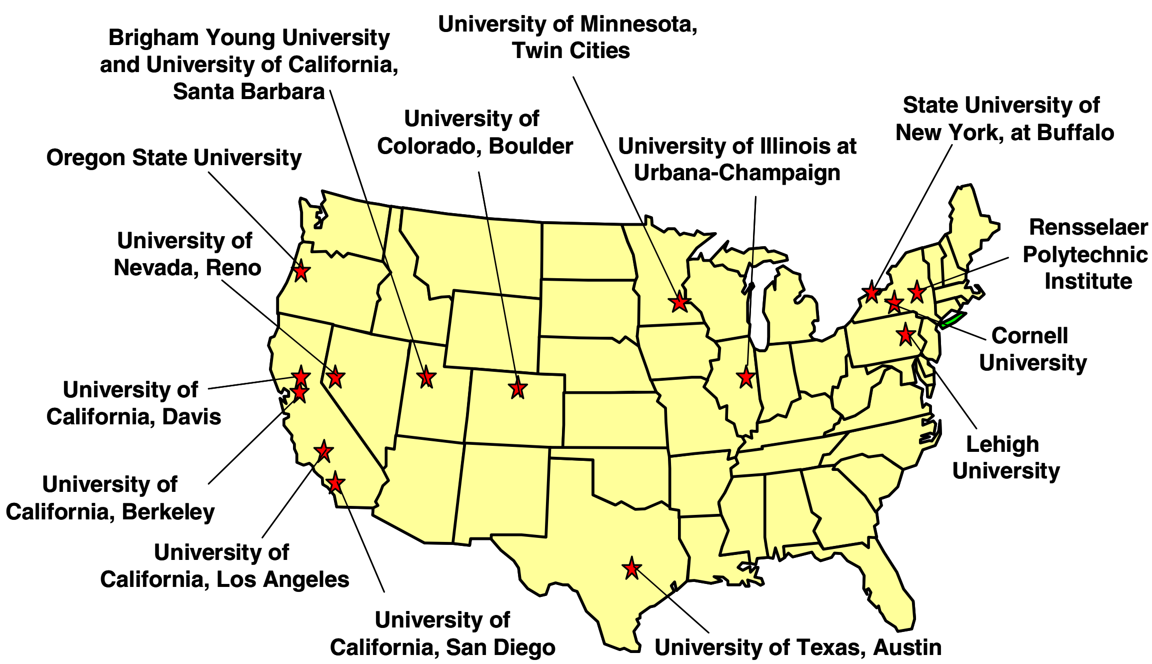


Figure 1 Locations of the fifteen shared-use NEES Equipment Sites that are distributed throughout the United States

OVERVIEW OF NEES@UTEXAS

The nees@UTexas equipment includes: (1) three mobile shakers that have diverse force and frequency capabilities and a tractor-trailer rig to move the two largest shakers to and from the field sites, (2) an instrumentation van that houses state-of-the-art data acquisition systems and a satellite link-up, (3) a large collection of field instrumentation that includes wired and wireless sensors that measure vibrational motion and pore water pressure, and (4) telepresence capabilities that allow for remote participation in field experiments.

Field Mobile Shakers and Tractor-Trailer Rig

The three mobile shakers of nees@UTexas are called: (1) T-Rex, (2) Liquidator, and (3) Thumper. Each mobile shaker was designed and built by Industrial Vehicles International, Inc. (IVI), in Tulsa, Oklahoma. T-Rex was introduced by IVI in 1999 and is capable of generating large dynamic forces in any of three directions (X, Y, or Z directions). A photograph of T-Rex is shown in Figure 2a. The shaking system is housed on an off-road vehicle so that it can be operated in difficult geologic environments. Some important characteristics of T-Rex are: buggy-mounted off-road vibrator; total weight of 29,030 kg; three vibrational orientations (vertical, horizontal in-line, and horizontal cross-line); and push-button transformation of shaking orientation. Additional characteristics of T-Rex are given in Table 1. These characteristics make T-Rex an excellent vibrational source for subsurface seismic exploration and earthquake motion simulation. The theoretical performance of T-Rex (the actual force output of the shaker is site dependent) in both the vertical and horizontal modes is shown in Figure 3a. As shown in the figure, the force output in the vertical mode is about 267 kN and decreases with frequency below 12 Hz. In the horizontal mode, the maximum force output is about 133 kN, one-half of the maximum force output in the vertical mode. This force output does not begin to decrease with frequency until about 5 Hz. Several modifications to T-Rex have been made as part of the NEES project to improve its performance and capabilities for earthquake studies. The two most important modifications are: (1) addition of an electronic controller so that external drive functions can be used to drive the shaker with sinusoidal, random, or earthquake motions, and (2) control of the static hold-down system of the shaker so that variable vertical stresses can be applied to the ground surface during staged testing.

