Performance of Mobile Hydraulic Shakers at nees@UTexas for Earthquake Studies

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ABSTRACT :

The U.S. National Science Foundation is supporting a nation-wide earthquake engineering program that is named the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). NEES is composed of a network of fifteen testing facilities, called Equipment Sites, which are distributed across the United States. The Equipment Site developed at the University of Texas at Austin is named nees@UTexas. There are three mobile shakers with diverse shaking capabilities at nees@UTexas. These three shakers are named T-Rex, Liquidator, and Thumper. T-Rex is capable of generating large dynamic forces in any of three directions (X, Y, or Z directions). Liquidator is designed to be a lower frequency vibrator and is a one-of-a-kind shaker. Thumper is ideal for geophysical testing in urban areas because it is highway-legal and has a moderate force output. Operational since October 2004, nees@UTexas is a 50% shared-use facility. In the past four years, mobile shakers at nees@UTexas have been used in research projects in the areas of: (1) deep shear-wave velocity profiling, (2) in-situ nonlinear shear modulus measurements of soil, (3) in-situ liquefaction tests, (4) soil-foundation-structure interaction studies, and (5) geophysical studies. In this paper, equipment of nees@UTexas is introduced, a comparison between the theoretical force output and measured force output is presented, and examples of previous NEES projects are discussed.

KEYWORDS: NEES Field Testing, Mobile Shakers, Seismic-Wave Velocities, Nonlinear Modulus Testing, Liquefaction

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 (NSF). NEES is composed of a network of 15 advanced testing facilities called Equipment Sites. nees@UTexas is one of the 15 Equipment Sites. nees@UTexas specializes in mobile, geotechnical, field equipment. The 15 equipment sites are linked together through the Information Technology infrastructure at NEESit. NEESit also provides collaborative tools, a centralized data repository (NEEScental), and earthquake simulation software. The 15 equipment sites and the NEESit are managed by a nonprofit organization, NEES Consortium, Inc. (NEESinc). One of the key features of NEES is the practice of shared-use. Equipment, computational tools, and data collected from research projects are available to the research community world-wide through the shared-use policy. Starting in October, 2004, nees@UTexas has been operated as a 50% shared-use facility. In the past four years, nees@UTexas has participated in 18 shared-use projects and numerous non-shared-used projects. To date, shared-use projects have been either projects funded by NSF through the NEESR program or projects funded by U.S. public agencies that obtain a shared-use status from NEESinc. However, other U.S. or international projects are possible. Non-shared-use projects are typically conducted by researchers at the University of Texas at Austin (UT), while shared-use projects are generally conducted by researchers from other universities, sometime in cooperation with UT researchers.

For potential users, two commonly asked questions are: (1) what are the force-frequency output characteristics of the shakers, and (2) how have the mobile shakers been used in past studies? In this paper, equipment at nees@UTexas is introduced. A comparison between the theoretical force output and actual force output of one shaker (named Thumper) is then discussed. Examples from previous projects are shown at the end of the paper. More information about the nees@UTexas equipment site and the NEES program can be found at http://nees.utexas.edu/ and http://www.nees.org/.

2. OVERVIEW of NEES@UTEXAS

The function of nees@UTexas is dynamic field testing of geotechnical and structural systems with large-scale mobile shakers. The equipment of nees@UTexas includes: (1) three mobile shakers, (2) a tractor-trailer rig to move the two largest off-road shakers, (3) an instrumentation van with an attachable trailer for housing state-of-the-art data acquisition systems, (4) a fuel-supply truck for refueling and field maintenance of the mobile shakers, and (5) a collection of field instrumentation. The three mobile shakers are named: T-Rex, Liquidator, and Thumper. Each mobile shaker has a diverse force and frequency capability. The vibrational force can be controlled either internally with the on-board controller or externally with an analog signal. All three shakers were designed and built by Industrial Vehicles International, Inc., in Tulsa, Oklahoma. Environmentally friendly vegetable-based hydraulic oil is used in all three shakers to limit any environmental impact if a leak occurs in the field.

