

Experience with nees@UTexas large-scale mobile shakers in earthquake engineering studies

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ABSTRACT: The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) is a US-wide program that is supported by the National Science Foundation. NEES is composed of a network of fifteen testing facilities, called Equipment Sites, that spread across the United States. The Equipment Site specializing in mobile, geotechnical, field equipment was developed at the University of Texas at Austin named nees@UTexas. Operational since October 2004, nees@UTexas is a 50% shared-use facility. In the past three years, nees@UTexas has conducted nine shared-used projects and numerous non-shared-use projects. Experience with the shakers is discussed for: (1) deep shear wave velocity profiling in the Mississippi Embayment, (2) in-situ nonlinear shear modulus measurements of soil, (3) field dynamic tests of 1/4-scale bridge bents founded on drilled shafts, and (4) in-situ liquefaction tests in Imperial Valley, CA. Test arrangements and representative results from these projects are also discussed.

1 INTRODUCTION

The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) is a US-wide program that is supported by the U.S. National Science Foundation. NEES is composed of a network of: (1) fifteen advanced testing facilities, called Equipment Sites, (2) an Information Technology infrastructure being developed by NEESit, and (3) a community-based non-profit organization name NEESinc. The 15 equipment sites are link together through the Information Technology infrastructure at NEESit. In addition, NEESit is in the process of providing collaborative tools, a centralized data repository (NEEScentral), and earthquake simulation software. NEES Consortium, Inc. (NEESinc) manages NEES as a national, shared-use research facility for the earthquake engineering community.

nees@UTexas is one of the fifteen Equipment Sites. It specializes in mobile, geotechnical, field equipment. In October, 2004, nees@UTexas began operation as a 50% shared-use facility. In the past three years, nees@UTexas has conducted a total of nine shared-use projects and numerous non-shared-used projects. Each of these studies would have been very difficult to perform before nees@UTexas was developed. Shared-use projects are research projects either funded by the National Science Foundation through the NEES program or funded by US public agencies that obtain a shared-use status from NEESinc. Shared-use projects are charged a reduced

rate for using the nees@UTexas equipment and are not charged for staff salary. However, shared-use projects are required to share all measured data and results with the public. Data collected in a shared-use project is required to be input into the NEEScentral data repository one year after completion of the project.

The shared-use equipment available at nees@UTexas and four example shared-used projects that utilized the nees@UTexas equipment site are discussed in this article. More information about the nees@UTexas equipment site and other NEESR projects can be found at <http://nees.utexas.edu/> and <https://central.nees.org/>.

2 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) an instrumentation trailer that provides additional work and storage space in the field, (4) a fuel-supply truck for refueling and field maintenance of the mobile shakers, (5) a collection of field instrumentation that measure vibrational motion and pore water pressure, and (6) telepresence capabilities that allow for remote participation in field experiments.

The three mobile shakers 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. All three shakers use vegetable-based hydraulic oil which will not raise environmental concerns if a leak occurs in the field.

T-Rex 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 1a. The shaking system is housed on an off-road, all-wheel-drive vehicle. The theoretical performance of T-Rex in both the vertical and horizontal modes is shown in Figure 2. 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 and decrease below 5 Hz.

Liquidator is designed to be a lower frequency vibrator and is a one-of-a-kind shaker. A photograph of Liquidator is shown in Figure 1b. The shaking system is specially designed to give a higher force output in the low-frequency range of 0.5 to 4.0 Hz. This makes Liquidator an excellent vibrational source for deep surface wave testing. The theoretical performance of Liquidator in both the vertical and horizontal modes is shown in Figure 2. As shown in the figure, the force output in both modes is about 89 kN and decreases with frequency below 1.3 Hz.

Thumper is a smaller shaker mounted on a standard Ford 650 truck. A photograph of Thumper is shown in Figure 1c. Thumper is ideal for geophysical testing in urban areas because it is highway-legal and has a moderate force output. The theoretical performance of Thumper is shown in Figure 2. As shown in the figure, the maximum force output is about 27 kN over the frequency range of 17 to 225 Hz.

T-Rex and Liquidator must be transported to and from field sites on a tractor-trailer rig. The tractor-trailer rig is part of the nees@UTexas vehicle fleet. It is important to note that the combined weights of one of the large shakers and the tractor-trailer rig are between 48,000 and 51,000 kg. Therefore, the complete system is overweight when moving on the highways and thus requires overweight permits to transport. More information about the shakers can be found in Stokoe et al. 2004.