Liquidator is the other large mobile shaker. Liquidator is designed to be a lower frequency vibrator than T-Rex and is a one-of-a-kind shaker. A photograph of Liquidator during field trials in January, 2004 is shown in Figure 2b. As seen in the photograph, Liquidator has the same off-road buggy design as T-Rex, but the shaking system is specially designed to give a higher force output in the low-frequency range of 0.5 to 4.0 Hz. Some important characteristics of Liquidator are: buggy-mounted off-road shaker; total weight of 27,200 kg; two vibration orientations (vertical or horizontal transverse); shop transformable shaking orientation in about one day; movable weight of about 6100 kg; and peak-to-peak movement of 40 cm. Additional characteristics of Liquidator are given in Table 1. These characteristics make Liquidator an excellent low-frequency vibrational source for deep surface wave testing and earthquake motion simulation. The large peak-to-peak movement of the mass is required to create high force levels at low frequencies and requires a one-of-a-kind isolation system that makes Liquidator unique. The theoretical performance of Liquidator (actual force output is site dependent) in both the vertical and horizontal modes is shown in Figure 3b. As shown in the figure, the force output in both modes is about 89 kN and decreases with frequency below 1.3 Hz. Because the force from Liquidator does not start to fall off until 1.3 Hz, it can generate significantly larger forces than T-Rex in the frequency range of 0.5 to 4 Hz.

a. High-force, three-axis shaker called T-Rex

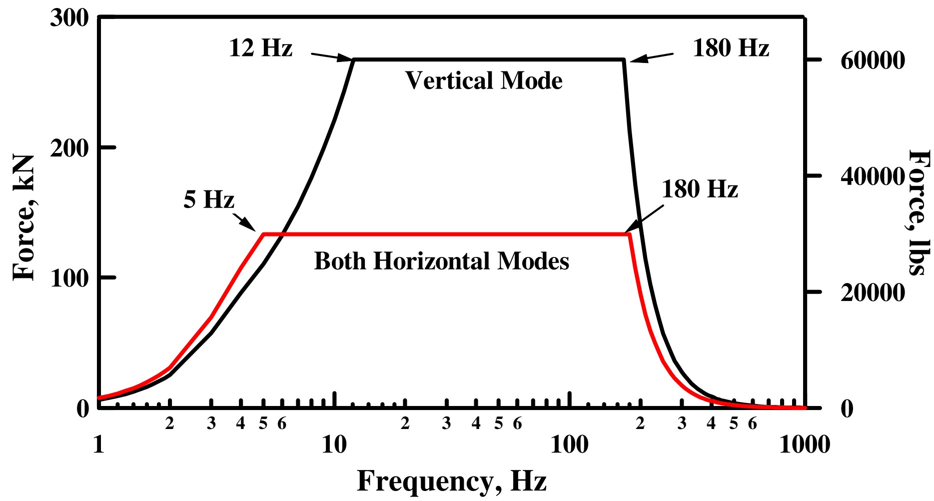
b. Low-frequency, two-axis shaker called Liquidator

c. High-frequency, three-axis shaker called Thumper

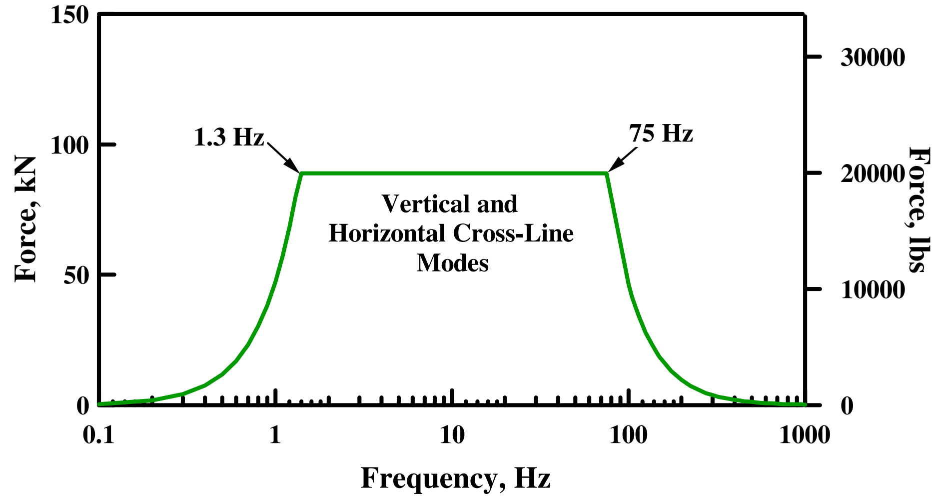
Figure 2 Photographs of the three mobiles shakers at nees@UTexas