T-Rex is capable of generating large dynamic forces in any of three directions (vertical, horizontal in-line, and horizontal cross-line). To change from one shaking direction to another only requires the push of a button in the driver’s cab. 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 force outputs of T-Rex in both the vertical and horizontal directions are shown in Figure 2. As shown in Figure 2, the maximum force output is about 267 kN in the vertical mode and about 133 kN in each horizontal mode. Liquidator is a one-of-the-kind shaker that is designed for lower

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

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

c. Urban, three-axis shaker called Thumper

d. Tractor-trailer with T-Rex

e. Instrumentation van and trailer

f. Maintenance and fuel-supply truck

Figure 1 Photographs of the three shakers, tractor-trailer rig, and other equipment of the nees@UTexas equipment site frequency operation. A photograph of Liquidator is shown in Figure 1b. In the past, Liquidator has only been operated in the vertical mode. However, it can be changed into the horizontal (shear) mode at the manufacturer in about two working days. The theoretical force output of Liquidator is also shown in Figure 2. The maximum force output is about 89 kN down to the frequency of 1.3 Hz. Like T-Rex, Liquidator is also mounted on an off-road vehicle. Both T-Rex and Liquidator must be transported to and from test sites on the tractor-trailer rig shown in Figure 1d. Lifting points were installed on both T-Rex and Liquidator for easy loading on a cargo ship. Thumper is the smallest shaker and is built on a Ford model F-650 truck. Thumper has a moderate force output which makes it ideal for testing in urban areas. Because Thumper is on a truck, it can be driven on the highway and can be readily (and economically) shipped overseas. A photograph of Thumper is shown in Figure 1c, and its theoretical performance is shown in Figure 2. The maximum force output of Thumper is about 27 kN over the frequency range of 17 to 225 Hz.

The instrumentation van is a customized Chevrolet cargo van that provides an air-conditioned workspace. A 2.4 m by 4.8 m cargo trailer is also available for field use. The trailer can be attached to the instrumentation van to provide additional working and storage space as shown in Figure 1e. The fuel-supply truck carries diesel fuel for T-Rex and Liquidator in the field (Figure 1f). It is also designed to carry spare parts and provide a working platform for maintenance. Field instrumentation at nees@UTexas includes: (1) three main data acquisition systems, (2) 52, 1-Hz vertical geophones, (3) 12, 1-Hz 3-D geophones, (4) 12, 10-Hz 3-D geophones, (5) prototype in-situ liquefaction sensors, and (6) cone penetrometer test (CPT) equipment. The three data acquisition systems are: (1) a VXI system – 72 channels, (2) a Dataphysics system – 32 channels, and (3) a Sercel 408XL system – 36 channels. The prototype liquefaction sensors were designed and constructed at UT (Cox et al., 2008). The main body of each sensor is a cylindrical, acrylic case with a conical tip. Housed in the acrylic case are a miniature pore water pressure transducer and a 3-component, micro-electrical mechanical systems accelerometer. The CPT equipment was manufactured by Fugro, Inc. There are four electrical cones at nees@UTexas with three different base areas of 5 cm^2, 10 cm^2, and 15 cm^2.

3. FORCE OUTPUT MEASUREMENT

Theoretical force outputs of the three shakers described in the previous section were provided by the manufacturer based on its design parameters. However, actual force outputs are also a function of the ground conditions at the test location and the control system. In theory, force output is governed by four physical limits. These four limits are: (1) stroke, (2) flow, (3) force, and (4) valve limits (Bay, 1997). The output of Thumper is calculated to have the highest peak force of 26.7 kN between 17 and 225 Hz which is controlled by the force limit. The design force limit is determined by multiplying the system pressure by the piston area. As frequency decreases below 17 Hz but above 7.3 Hz, the force output is controlled by the flow limit of the servo valve (101 l/m). When the frequency is below 7.3 Hz, the maximum force output is limited by the maximum stroke of the reaction mass (±3.8 cm). On the other hand, as shaking increases above 225 Hz, the mechanical switch in the servo-valve requires a higher current to overcome the inertia. The force output is limited by the amount of movement of the mechanical switch at frequencies above 225 Hz, with the force output decreasing as frequency increases.