The instrumentation van is a customized Chevrolet cargo van that includes a diesel generator, an air-conditioned workspace, and a fully-integrated computational network. The fuel-supply truck can carry diesel fuel for T-Rex and Liquidator in the field. It is also designed to carry spare parts and tools for maintenance. The instrumentation trailer is a 2.4 m by 4.8 m cargo trailer. It can be towed by either the instrumentation van or the fuel-supply truck. The interior of the trailer is divided into two parts. The front part of the trailer is air conditioned and is used



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



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



c. Urban, three-axis shaker called Thumper

Figure 1 Photographs of nees@UTexas shakers

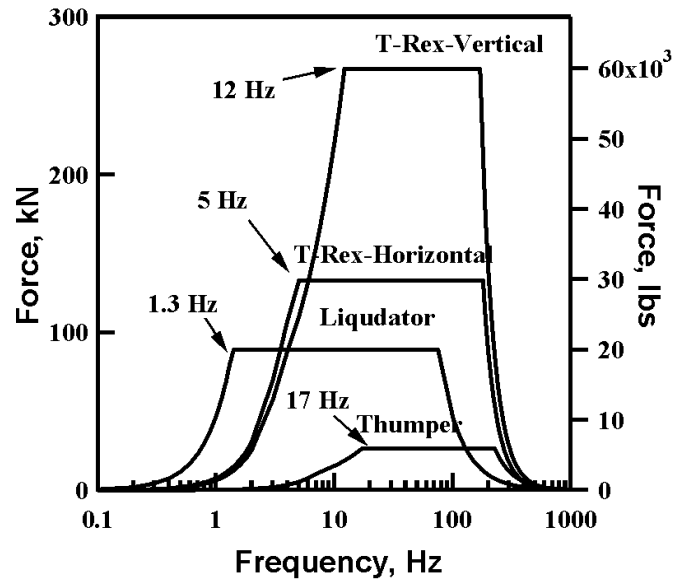


Figure 2 Theoretical force outputs of the three mobile shakers at nees@UTexas (modified from Stokoe et al., 2004)

as work space. The rear part of the trailer is used to carry tools and equipment to the field.

There are three main data acquisition systems at nees@UTexas site. These systems are: (1) a VXI system, (2) Data Physics system, and (3) a Sercel 408XL system. The VXI system includes 64 channels of acquisition at a sampling rate of 50 kS/s and 8 channels of acquisition at a sampling rate of 196 kS/s. The Data Physics system includes 32 channels

of acquisition at a sampling rate of 200 kS/s. The Sercel 408XL is designed for the seismic testing and oil exploration industries. It is capable of connection to receivers via digital telemetry cables or via wireless radio links. It can process up to 2000 channels of data. However, only 40 channels are presently available. All three systems can be used in either the instrumentation van or the instrumentation trailer.

The field instrumentation available at nees@UTexas includes 1-Hz and 10-Hz geophones, prototype in-situ liquefaction sensors, and Cone Penetrometer Test (CPT) equipment. The prototype liquefaction sensors were designed and constructed at the University of Texas (Cox 2006). A picture of one liquefaction sensor is shown in Figure 3. The main body of the sensor is a cylindrical, acrylic case with a conical tip. The sensor is compact, measuring 12.7 cm from tip-to-top and 3.8 cm in diameter. Each sensor has a total unit weight of approximately 1.44 g/cm³. It houses a miniature pore water pressure transducer (PPT) and a 3-component, Micro-Electrical Mechanical Systems (MEMS) accelerometer. During tests, the liquefaction sensors are installed at multiple points in the ground to monitor ground motion and pore pressure generation at each point.

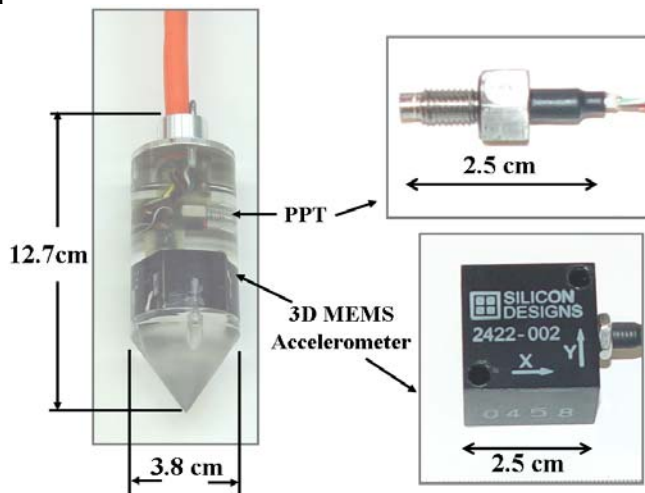


Figure 3 Picture of an in-situ liquefaction sensor (modified Cox, 2006)

