Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1076

# ESTIMATING DYNAMIC STRAINS IN SOIL GENERATED BY THE LARGE MOBILE SHAKERS AT NEES@UTEXAS

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## ABSTRACT

Five large-scale mobile shakers that are part of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) are available for shared-use projects. These mobile shakers are operated by an NSF-supported equipment site at the University of Texas, nees@UTexas. The shakers have been used on a wide range of projects to load geotechnical and structural systems. A key concern in planning projects that involve loading soil is estimating dynamic strains that can be induced by the shakers. Recent data obtained from two shared-use projects involving nonlinear shear moduli measurements and liquefaction testing is presented. A simplified method to estimate dynamic strains using trapezoid stress distribution is proposed and verified with data from the two shared-use projects.

## 1. Introduction

The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) is a U.S.-wide collaborative program that is supported by the U.S. National Science Foundation (NSF). NEES is composed of a network of 14 advanced, large-scale testing facilities called Equipment Sites. One equipment site, named nees@UTexas, is located at the University of Texas at Austin (UT). nees@UTexas specializes in large, mobile field equipment that can be used to dynamically load geotechnical and structural systems. 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 world-wide research community through the shared-use policy. NEEScomm and NSF also foster international cooperative efforts in earthquake engineering through the NEES program.

Starting in October, 2004, nees@UTexas began shared-use operation. Since that time, nees@UTexas has participated in more than 20 shared-use projects and numerous non-shared-used projects. Each of these studies would have been very difficult (if not impossible) to perform if the large mobile shakers of nees@UTexas did not exist. 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 obtained a shared-use status by petitioning the governing NEES organization. Additional shared-use projects founded by other U.S. and international organization are possible in the future. 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

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results with the public. Data collected in a shared-use project are available at the NEEScentral data repository approximately one year after completion of the project. Copies of measured data and results of shared-use projects using nees@UTexas equipment can be found at the websites of NEEScental (https://central.nees.org/) and nees@UTexas (http://nees.utexas.edu/).

In this paper, equipment operated by nees@UTexas is first introduced. Equipment and test setups used in previous soil studies involving in-situ nonlinear shear modulus measurements and cyclic loading tests leading to liquefaction are then discussed. With these data, a first-order approximation to estimate shear strains in soil that can be generated with the large mobile shakers in future experiments is presented and discussed.

## 2. Overview of nees@UTexas

The large-scale mobile shakers of nees@UTexas are used to dynamically excite geotechnical and structural systems in the field. This equipment includes: (1) five mobile shakers, (2) a tractor-trailer rig to move the three off-road shakers, (3) an instrumentation van and trailer that houses electrical power generation capabilities and state-of-the-art data acquisition systems, (4) a field supply truck for refueling and field maintenance of the mobile shakers, (5) a collection of field instrumentation that is used to measure vibrational motion and pore water pressure, and (6) telepresence capabilities that allow remote participation in field experiments.