Two different methods can be used to measure the actual force outputs of the mobile shakers. The first method uses a load cell to measure the force output directly. The second method uses accelerometers mounted on the reaction mass and base plate of the shaker from which the force output can be calculated. Figure 3 shows a photograph of the shaker of Thumper at the rear of the truck. As shown in the figure, airbags are used to isolate the shaker from the truck. The air bags act as a low pass filter, and transfer only static force. If one takes a free body of the Thumper shaker and ignores the hydraulic system, the only external dynamic force is the dynamic ground force which is also the dynamic force output of Thumper. The dynamic force output, F_d, can be determined as (Wei, 2008):

$$F_d = m_{RM} * a_{RM} + m_{BP} * a_{BP} \tag{3.1}$$

where: m_{RM} is the mass of the reaction mass, a_{RM} is the reaction-mass acceleration, m_{BP} is the mass of the base

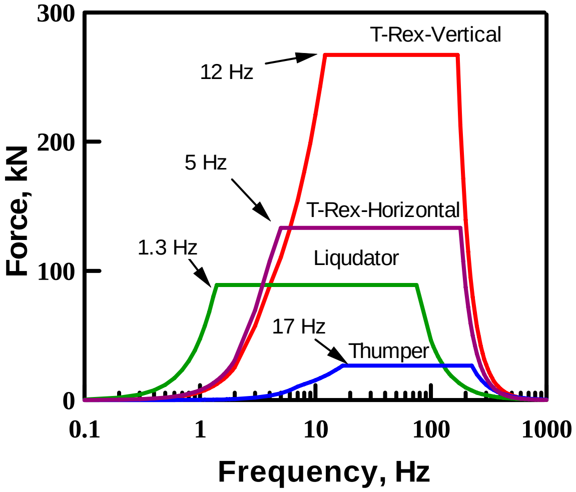


Figure 2 Theoretical force outputs of the three mobile shakers (Stokoe et al., 2008)