Table 1 Characteristics of the three mobile shakers at nees@UTexas

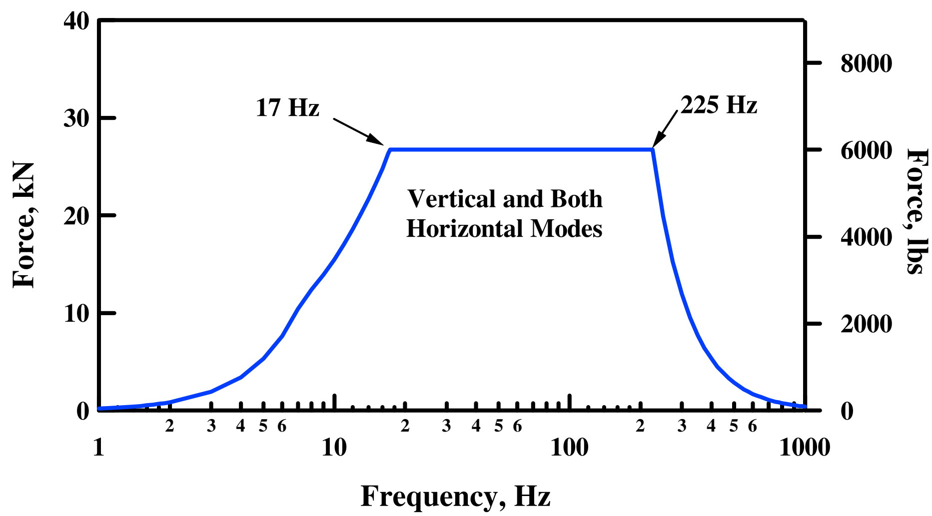
Shaker	T-Rex	Liquidator`	Thumper
Vehicle Type	Buggy-mounted shaker, articulated body	Buggy-mounted shaker, articulated body	Built on Ford F650 Truck
Driving Speed	Hydraulic drive system (<15 mph)	Hydraulic drive system (<15 mph)	Highway Speeds
Total Weight	29,030 kg (64,000 lb)	27,200 kg (59,900 lb)	9980 kg (22,600 lb)
Length	9.8 m (32 ft)	9.8 m (32 ft)	7.1 m (23 ft)
Width	2.4 m (8 ft)	2.4 m (8 ft)	2.4 m (8 ft)
Height	3.2m (10.5 ft)	3.2m (10.5 ft)	2.4 m (8 ft)
Hydraulic System Pressure	207 bar (3,000 psi)	207 bar (3,000 psi)	476 bar (4000 psi)
Vibrator Pump Flow	757 l/m (200 gpm)	530 l/m (140 gpm)	151 l/m (40 gpm)
Vibration Orientations	(1) Vertical, (2) Horizontal in-line, and (3) Horizontal cross-line	(1) Vertical, and (2) Horizontal cross-line	(1) Vertical, (2) Horizontal in-line, and (3) Horizontal cross-line
Shaking Orientation Transformation	Push-button transformation of shaking orientation	Shop transformable in about one day	Field transformable in about four hours
Maximum Output Force: (1) Vertical, and (2) Shear	(1) 267 kN (60,000 lb) (2) 134 kN (30,000 lb)	(1) 89 kN (20,000 lb) (2) 89 kN (20,000 lb)	(1) 26.7 kN (6000 lb) (2) 26.7 kN (6000 lb)
Base Plate Area	4.11 m^2 (44.2 ft^2)	4.34 m^2 (46.7 ft^2)	0.698 m^2 (7.50 ft^2)
Moving Mass: (1) Vertical, and (2) Shear	(1) 3,670 kg (8,100 lb) (2) 2,200 kg (4,850 lb)	(1) 13,475 lb (6,110 kg) (2) 13,475 lb (6,110 kg)	(1) 311 lb (140 kg) (2) 311 lb (140 kg)
Stroke (Peak to Peak): (1) Vertical, and (2) Shear	(1) 8.9 cm (3.5 in.) (2) 17.8 cm (7.0 in.)	(1) 40.6 cm (16.0 in.) (2) 40.6 cm (16.0 in.)	(1) 7.6 cm (3.0 in.) (2) 7.6 cm (3.0 in.)
Hydraulic Oil	Vegetable-based hydraulic oil	Vegetable-based hydraulic oil	Vegetable-based hydraulic oil
Special Features	(1) Cone pushing capacity (2) Hydraulic pressure take-off (3) Variable vertical hold-down force (4) Must be transported by tractor-trailer rig	(1) Optimized for low freq. (down to 0.5 Hz) (2) Cone pushing capacity (3) Hydraulic pressure take-off (4) Must be transported by tractor-trailer rig	(1) Built for high-frequency output (above 200 Hz) (2) Built for use in urban environments (3) Can be driven on highways



a. Theoretical force output of T-Rex



a. Theoretical force output of Liquidator



c. Theoretical force output of Thumper

Figure 3 Theoretical force outputs of the three mobile shakers at nees@UTexas

Thumper is designed to be a moderate- to high-frequency vibrator used in seismic reflection and surface wave projects. A photograph of Thumper is shown in Figure 2c. As can be seen in the photograph, Thumper is housed on a much smaller vehicle, which aids in its transportation to and from sites and also allows it to be used in urban environments. Some important characteristics of Thumper are: mounted on a Ford F650 truck; total weight of about 9,900 kg; three vibration orientations (vertical, horizontal in- line, and horizontal cross-line); and field transformable shaking orientation in about four hours. These characteristics make Thumper an excellent vibrational source for shallow (depths less than 100 m) seismic reflection profiling and surface wave testing. The theoretical performance of Thumper (actual force output is site dependent) is shown in Figure 3c. As shown in the figure, the maximum force output is about 27 kN over the frequency range of 17 to 225 Hz. The force output decreases outside of this frequency band. The relatively low-force output (27 kN) makes Thumper an excellent shaker for testing in urban environments where disturbance or possible damage are concerns.

T-Rex and Liquidator must be transported to and from field sites on a tractor-trailer rig. The tractor-trailer rig that is part of the nees@UTexas vehicle fleet is shown in Figure 4. However, it is important to note that the combined weights of one of the large shakers and the tractor-trailer rig are between 45,000 and 48,000 kg. Therefore, the complete system is overweight when moving on the highways and thus requires overweight permits to transport. Also, two special features have been added to T-Rex and Liquidator to increase their usefulness. The first feature is a cone or sensor pushing capability that has been added on the back bumper. Pushing (or pulling) is done with the hydraulic cylinder controlled by a variable-flow value. This arrangement on the back of T-Rex is shown in Figure 5a. The second special feature is a hydraulic take-off so that either large shaker can be used to power other hydraulic equipment in the field. The hydraulic take-off on T-Rex is shown in Figure 5b.