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


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


c. Single-axis, vertical shaker called Raptor

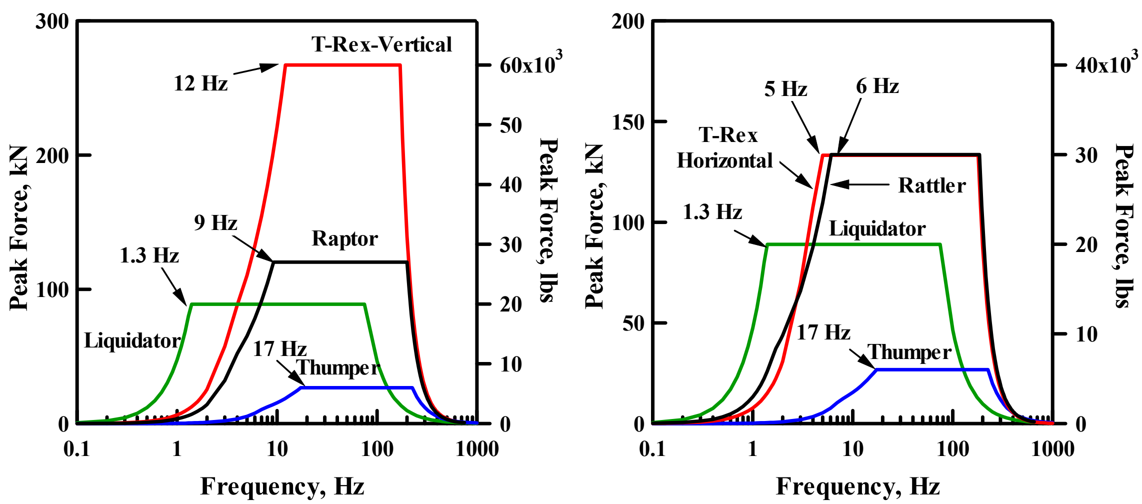

d. Single-axis, horizontal shaker called Rattler


e. Urban, three-axis shaker called Thumper


f. Tractor-trailer rig with T-Rex

Figure 1 Photographs of the five mobile shakers and the tractor-trailer rig

Photographs of the five mobile shakers named: (1) T-Rex, (2) Liquidator, (3) Raptor, (4) Rattler, and (5) Thumper are shown in Fig.1. Information about T-Rex, Liquidator, and Thumper can be found in Menq et al. (2008) and nees@UTexas website (http:\\nees.utexas.edu). In 2009, two shakers, Raptor and Rattler, were added to the nees@UTexas equipment. These two shakers were transferred from the Lawrence Berkeley National Laboratory. Raptor is a 1982 International Paystar model Y-1100 vertical shaker. This type of shaker is called a compression-wave (P-wave) shaker in the geophysical exploration community. The theoretical performance of Raptor is shown in Fig. 2a, along with those of T-Rex, Liquidator and Thumper. The maximum force output is about 120 kN. Raptor is ideal for locations where the force output of Thumper (27 kN) is not sufficient but the operation of T-Rex would likely be prohibited or would certainly draw unwanted attention. Rattler is a horizontal (shear-wave) vibrator that is a 1980 Mertz Model 13-609. It is mounted on an off-road vehicle. The theoretical performance of Rattler is shown in Fig. 2b. T-Rex, Liquidator, and Rattler must be transported to and from test sites on the tractor-trailer rig shown in Fig. 1f or other similar transportation system. Rattler has a maximum force output of 134 kN which is the same rating as T-Rex in the shear mode. One benefit of having two shear-wave vibrators (T-Rex and Rattler) is that they can be on the site surface as desired and have their force outputs synchronized, phase shifted or randomized. This flexibility with two sources offers numerous testing opportunities. For instance, an instrumented portion of a field site could be excited in a condition closer to a plane-strain condition for in-situ liquefaction and nonlinear soil testing. Of course, the same flexibility can be created in vertical shaking with the two P-wave sources, T-Rex and Raptor.




(a) Vertical Force Output (b) Horizontal Force Output

Figure 2 Theoretical force outputs of the five mobile shakers

## 3. CONTROL of NEES@UTEXAS SHAKERS FORCE OUTPUT

To optimize the performance of the shakers in field experiments, one should have a general understanding of the operational principles of electro-hydraulic shakers. A schematic diagram of a hydraulic shaker operating in the vertical mode is shown in Fig. 3. Ground vibrations from the hydraulic shaker are generated by altering the hydraulic oil pressure in opposite chambers of a piston-reaction-mass system. The direction of oil flow is controlled by a servo valve. In general, the oil flow rate is proportional to the servo valve displacement, and the valve displacement is proportional to the electrical driving voltage (current) applied to the servo valve. In the other words, the greater the driving voltage, the stronger the shaking force. For T-Rex, the controller is set for a maximum force output (266 kN in the vertical mode and 134 kN in the shear mode) when it receives a 5 V (peak) driving voltage. Users can select a lower driving voltage to have a lower force output. However, a minimum of 0.5V (10%) is needed to overcome friction and to generate a smooth output signal.

In theory, the maximum force output is governed by four physical limits. These four limits are: (1) stroke, (2) flow, (3) force, and (4) valve limits (Bay, 1997). Theoretical force outputs of the five nees@UTexas shakers shown in Fig. 2 were calculated based on these four limits. However, actual force outputs are also a function of the ground conditions at the test location and the control system. As an example, the force output of Thumper measured with a load cell placed between the loading plate and the ground is shown in Fig. 4. An external stepped-sine function was used to drive Thumper, sweeping from 200 Hz down to 3 Hz in 200 linear steps. By comparing the measured force output with the theoretical force output, one finds that the measured force output is higher than predicted between about 40 and 110 Hz. This difference is a result of ground movement and resonances. In this test, a 90% drive signal was selected to prevent the shaker from decoupling from the ground. The reason that the measured force outputs are lower than the theoretical force outputs at frequencies below about 30 Hz and above about 120 Hz is that the driving voltage was limited.