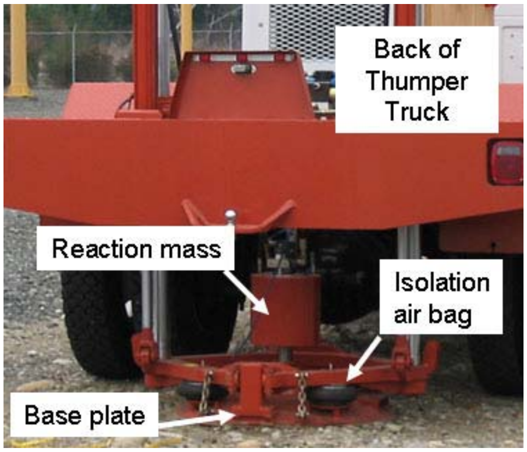


Figure 3 A photograph of Thumper ready to shake the ground

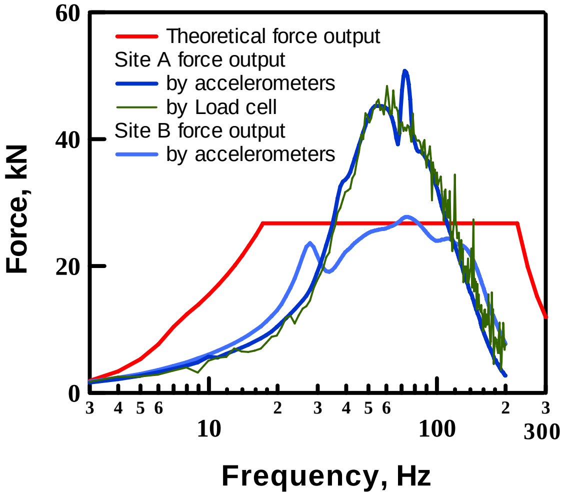


Figure 4 Theoretical and measured force outputs of Thumper at two sites

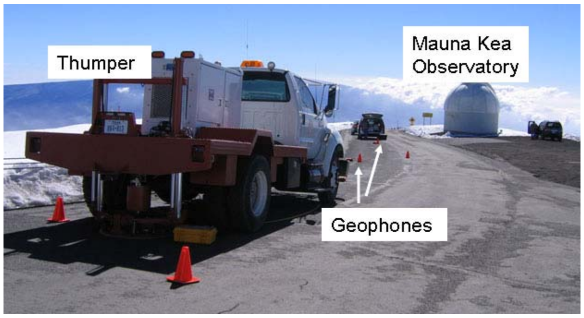
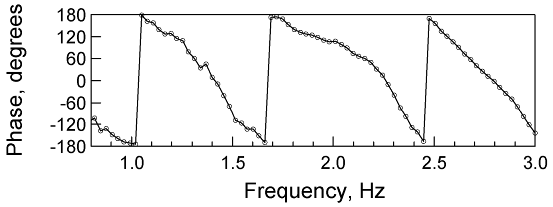
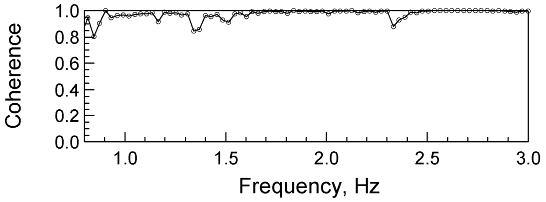


Figure 5 SASW test at Mauna Kea Observatories, Hilo, Hawaii



(a) Cross Power Spectrum Phase



(b) Coherence

Figure 6 (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 (Rosenblad et al., 2008)

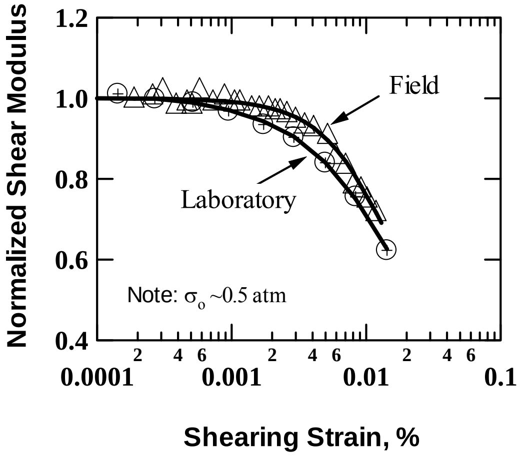


Figure 7 Field and laboratory measurement of the nonlinear shear modulus of a lightly cemented soil (Park, 2008)

plate, and a_{BP} is the base-plate acceleration. Although, using a load cell is a direct measurement, it requires a stiff ground to support the load cell. For many operations, the stiffness of test site close to the surface varies from soft soil to moderately stiff soil so that it is not possible to have a stiff foundation at the shaking points.

Two locations (Site A and Site B) on the campus of UT were selected to measure the force output of Thumper. Both locations have about 1 meter thick of soft soil on top of a thick limestone layer. The only difference is that there is a layer of asphalt pavement at the first test location (Site A). An external stepped sine function from an analyzer (Dataphysics Corp. SignalCalc Mobilyzer) was used to drive the Thumper shaker from 200 Hz down to 3Hz in 200 linear steps. In the external-drive mode, the Thumper force output is controlled by an external analog drive signal. The drive signal can vary between 0 and 10 volts, and is used to control the current that moves the pilot stage servo-valve. The force output of Thumper is proportional to the amplitude of the analog drive signal, with 10 volts representing the maximum force output.

The force outputs of Thumper determined at both Sites A and B are shown in Figure 4. Accelerometer and load-cell measurements were both used in determining the actual ground force at Site A. Because Site B is a soft ground, only the ground force calculated from the accelerometers is available. As shown in the figure, force output measured from a load cell is noisier than that calculated from the accelerometers. In general, the force output calculated from the accelerometers follows closely with that measured from a load cell. However, upon closer examination, one finds that the ground force determined from the accelerometers is about 20% higher around 80 Hz. The difference at 80 Hz is caused by the rocking resonant mode of the shaker. Because accelerometers are not mounted right at the center of the reaction mass and base plate, rocking motion increases the accelerometer outputs. Overall, the force output calculated from the accelerometers is close to that measured from the load cell, and can be used for most applications.