Instrumentation Van and Data Acquisition Systems

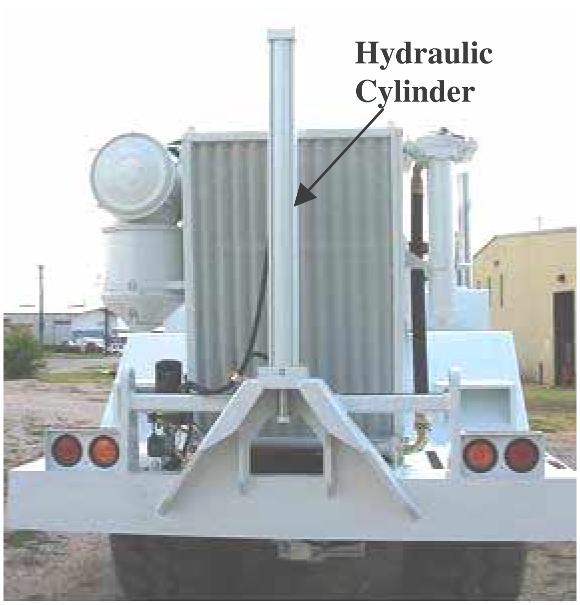
The field instrumentation van is a customized Chevrolet cargo van that includes a diesel generator, an air-conditioned workspace, and a fully-integrated computational network. The instrumentation van is shown in Figure 6. The computational network includes two Sun workstations, a PC server and laptop computer, a local wireless network, and a satellite modem with up to 512 kbps transmission rate. This computational infrastructure allows for significant analytical capabilities while in the field. Additional equipment housed in the instrumentation van includes: digital video cameras, teleconferencing equipment, disk storage, and a power backup system.

The instrumentation van also houses the two main data acquisition systems: (1) a VXI system and (2) a Sercel 408XL system. The VXI system includes 48 channels of acquisition at a sampling rate of 50 kS/s. The VXI hardware is controlled by software supplied by Data Physics. This software permits traditional data acquisition, and also has significant signal analyzer functions (e.g., swept-sine, playback, and zoom measurements). The Sercel 408XL is a state-of-the-art data acquisition system for the seismic testing and oil exploration industries. It can process up to 2,000 channels of data and is capable of connection to receivers via digital telemetry cables or via wireless radio links. Cabled receivers communicate their data over a digital network, so cables consist of only a twisted pair, making them light-weight. Wireless receivers can transmit their data from locations up to about 30 km away, depending on antenna and topographic conditions. Recording is available at 1, 2, and 4 millisecond time intervals when the wireless units are mixed with the cabled system. If only cabled receivers are in use, sample intervals as small as one-quarter millisecond are available.

Field Instrumentation

The field instrumentation available at nees@UTexas includes 1-Hz and 10-Hz geophones and a suite of in situ liquefaction sensors. Twelve sets of 3-component (3-D), 1-Hz geophones and twelve sets of 3-D

Figure 4 Photograph of the tractor-trailer rig used to transport T-Rex and Liquidator



a. Hydraulic cylinder used to push (or retrieve) sensors into ground

b. Hydraulic take-off so the pump can power other systems

Figure 5 Special features added to T-Rex and Liquidator

Figure 6 Photograph of the instrumentation van used in the field for data recording, processing, and teleparticipation

10-Hz geophones are available and are compatible with both the Sercel and VXI data acquisition systems. Sixteen additional 1-D (vertical), 1-Hz geophones are also available and compatible with both systems. The 1-Hz and 10-Hz geophones are used only for particle motion measurements (in terms of particle velocities) at the ground surface.

The in situ liquefaction sensors are being designed and constructed at the University of Texas, and will consist of three, orthogonally-oriented, 28-Hz geophones and a miniature pore pressure transducer housed in a single acrylic case. A prototype, 2-D version of this sensor, which has performed well in other studies [1, 2, 3], is shown in Figure 7. The 3-D liquefaction sensors will be relatively small, measuring about 18 cm in length and 3.6 cm in diameter, and have a total unit weight approximately equal to saturated, loose sand. The 28-Hz geophones were chosen to minimize the size of the sensors, but these geophones are not ideal for measuring vibrations at frequencies less than about 20 Hz. Therefore, additional liquefaction sensors utilizing micro-electro-mechanical-system (MEMS) accelerometers are also under consideration. The liquefaction sensors will be installed at multiple points in the ground to monitor ground motion and pore pressure generation at each point.