In practice, the force output of a vertical shaker is not measured with load cells but is estimated using accelerometers mounted on the base plate and reaction mass. This force estimation is based on the following. First, airbags are used to isolate the vibrations from the truck as illustrated by the schematic in Fig. 3. The air bags act as a low pass filter, and transfer only static force to the base plate in contact with the ground. If one takes a free body of the shaker and ignores the hydraulic system, the only external dynamic force is the dynamic ground force, which is also the dynamic force output of the shaker. The dynamic force output in the vertical direction, $F_d$, can be expressed as (Wei, 2008):

$$F_d = m_{RM} \times a_{RM} + m_{BP} \times a_{BP} \quad (1)$$

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 plate, and $a_{BP}$ is the base-plate acceleration. Comparison between the force output of Thumper determined with Eq. 1 and the force output measured with a load cell placed beneath the center of the loading plate is also shown in Fig. 4. The force output calculated from the accelerometers follows closely with that measured using the load cell as seen by both curves falling nearly on top of each other in this set of measurements.

A schematic of a hydraulic shaker oriented in the horizontal shaking (shear) mode is shown in Fig. 5. As in the vertical mode, air bags are used as a low pass filter to isolate the shaking mechanism from the hold-down mass of the truck so that, in principle, the only external force in the horizontal direction is from the ground. Eq. 1 can also be used to estimate the force output in the shear mode. However, as shown in Fig. 5, the reaction mass of the shaker is located at some distance above the ground-base-plate interface, so, in addition to a shear force, there is a rotational moment applied to the ground. The combined shear force and rotational moment causes coupled translation and rocking in the base plate. The rocking creates alternating vertical stresses beneath the base plate that are largest near the perimeter. In-situ nonlinear measurements in shear of soils and liquefaction tests are conducted under the base plate along the center line of the loaded area in an attempt to reduce the impact of rocking.