By comparing force outputs between Sites A and B, it is easy to find that force output at Site A is much higher than that at Site B between 30 and 120 Hz. This difference is a result of ground resonance at Site A which causes the force output at Site A to be higher than that of the theoretical force output limits discussed earlier. It should be noted that the drive signal at Site A was limited to 9 volts, because the peak dynamic force is near the static hold down force of 53 kN. On the other hand, the drive signal is set at 10 volts at Site B to achieve the maximum force output. Because the drive signal was higher at Site B, the force output at Site B is higher than Site A outside the resonance region at frequencies below 30 Hz and above 120 Hz. If the drive signal were increased, the actual force output would approach the theoretical force output. However, the external drive signal is limited to 10 volts by the manufacturer to reduce the possibility of decoupling between the shaker and ground.

4. EXAMPLE STUDIES

Over the past four years, 18 completed or on-going shared-use projects have employed the nees@UTexas equipment. These projects cover a wide spectrum of research topics. Researchers include both geophysical scientists and structural and geotechnical engineers. Based on the characteristics of the projects, these 18 share-use projects can be separated into five groups as: (1) Spectral-Analysis-of-Surface-Waves (SASW) measurements used for deep shear-wave-velocity profiling, (2) in-situ measurements of nonlinear shear moduli of soil, (3) in-situ liquefaction tests, (4) soil-foundation-structure interaction studies, and (5) geophysical studies. Example projects from each group are discussed in the following sections.

4.1 Spectral-Analysis-of-Surface-Waves (SASW) Measurements

Five of the 18 shared-use projects are in this group. All three shakers are effective sources for SASW measurements. However, because Liquidator has the best performance at low frequencies, it is often chosen for deep shear-wave-velocity measurements in rural areas. In these tests "deep" generally refers to depths ≥ 250m. On the other hand, Thumper is often used as the dynamic source in urban areas. The other advantage of using Thumper is that, because of its small size, it can be economically moved to the site. As an example, Thumper was shipped to Hilo, Hawaii in January 2008 for a shared-use project (Title: SASW measurements at the USGS

Hawaiian strong motion network, Principal Investigator (PI): Ivan Wang at URS Corp., funded by the U.S. Federal Emergency Management Agency). Figure 5 shows a picture of Thumper in a SASW test setup at the Mauna Kea Observatories. The maximum depth for shear-wave-velocity measurements using Thumper range from about 50 to 100 m, depending upon the stiffness profile.

When Liquidator is used, shear-wave-velocity measurements can be extended to about 250 to 400 m deep. A SASW test conducted near Tiptonville, TN in the Mississippi Embayment for a NEESR project (Title: Study of surface wave methods for deep shear-wave velocity profiling applied to the deep sediments of the Mississippi Embayment, PI: Brent Rosenblad at University of Missouri-Columbia, 2006, funded by the NEESR program) is a good example of this type of measurement. In this project, a stepped-sine excitation was used to drive Liquidator in the frequency range of 20 Hz down to 0.8 Hz. Ground vibrations were recorded using Mark Products L-4 geophones. Figure 6a shows an example of an unwrapped phase plot developed from the stepped sine excitation using receivers located 300 m and 600 m from the source. In this case, Liquidator was stepped through 75 frequencies from 3 Hz down to 0.8 Hz. At each frequency, Liquidator vibrated for about 50 cycles for short-receiver spacings to about 200 cycles for the lowest frequency measurements recorded at the furthest distances. Figure 6b shows the coherence function recorded between the two receivers spaced 300 m apart. As can be observed from this figure, high coherence levels, indicative of high signal-to-noise ratios, were recorded over the full frequency range. This phase plot was unwrapped and used to calculate surface wave velocities for wavelengths up to 600 m long. Given the high coherence values at frequencies below 1 Hz, it is likely longer wavelengths may have been measured with slightly longer receiver spacings. The results from this study showed Liquidator to be a very effective source for exciting low-frequency surface wave energy (Rosenblad et al, 2008).