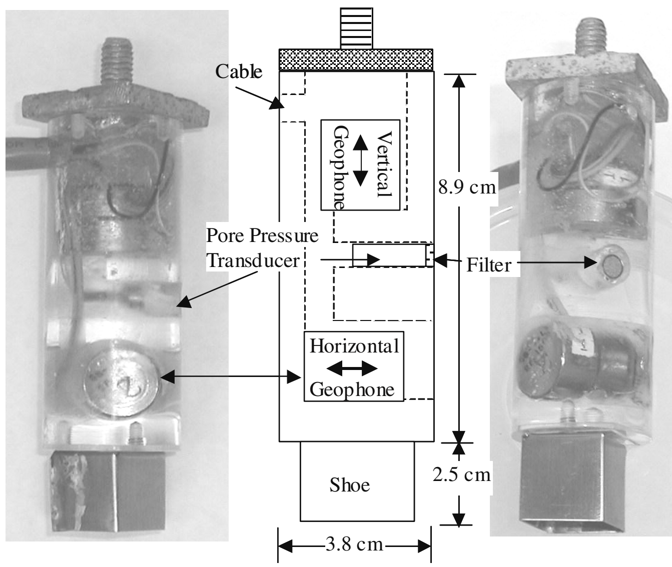


Figure 7 Schematic of in situ liquefaction test sensor used in earlier studies [1]

Remote Participation

The computational network and infrastructure housed within the instrumentation van allows for high-speed data acquisition, data viewing, and data analysis while in the field. However, a significant objective of NEES is the participation of remote researchers, as well as the general public, in experimental activities. The NEESgrid IT infrastructure (www.neesgrid.org), developed by the National Center for Supercomputing Applications at the University of Illinois, facilitates this remote usage, called teleparticipation. Specifically, NEESgrid services allow remote users to view data in real time, observe experiments, control some components of the experiment, communicate with researchers at the laboratory or field site, and link experimental data with computer simulation. To access these services, a remote user requires only internet access and a web browser.

To link the nees@UTexas field network and computational infrastructure to remote users, a satellite modem is utilized along with a NEES Point of Presence (NEESpop) server housed on the University of Texas (UT) campus. Inquiries from remote users (e.g., requests for data channels, video) are routed first to the NEESpop at the UT campus, rather than directly to the NEESpop in the field instrumentation van because of the limited bandwidth (512 kbps) across the satellite modem. The campus NEESpop then requests the data from the field NEESpop, the field NEESpop transmits the requested data, and the campus NEESpop multiplexes that data over the high-speed internet to the remote users who requested it. This command structure minimizes the amount of data transmitted over the limited bandwidth of the satellite modem.

There are several NEESgrid telepresence activities supported by nees@UTexas. Two digital cameras send visual data of field experiments to remote viewers. One camera also allows remote users to control its pan, tilt position and zoom level. Video teleconferencing between field personnel and remote users is available through Polycom hardware and software. Remote users can view multiple channels of data in near real-time, and can download data from the campus NEESpop via gridFTP shortly after experiments are over. These telepresence capabilities allow real-time interactions between field and remote researchers, improving the field experiment process.

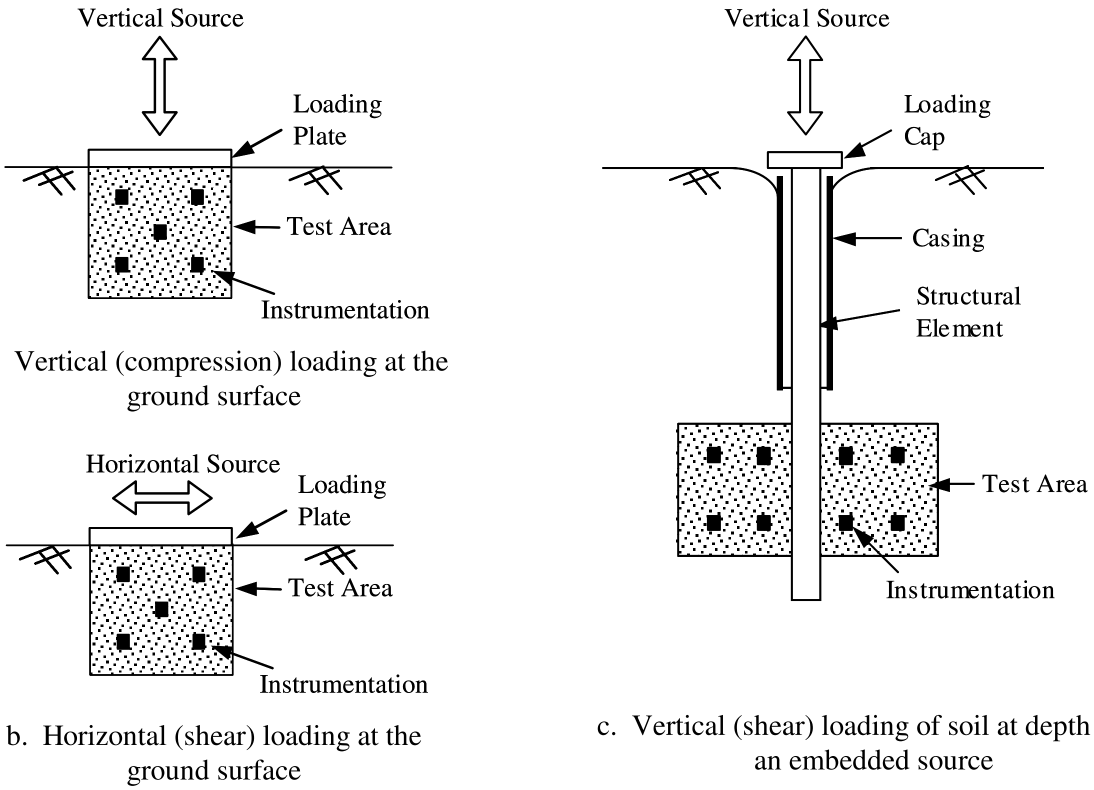
EXAMPLE STUDIES USING THE NEES@UTEXAS EQUIPMENT