3 EXAMPLE STUDIES USING THE NEES@UTEXAS EQUIPMENT

A total of nine share-use projects have been conducted with nees@UTexas equipment in the past three years. These projects cover a wide spectrum of research topics. Researchers include both geophysical scientists and structural and geotechnical engineers. Because of the space limitation, only four projects are briefly discussed.

3.1 Deep Shear Wave Velocity Profiling in the Mississippi Embayment

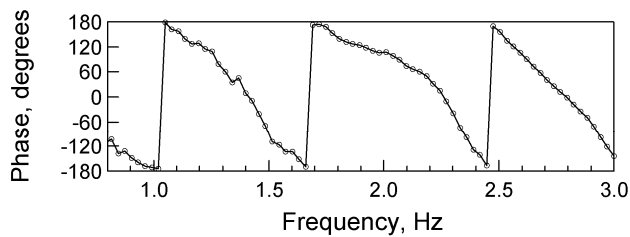
In this study, Liquidator was used as an active source for surface wave velocity measurements in the Mississippi Embayment region of the central United States (Rosenblad et al. 2007). The region is located on the seismically active New Madrid Seismic Zone (NMSZ) and is vulnerable to large amplifications from earthquake motions. One of the critical input parameters needed for site response analysis is the small-strain shear wave velocity (V_s) profile. Soil deposits in this region are hundreds of meters thick, but are poorly characterized at depths below 60 m. The objectives of the study were (1) to study different surface wave measurement techniques and (2) to develop shear wave velocity profiles to depths of 200 to 300 m.

Measurements were performed at five locations in the states of Tennessee and Arkansas. The deep V_s profiles presented in Rosenblad et al, 2007 were determined using the Spectral-Analysis-of-Surface-Waves (SASW) method. The SASW method is a non-intrusive seismic method where the dispersive characteristics of Rayleigh-type surface waves propagating through a layered material are measured and then used to determine the V_s profile.

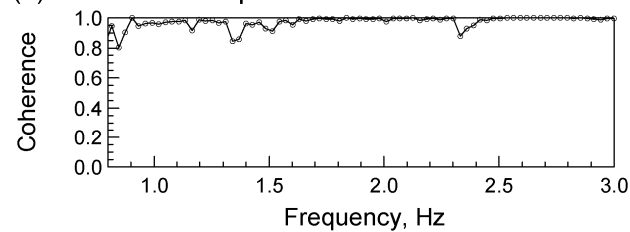
Liquidator was used to excite the requisite low-frequency surface wave energy (down to 0.7 Hz) for deep V_s profiling. A 300-m long array of 16, 1-Hz vertical geophones from the nees@UTexas site were used to measure the surface wave motions generated by the source. Wavelengths of 600 m were successfully measured in this study.

The stepped sine function available from the VXI analyzer was used to externally drive Liquidator from 20 Hz down to 0.7 Hz. The analyzer was also used to record the output from the geophones. The integration time and number of averages taken at each frequency were adjusted based on the quality of the measurement as indicated by the coherence value (indicative of signal-to-noise ratio). Figures 4a and 4b show an example of the wrapped phase and coherence values, respectively, measured between receivers located at 300 m and 600 m (the longest spacing) from the source at one site. In this case, the source was stepped through 50 frequency points from 3 Hz down to 0.8 Hz over a period of about 45 minutes. As shown in the figure, even at frequencies below 1 Hz, the coherence values are higher than 0.8.

The V_s profiles that were determined for the sites are presented in Rosenblad et al. (2007). The median profile and variability generated from the five sites is in general agreement with the reference profile that has been developed for the Mississippi Embayment (Romero & Rix 2001). Disparities between the V_s profiles at some sites were shown to be associated with differences in soil lithology.



(a) Cross Power Spectrum Phase



(b) Coherence

Figure 4 (a) Wrapped phase plot from the cross-power spectrum and (b) coherence function measured with receivers located 300 m and 600 m from the source at one site.