4.2 In-Situ Measurements of Nonlinear Shear Moduli of Soil

There are two projects in the second group. Both projects used nees@UTexas mobile shakers to create nonlinearities in the zone of soil near the shaker. The main difference between these two projects is the arrangement of the sensor array. In the first project, a 0.95-m concrete foundation was used as the loading platform over which T-Rex was placed. Buried sensors in the soil underneath the footing were used to measure nonlinear shear wave motion propagating in the soil (Park, 2008). The other project arranged sensors on the ground surface around the loading plate (Pearce et al, 2007, Lawrence et al, 2008).

As an example, Figure 7 shows the nonlinear shear modulus measured in the field in the first project (Title: in-situ determination of soil modulus and damping as a function of level of strain, PI: Giovanna Biscontin at Texas A&M University, 2005, funded by the NEESR program). Intact specimens were also obtained from the site and tested in the laboratory with a resonant column and torsional shear device. Test results from the laboratory are also shown in Figure 7. The laboratory specimen was hand carved from the soil beneath the footing after large-strain in-situ testing was completed. Cementation of the soil was somewhat broken down after the large-strain test in the field. As a result, the normalized shear modulus curve obtained from the field showed slightly more linear behavior than the same curve determined in the laboratory.

4.3 In-situ Liquefaction Test

Three of the 18 projects used T-Rex to liquefy soil in the field. A general test setup for the in-situ liquefaction test is shown in Figure 8 (Title: Collaborative study of field evaluation of liquefaction resistance at previous liquefaction sites in southern California, PI: Kenneth H. Stokoe, II and Ellen Rathje, at the University of Texas at Austin, 2006, funded by the U.S. Geological Survey). During testing, T-Rex was used to generate vertically propagating (downward), horizontally polarized shear waves of varying amplitudes that propagated through an instrumented portion of a liquefiable soil mass. Liquefaction sensors were installed in a two-dimensional, trapezoidal array within the liquefiable soil layer. The tests were successful at measuring: (1) excess pore water pressure generation, and (2) nonlinear shear modulus behavior in the native soil deposit as a function of induced cyclic shear strain and number of loading cycles. An example of the in-situ pore pressure generation curves is shown in Figure 9. Excess pore water pressure in the soil was not generated until shear strains greater than the cyclic threshold shear strain of about 0.002% had been induced. Further results and comparisons may be found in Cox et al. (2009).

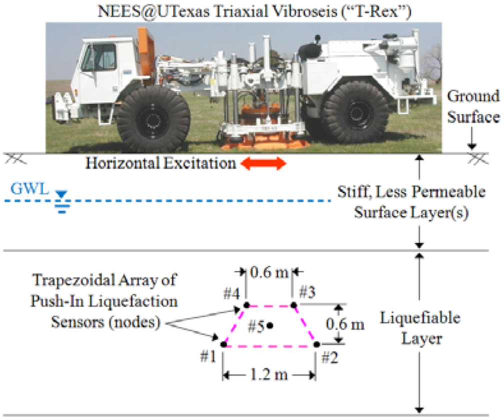


Figure 8 Test arrangement of in-situ liquefaction test (Cox et al., 2009)

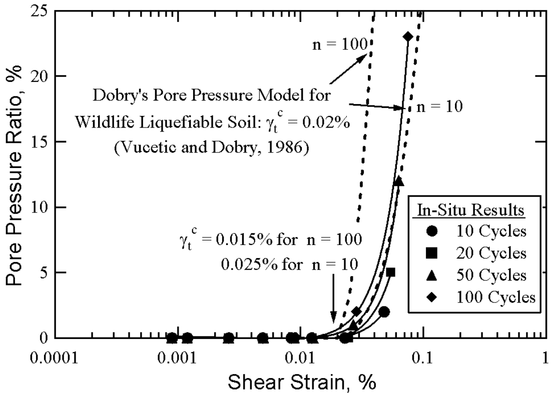


Figure 9 Pore pressure generation curves obtained from in-situ liquefaction tests (Cox et al., 2009)