Examples of two general categories of field studies using the large mobile shakers are briefly discussed below. The loading, sensor, and recording systems used in these studies were actually smaller, less capable systems because the nees@UTexas equipment did not exist. These studies are called prototype studies. The prototype studies involved initial work in developing new field tests to: (1) characterize the nonlinear shear modulus of soil in situ, and (2) directly evaluate in situ the liquefaction resistance of sand. Both examples illustrate new directions in experimental testing that will be possible with the NEES Equipment Sites and will enrich our fundamental understanding and design methodologies in earthquake engineering.

In Situ Evaluation of Nonlinear Soil Properties

Currently, there is almost a complete dependence on laboratory testing to measure nonlinear soil properties for dynamic response analyses. The pertinent nonlinear properties used in a typical site response analysis involving vertically propagating shear waves are the variation of the shear modulus, G, and the material damping ratio in shear, D, with shearing strain, γ. Curves that describe the nonlinear variation of normalized shear modulus (G/G_{max}, where G_{max} equals the small-strain shear modulus) with strain are evaluated in the laboratory and combined with G_{max} measured in situ with seismic tests to describe the G - log γ curve in the field. Curves that describe the nonlinear variation of material damping ratio with strain are also evaluated in the laboratory. At this time, there is no robust field seismic measurement of small-strain material ratio, D_{min}, that can be used to link the field and laboratory D - log γ curves. Therefore, the laboratory curves are typically adjusted using engineering judgment before they are used to describe the damping characteristics of the soil in the field.

To begin to measure nonlinear soil properties in situ, a generalized test method is under development at UT [2,3]. This method involves applying static and dynamic loads to a soil deposit using a large, mobile hydraulic shaker and measuring the dynamic response of the soil mass with embedded instrumentation. The resulting field test is a load-controlled dynamic test that induces nonlinearity in the soil. T-Rex and Liquidator have excellent capabilities for this application. Three generalized test configurations are illustrated in Figure 8. Two configurations involved loading the surface of the soil deposit, either in compression (Figure 8a) or in shear (Figure 8b). In the third configuration, the soil is loaded at depth by shaking a structural element extending into the test area. Initial developmental work has focused on loading the surface of the soil deposit in the vertical and horizontal directions. The magnitudes of the induced strains and the nonlinear variations in shear and Young's moduli with strain have been evaluated.



a. Vertical (compression) loading at the ground surface

b. Horizontal (shear) loading at the ground surface

c. Vertical (shear) loading of soil at depth with an embedded source

Figure 8 Generalized test configuration for in situ evaluation of nonlinear soil properties

As with laboratory testing to evaluate nonlinear soil properties, a series of shaking tests is performed in the field, starting from a low loading level. The loading level is gradually increased until significant nonlinearity is measured or the capacity the shaker is reached. In the prototype tests involving nonlinear shear modulus measurements in an unsaturated silty sand, an older Vibroseis owned by UT was used to statically load a footing on the ground surface. A total of four static load levels was used. At each static load level, horizontal impacts were applied to the footing using a pendulum arrangement. The horizontal impacts were increased in magnitude until the maximum force level was reached. The horizontal dynamic motions at various locations beneath the footing (as shown in Figure 8b) were measured with embedded geophones. These results were then used to calculate the linear and nonlinear shear wave velocities, shear moduli and shear strains in the soil beneath the footing [3]. These results are shown in Figure 9 in terms of normalized shear modulus, G/G_{max}, versus shear strain. Clearly, nonlinearity was measured, although the horizontal dynamic forces were not large enough to create shear strains above 0.01 %. Once T-Rex or Liquidator is used as a source, significantly higher strains will be possible, likely exceeding failure strains.

In Situ Evaluation of Liquefaction Resistance

The current state of in situ liquefaction analyses depends heavily on correlations between in situ testing parameters (i.e. Standard Penetration Test blow count, N-value, Cone Penetration Test tip resistance, q_c value, or in situ shear wave velocity, V_S) and the cyclic stress ratio to cause liquefaction ($CSR_L = \tau/\sigma_v'$, where τ = cyclic shear stress, and σ_v' = initial vertical effective stress). These correlations have been developed from case studies of sites that did and did not liquefy during previous earthquakes [e.g. 4, 5, 6]. To evaluate the liquefaction potential of a site, the CSR_L is compared to an estimate of the CSR generated by the design earthquake. This procedure is useful for cases where liquefaction susceptibility is very high