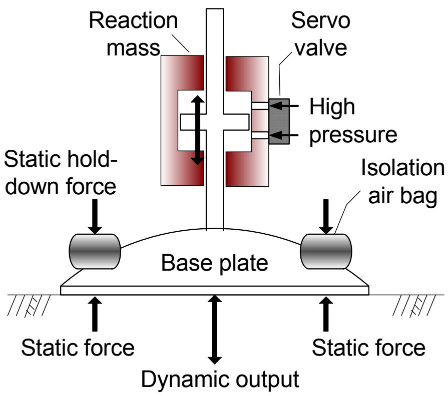



Figure 3 Schematic of a shaker in the vertical mode

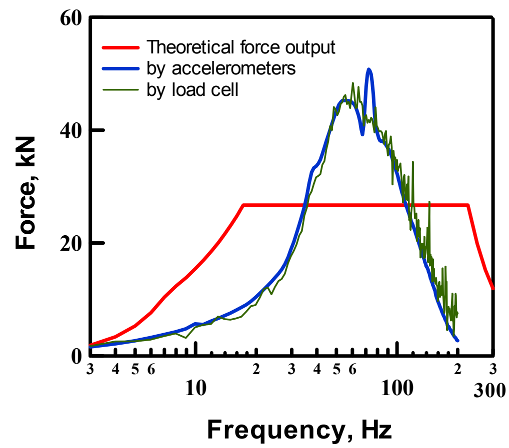



Figure 4 Theoretical and measured force outputs of Thumper in the vertical mode

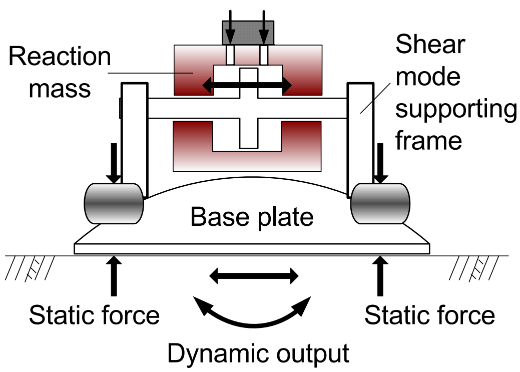



Figure 5 Schematic of a shaker oriented in the horizontal (shear) mode

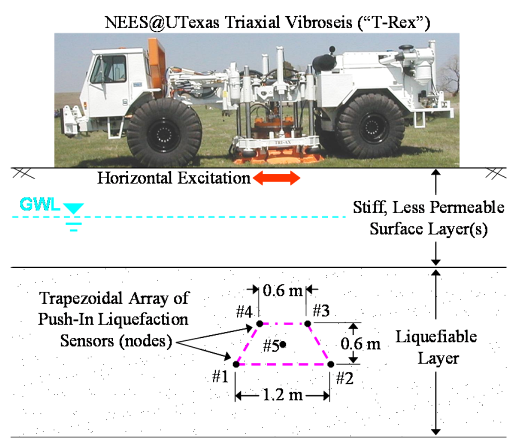



Figure 6 Field arrangement used to conduct in-situ liquefaction testing.

## 4. In-Situ Liquefaction Tests in Imperial Valley, CA

In-situ liquefaction testing involves dynamically loading a native soil deposit in a manner similar to an earthquake while simultaneously measuring its response with push-in liquefaction sensors. During testing, T-Rex is used to generate vertically propagating (downward), horizontally polarized shear waves (S waves) of varying amplitudes that propagate through an instrumented portion of a liquefiable soil mass (Fig. 6). Newly-developed, push-in liquefaction sensors are installed from the ground surface in a two-dimensional (2-D), trapezoidal array within the liquefiable soil layer and are retrievable upon completion of testing. Field liquefaction tests following this approach have been successfully conducted at the Wildlife Liquefaction Array (WLA) in Imperial Valley, CA (Cox et al., 2005). The WLA is also part of the NEES Equipment Site at the University of California at Santa Barbara that is designated for the study of soil liquefaction (http://nees.ucsb.edu/). In-situ tests were conducted in a liquefiable silty sand layer approximately 3.6 m below the ground surface. The tests were successful at measuring: (1) excess pore water pressure generation during dynamic loading, 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 at WLA is shown in Fig. 7. The in-situ pore pressure generation curves compare favorably with laboratory tests (Vucetic and Dobry 1986). Excess pore water pressure in the soil was not generated until shear strains greater than the cyclic threshold shear strain of about 0.02% had been induced. Further results and comparisons may be found in Cox (2006).

Cyclic shear strain can be determined from finite element theory using the displacements evaluated by integrating the signals from the MEMS accelerometers that are in the liquefaction-sensor array. The linear and nonlinear shear moduli of the soil deposit are obtained from the shear wave velocities determined during testing based on wave propagation theory as:

$$G = \rho \cdot V_S^2 \tag{2}$$

where G = shear modulus of the soil, ρ = the mass density of the soil, and $V_S$ = the shear wave velocity of the soil determined over a range in shear strains. The horizontal excitation and associated vertically propagating shear waves generated by T-Rex are measured by the horizontal components of the embedded instrumentation as they propagate through the instrumented array. The instantaneous shear wave velocity in the instrumented soil mass may be obtained by dividing the vertical distance between sensors by the time lag between the top and bottom sensors. From shear modulus and shear strain, γ, shear stress, τ, is calculated as:

$$\tau = G \cdot \gamma \tag{3}$$

If the shear stress is assumed to be uniform over an equivalent loaded area, $A_{eq}$, and the loading frequency is much lower than the resonant frequency of shaker- soil-mass system, the equivalent loaded area can then be obtained by dividing the shear force by the shear stress.

In geotechnical engineering, stress at depth induced by a load at the surface may be estimated using a trapezoidal approximation for the increase in area with depth. The stress at depth beneath the central portion of the surface load is estimated by dividing the load by an equivalent area with dimensions that are increased in a vertical-to-horizontal ratio often assumed to be 2-to-1 as illustrated in Fig. 8. The area directly under the base plate of T-Rex is 5.2 $m^2$ (2.3 m by 2.3 m). At the average instrumentation depth in the liquefaction experiment of about 3.6 m (1.6 times the width of the loading plate, B), the equivalent area is 35.4 $m^2$ if a 2-to-1 ratio is used and 17.0 $m^2$ if a 4-to-1 ratio is used. The shear strains estimated with both projected areas versus the shear strains determined in the liquefaction experiment from displacements determined by integrating the measured outputs of the MEMS accelerometers (denoted as Displacement-Based (DB) shear strains in the figure and hereafter) at different force levels are shown in Fig. 9. As seen in the figure, shear strains calculated using an equivalent loaded area based on a 2-to-1 ratio underestimate the DB shear strains by a factor of about 2. The shear strains estimated with a 4-to-1 ratio are closer to the DB shear strains at most of the loading stages.