3.2 In-Situ Nonlinear Shear Modulus Measurements in Soil

Generally, the nonlinear behavior of soil is characterized by a reduction in the shear modulus (G) and an increase in the material damping ratio with increasing shearing strain (γ). Evaluation of the nonlinear shear modulus of soil for use in geotechnical engineering often involves field and laboratory tests. In current practice, the shear modulus reduction curve is determined in the laboratory and then combined (scaled) with the in-situ, small-strain shear modulus obtained from field seismic tests. However, with the large nees@UTexas shakers, it is possible to determine shear modulus reduction curves in the field.

Figure 5 illustrates testing arrangements to measure nonlinear compression and shear wave propagation in situ with a footing. An array of three-dimensional (3-D) sensors is embedded below the ground surface. The 3-D sensors are placed in hand-augered boreholes and backfilled with recovered soil. Each sensor consists of three geophones with a natural frequency of 14 Hz. The geophones are glued in acrylic cases using epoxy. Each sensor has the approximate unit weight of the soil. After the sensor array is installed, a concrete footing is constructed. The footing is circular and has a diameter of 0.90 m and thickness of 0.30 m. The footing is reinforced with 1.3-cm diameter rebar. Before pouring the concrete, 3-D geophones are attached to the lower rebar which are close to bottom of the footing. These geophones are used to monitor the motion of the footing.

In the nonlinear tests, the dynamic loads are applied with either Thumper or T-Rex. The shakers apply dynamic loads over a wide range, from loads that create only small strains (less than 0.001%) to loads that create significant nonlinear responses (at

strains above 0.05%). A load cell is placed between the loading plate and the footing to measure both static and dynamic loads.

An example of the results from an in-situ nonlinear dynamic test is illustrated in Figure 6. In this example, the surface footing was staged loaded to evaluate the $G - \log \gamma$ relationship of a poorly graded sand and silty sand (SP-SM) that was lightly cemented. Measurements of G in the linear range and in the nonlinear range were clearly conducted.

An intact sample of this soil was also tested in the laboratory using a combined resonant column and torsional shear (RCTS) device. The laboratory $G - \log \gamma$ relationship is included in Figure 6. Good agreement exists between the field and laboratory values of G .

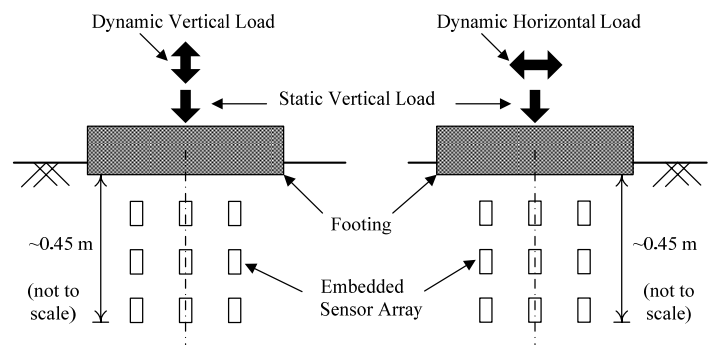


Figure 5 Generalized testing arrangements to measure nonlinear compression and shear wave propagation in situ with a footing (from Stokoe et al. 2006)

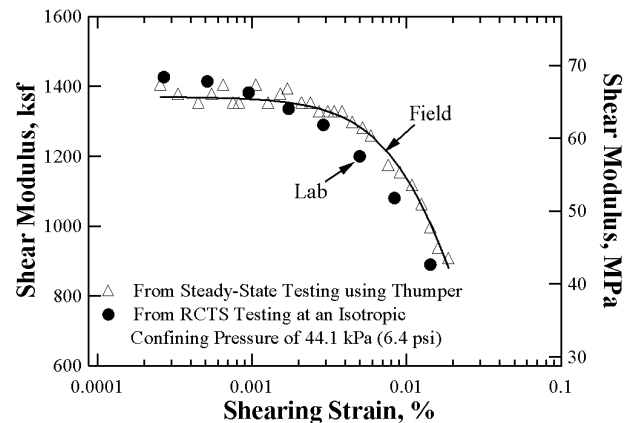


Figure 6 Field measurement of the nonlinear shear modulus of a lightly cemented sand using a horizontally excited surface footing (from Stokoe et al. 2006)