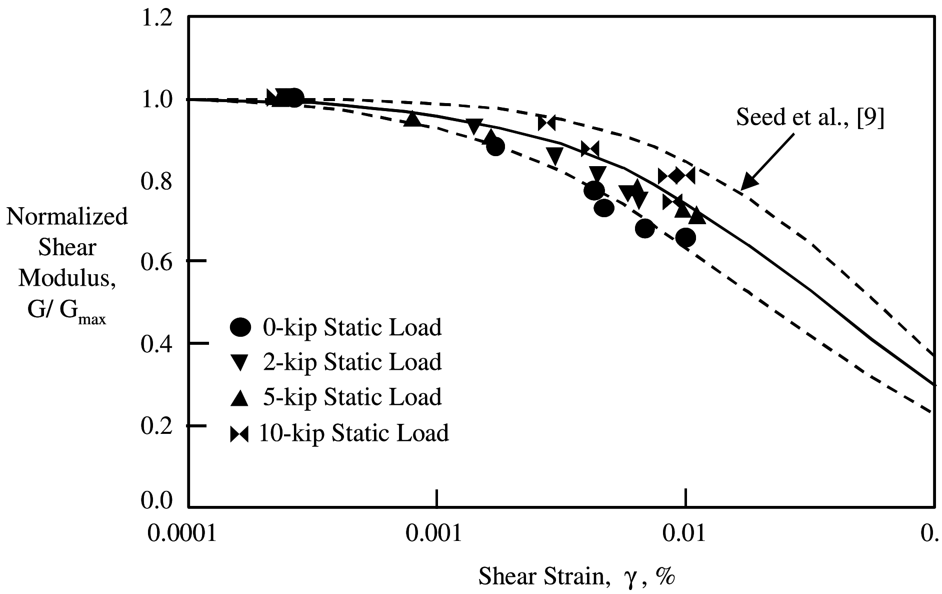
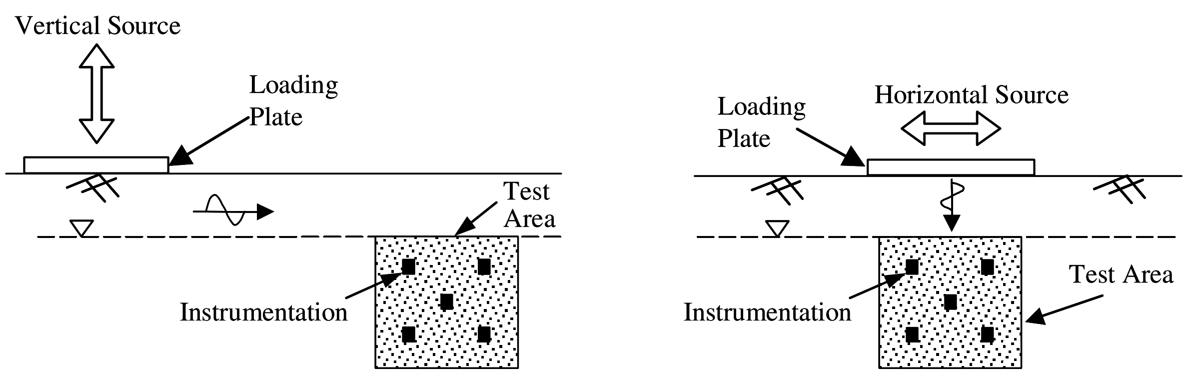


Figure 9 In situ nonlinear measurements of shear modulus determined using the test configuration shown in Figure 8b [3]

or very low, but the uncertainties in the correlations make this method less reliable for marginal cases. Further, this analysis does not directly provide information regarding pore pressure generation characteristics, nor the residual shear strength of the soil. Laboratory experiments cannot be used to evaluate this information for the in situ soil because sampling invariably disturbs the soil and makes the laboratory results inaccurate.

An in situ dynamic liquefaction test is under development at UT [1, 7, 8]. It is designed to measure pore water pressure generation in situ under dynamic loading without having to wait for an earthquake. The dynamic loading is provided by a large, mobile, hydraulic shaker. T-Rex and Liquidator have been developed to act as sources in this type of testing. Two generalized test configurations are illustrated in Figure 10. In Figure 10a, the source is offset from the test area, and mainly Rayleigh waves are used to load the test area. In Figure 10b, the source is located directly over the test area, and shear waves are



a. Source offset from test area and loading with Rayleigh waves

b. Source directly above test area and loading with shear waves

Figure 10 Generalized test configurations for in situ evaluation of liquefaction resistance

used to load the test area. (The embedded source configuration shown in Figure 8c is also a possible configuration.) In either case, the level of shaking is controlled by specifying the vibration levels (number of cycles and amplitudes) to the shaker. The stress waves induce cyclic shear strains which, in turn, generate excess pore water pressure in the test area. One benefit of the test method is that cycling can be performed over a wide range in strains so that the smallest strain at which excess pore water pressure is generated, called the cyclic threshold strain (γ_t^c), can be evaluated.