## 5. In-Situ Measurements of Nonlinear Shear Moduli of Soil near Austin, TX

The testing arrangement used to measure nonlinear shear wave propagation in situ with a footing near Austin, TX is illustrated in Fig. 10. An array of 14-Hz geophones was embedded below the ground surface. The geophones were placed in hand-augered boreholes and that were backfilled with soil. After the sensor array was installed, a circular concrete footing, with a diameter of 0.9 m and thickness of 0.3 m, was constructed. In the nonlinear tests, the dynamic loads were applied with Thumper and T-Rex. The shakers were used to apply dynamic loads over a wide range, from loads that created only small strains (less than 0.001%) to loads that created significant nonlinear responses (strains above 0.01%).

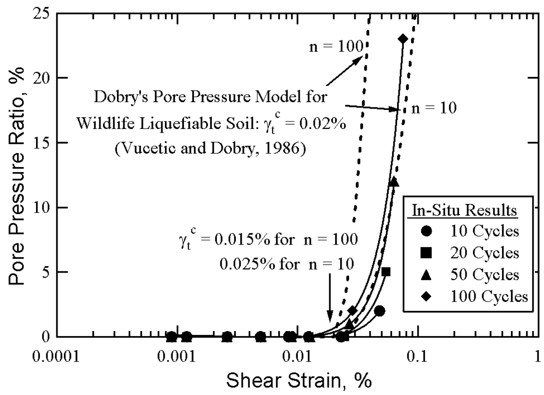



Figure 7 Pore pressure generation curves obtained from in-situ liquefaction tests at the Wildlife Liquefaction Array (Cox 2006).

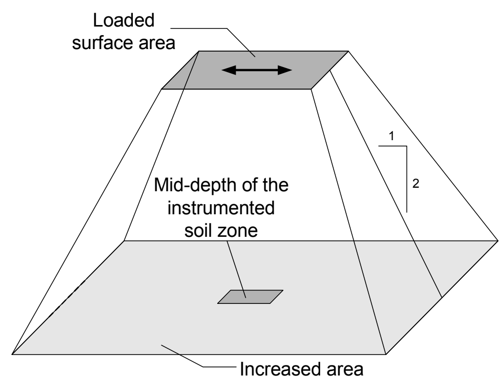



Figure 8 Illustration of the increase in equivalent loaded area with depth based on a trapezoidal approximation

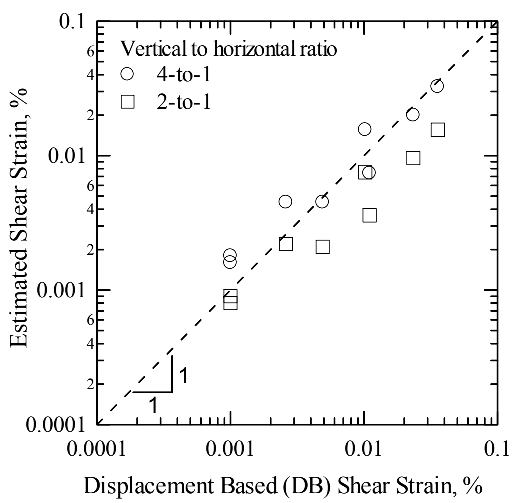



Figure 9 Comparison between estimated shear strains and DB shear strains at WLA.

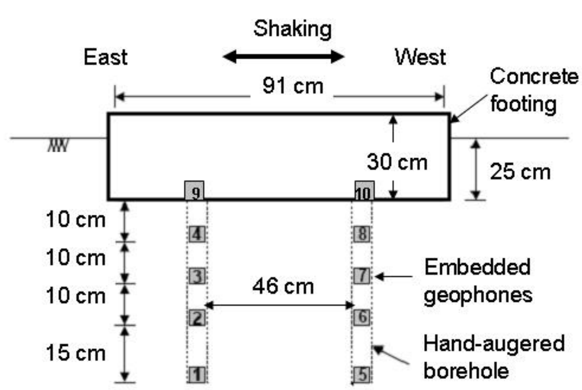



Figure 10 Field arrangement used to conduct nonlinear shear moduli measurements (Park, 2010)