3.3 Field Dynamic Tests of 1/4-Scale Bridge Bents Founded on Drilled Shafts

This study is part of a collaborative research project to study soil-foundation-structure interaction (Wood et al. 2004, Agarwal et al. 2006). The prototype structure that was modeled in this investigation is a continuous, reinforced concrete bridge with drilled shaft foundations. This type of structure is common throughout the US. Although the seismic response of the ductile reinforced concrete structural elements is well understood, the extent to which nonlinear be-

behavior of the soil and/or foundation influence the performance of the complete system is not well understood. Due to the size and complexity of the prototype system, it was not possible to test a single physical model and reproduce all key aspects of the system. Four complementary experimental programs, which involved three NEES equipment sites and four non-NEES universities, were developed to investigate the response of critical components.

nees@UTexas was responsible for testing two, 1/4-scale, isolated bridge bents on drilled shaft foundations constructed at a field site in Austin, TX. nees@UTexas mobile field shakers have the advantage of studying soil-foundation-structure interaction of the bridge bents in the field at actual settings. The specimens were tested dynamically using three types of loading. Initially, the specimens were struck with a modal hammer to generate the free vibration response in the linear range. In the second series of tests, T-Rex was used to induce sinusoidal motion in the test specimens by exciting the ground surface in the vertical and two horizontal directions. For the third series of tests, the linear shaker from Thumper was mounted at midspan of the beam (Fig. 7) and used to excite the bent horizontally initially in the linear range and then in the nonlinear range.

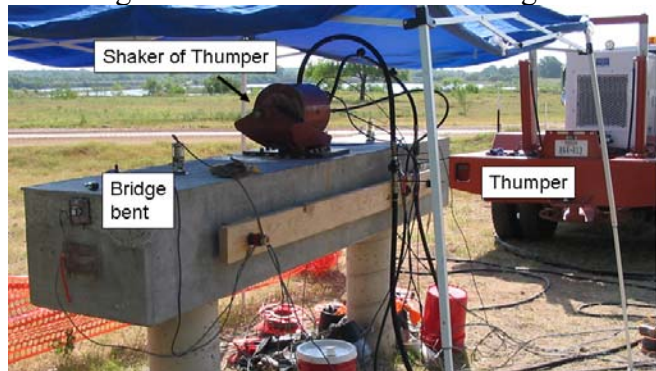


Figure 7 Harmonic excitation of Bent 2 using shaker from Thumper

When tests were conducted using higher force levels with Thumper, inelastic response was observed. The structure would appear to have achieved resonance at a given excitation frequency. After a number of cycles with increasing response amplitude, the amplitude of the vibrations would decrease suddenly. The amplitude of the response would then increase when the specimen was excited at the next frequency, only to drop again. This pattern was repeated several times during the stepped sine loading histories at the higher force levels. No cracking of the concrete was observed after the test. The decreasing of the natural frequency resulted from gaps that opened between the edges of the drilled shafts and the surrounding soil during these tests.

At the end of dynamic loading, the wenches mounted in front of both T-Rex and Liquidator were used to cyclically load the bridge bents to failure.

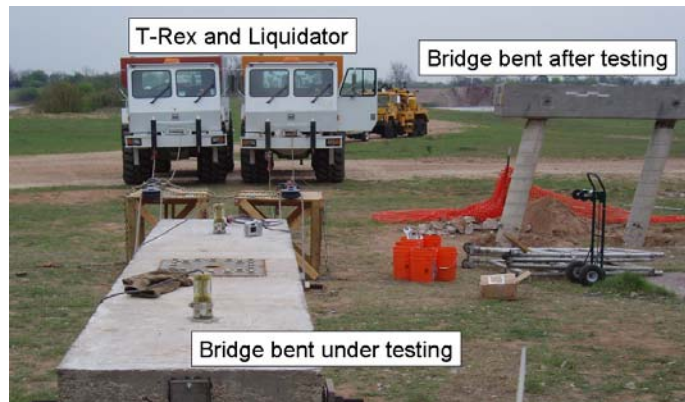


Figure 8 Cyclically load test with T-Rex and Liquidator

Figure 8 shows one of the bridge bents that was cyclically loaded with both T-Rex and Liquidator. The other bridge bent after cyclically test is also shown in the figure.