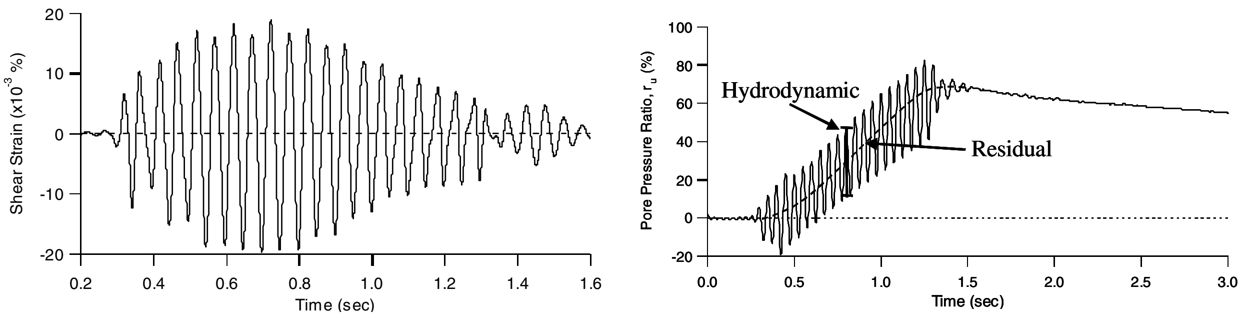
To establish the liquefaction characteristics of the soil, a series of shaking tests is performed in the field, starting from a low loading level. The loading level is gradually increased until significant nonlinearity is measured or the capacity the shaker is reached. In the prototype tests, an older Vibroseis owned by UT was used to statically load a footing on the ground surface and generate Rayleigh (R) waves, as illustrated in Figure 10a. Also in the prototype tests, a reconstituted, saturated sand specimen was constructed in the field, with the top of the specimen essentially at the ground surface. The R waves propagated through the reconstituted test area and induced a controlled number of cycles (20 cycles were used at each load level) of shear strain and shear stress. The embedded instrumentation in these tests consisted of five liquefaction sensors like the one shown in Figure 7.

The shear strains within the reconstituted test specimen were evaluated using particle velocity data recorded by the embedded geophones at multiple points in the test region. Pore water pressure buildup and dissipation were recorded using the miniature pore pressure transducers. Therefore, the coupled behavior between the dynamic response of the soil skeleton, represented by shear strain, and the excess pore water pressure was measured. Also, the pore pressure generation characteristics of the soil, expressed as excess pore pressure ratio versus mean shear strain amplitude for a specific number of loading cycles, were measured in the field. This measurement is analogous to the technique developed by Dobry et al. [10] from cyclic strain-controlled laboratory tests.

The fundamental data and example measurements are shown in Figures 11 and 12 and discussed below.

1. The shear strain-time histories (Figure 11a) were evaluated using the geophone records and a displacement-based method as discussed by Rathje [7]. The geophone data also provide information about the stress waves propagating through the test area during low and high levels of shaking.
2. Excess pore water pressure ratio-time histories (Figure 11b) were obtained. The excess pore pressure ratio (r_u) is defined as $\Delta u/\sigma'_v$, where Δu is the excess pore water pressure and σ_v' is the vertical effective stress. For these tests, the vertical effective stress was estimated as 13 kPa [7]. The r_u-time histories contain both hydrodynamic and residual components. Combined with the shear strain-time histories, the coupled behavior between the induced shear strain and excess pore pressure generation is evaluated.
3. The pore pressure generation curve of the specimen was established by compiling the dynamically induced shear strain level and generated excess pore water pressure ratio with respect to a specific number of loading cycles (Figure 12). The cyclic threshold strain (γ_t^c), the strain at which residual pore pressures are developed, was readily identified from the shapes of the pore pressure generation curves.

The measured excess pore pressure ratio versus shear strain for specific numbers of loading cycles (Figure 12) clearly demonstrates the viability of the field test method. More information can be found in Chang [1] and Rathje [7].



a. Shear strain-time history calculated for one large-strain testing series

b. Excess pore pressure ratio-time history measured during and after the straining shown in Figure 11a

Figure 11 Examples of the calculated strain-time history and the measured pore water response in the center of the test specimen during prototype liquefaction testing [after 1].

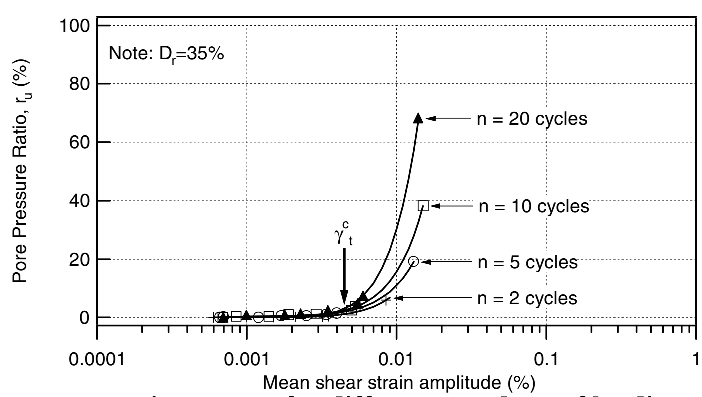


Figure 12 Pore pressure generation curves for different numbers of loading cycles evaluated in the prototype tests (after [1])

CONCLUSIONS

Development of the George E. Brown, Jr. Network for Earthquake Engineering Simulation is nearly completed. The fifteen Equipment Sites that are distributed across the United States will begin functioning on October 1, 2004 for shared use with practitioners, researchers and academicians. It is planned that the network will operate for the next 10 years, with the operations overseen by the NEES Consortium Inc. The nees@UTexas Equipment Site has nearly completed the field trials with the three mobile shakers; T-Rex, Liquidator and Thumper. The instrumentation van and data acquisition systems are operational. Work is continuing to complete the satellite link-up so that telepresence capabilities will be available during the field experiments.

Two examples of large-scale field testing with an older mobile field shaker that is owned by UT show some potential experiments that can be conducted by future investigators with the nees@UTexas equipment. This NEES large-scale field equipment represents a significant advance over current field capabilities and offers geotechnical earthquake engineers opportunities for direct field testing that have previously been possible only in the laboratory.

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