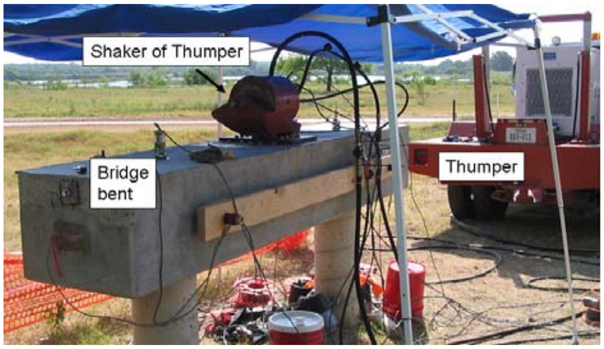


Figure 10 Harmonic excitation of Bent 2 using shaker from Thumper (Stokoe et al., 2008)

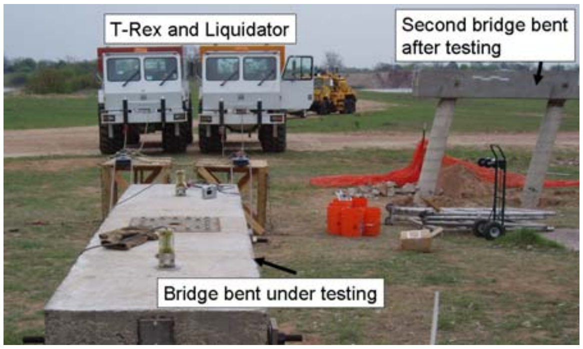


Figure 11 Cyclic load tests to failure of prototype bridge bent with T-Rex and Liquidator (from Stokoe et al., 2008)

4.4 Soil-Foundation-Structure Interaction Studies

Two projects using the three mobile shakers have been conducted in this group. The nees@UTexas mobile field shakers have the advantage of studying soil-foundation-structure interaction in the field at actual settings. In a collaborative research project (Title: Collaborative research: using NEES as a testbed for studying soil-foundation-structure interaction, PI: Sharon Wood, at the University of Texas at Austin, 2004, funded by the U.S. NSF), the shakers were used to test two, ¼-scale, isolated bridge bents on drilled shaft foundations at a field site in Austin, TX. The prototype structure that was modeled in this investigation is a continuous, reinforced concrete bridge with drilled shaft foundations. The specimens were tested dynamically: (1) using T-Rex to induce sinusoidal motion in the test specimens by exciting the ground surface in the vertical and two horizontal directions around the bents, and (2) by mounting the linear shaker from Thumper at mid-span of the beam (Figure 10) and exciting the bent horizontally in the linear and nonlinear ranges. When tests were conducted using higher force levels with the Thumper shaker mounted on the beam, inelastic response was observed (Agarwal et al., 2006). At the end of dynamic loading, the winches mounted on the front of both T-Rex and Liquidator were used to cyclically load the bridge bents to failure (Figure 11).

4.5 Geophysical Studies

There are 6 projects in the past four years that were focused on geophysical studies. Most of the projects in this group used Thumper as a dynamic source to image the upper 1 km of the geologic materials in a 10-km long seismic reflection profile. These studies have been used to detect faults that may be hidden under the recent alluvial cover in the seismically active area, and to help refine earthquake ground motion simulations. One of the projects (Title: Northwest Nevada seismic experiment, PI: Simon Klemperer, at Stanford University, 2004, funded by the U.S. NSF) used T-Rex as a dynamic source in a 40-km long 2-D crustal-scale profile that produced an upper-crustal velocity model for 5-km deep. Test results demonstrated the ability of T-Rex in collecting useful upper-crustal reflection and refraction data (Lerch et al., 2008).

5. CONCLUSIONS

Mobile shakers at the nees@UTexas equipment site are discussed in this paper. Force-output measurements of Thumper using both a load cell and accelerometers mounted on the shaker show good agreement. The measurements show that the actual force output is site dependent. Example projects are also discussed which show that the mobile shakers of nees@UTexas are capable of: (1) determining shear wave velocity profiles to depths of 300 m or more (2) creating large shearing strains near the shaker that permit evaluations of nonlinear shear modulus and liquefaction in the field, (3) loading scaled structures in various ways for soil-foundation-structure interaction studies, and (4) being an effective vibrational source for crustal-scale profiling depth of 5 km.

6. ACKNOWLEDGEMENTS

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