3.4 *In-Situ Liquefaction Tests in Imperial Valley, CA*

This project was directed towards the development and implementation of a new in-situ liquefaction test that can be used to evaluate the coupled response between excess pore water pressure generation and nonlinear shear modulus behavior. The test involves dynamically loading a native soil deposit in a manner similar to an earthquake while simultaneously measuring its response with push-in sensors. During testing, T-Rex is used to generate vertically propagating (downward), horizontally polarized shear waves (S_{vh} waves) of varying amplitudes that propagate through an instrumented portion of a liquefiable soil mass (Fig. 9). Newly-developed, push-in liquefaction sensors (Fig. 3) are installed from the ground surface in a two-dimensional (2D), trapezoidal array within the liquefiable soil layer and are retrievable upon completion of testing.

The validity of the in-situ liquefaction testing equipment, field technique and data analysis procedures have been demonstrated by conducting field experiments at the Wildlife Liquefaction Array (WLA) in Imperial Valley, California. WLA has been intensely studied over the past 25 years and is one of the most researched soil liquefaction sites in the world. It has also recently been designated as a NEES site for the study of soil liquefaction (<http://nees.ucsb.edu>).

In-situ tests were conducted in a liquefiable soil deposit approximately 3 to 4 m below the ground surface. The tests were successful at measuring: (1) excess pore water pressure generation, and (2) nonlinear shear modulus behavior in the native silty-sand deposit as a function of induced cyclic shear strain and number of loading cycles. An example of the in-situ pore pressure generation curves obtained

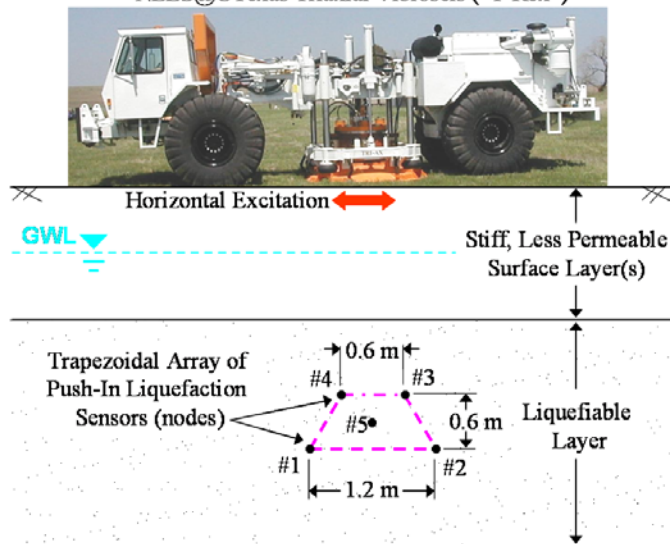


Figure 9 Test arrangement of in-situ liquefaction test.

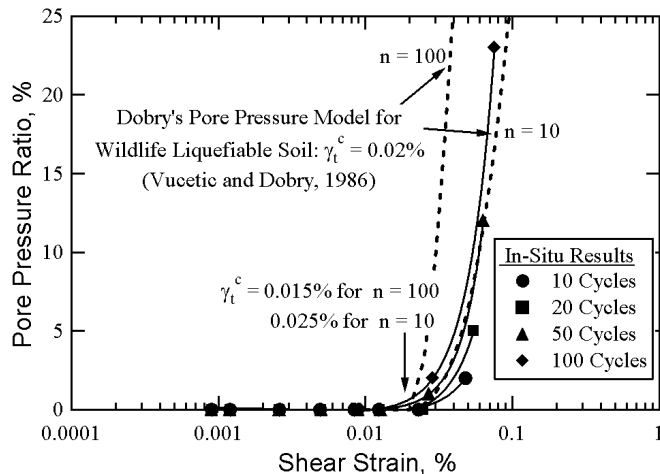


Figure 10 Pore pressure generation curves obtained from in-situ liquefaction tests at the Wildlife Liquefaction Array.

at WLA is shown in Figure 10. The in-situ pore pressure generation curves compare favorably with laboratory tests (Vucetic & Dobry 1986). Excess pore water pressure in the soil was not generated until shear strains greater than the cyclic threshold shear strain had been induced. Further results and comparisons may be found in Cox (2006).

4 CONCLUSIONS

The mobile shakers and associated equipment acquired by the nees@UTexas equipment sites are unique and tailored to earthquake engineering related research. The shared-use policy makes the equipment available for researchers in the US, and utilizes the equipment site to its full potential. More studies can be expected from future shared-use projects.

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