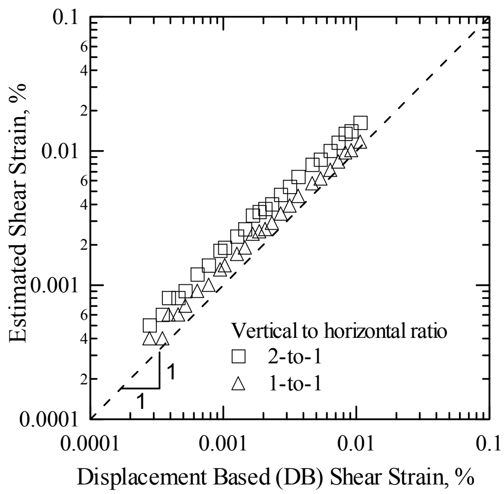



Figure 11 Comparison between estimated shear strains and DB shear strains at Austin, TX site.

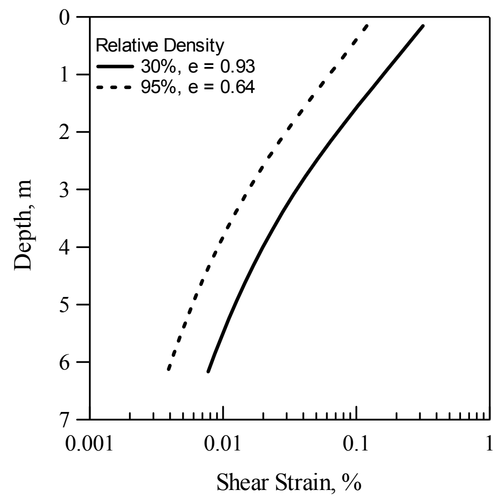



Figure 12 Estimated shear strain range underneath the loading plate of T-Rex from horizontal shaking.

Because of the inertia of the concrete footing and interaction of the soil at the sides of the footing, the shear force applied at the base of the footing was less than the force output of Thumper applied to the top of the footing. To use the trapezoidal approximation, one needs to estimate the shear stress at the bottom of the footing. This estimate was made using geophones #8 and #4 (Fig. 10) to evaluate the shear moduli, and shear strains in the soil at the base of the footing. With the estimated shear stress at the bottom of the footing, shear strains at deeper depths were then estimated using the trapezoidal approximation. The comparison between the DB shear strains determined with geophones #4 and #2 during the experiment (Park, 2010) and the shear strains estimated using the trapezoidal approximation is presented in Fig.11. The mid-depth of the two geophones is 20 cm (about 0.2 times the footing width; hence 0.2 B) below the base of the footing. At this depth, the equivalent area is 0.98 $m^2$ with a 2-to-1 ratio, and 1.36 $m^2$ with a 1-to-1 ratio. Shear strains calculated with both equivalent areas are shown in Fig. 11. Contrary to the liquefaction study discussed above, shear strains calculated using an equivalent loaded area with a 2-to-1 ratio overestimate the DB shear strains by a factor of about 2. The DB shear strains are more closely estimated using an equivalent area based on a 1-to-1 ratio. This difference is thought to be a result of the proximity of the instrumented zone in this experiment. Although not shown here, the estimated shear strains with a 2-to-1 ratio are closer to the DB shear strains than the estimated shear strains with a 1-to-1 ratio at an average depth of 37.5 cm (depth = 0.4 B) when geophones #2 and #1 are used. In other words, the vertical-to-horizontal ratio seems to vary from a 1-to-1 ratio at the depth of 0.2 B to a 2-to-1 ratio at the depth of 0.4 B. With data from the liquefaction experiment, the vertical-to-horizontal ratio extended to 4-to-1 at the depth of 1.6 B. However, if a vertical-to-horizontal ratio of 2-to-1 is used in all conditions, the estimated shear strains are about 2 times higher at shallow depths (depths ≤ 0.2 B) and about 0.5 time smaller at larger depths (depths ~ 1.6 B). This difference is considered acceptable in designing field studies.

## 6. Suggested Method for Estimating Shear Strains under the Loaded Area

Rigorous methods like finite element analyses can be used in estimating the strain distribution in soils beneath the nees@UTexas shakers. However, these methods require a significant number of parameters to define the soil model. In the planning stages of field experiments, these parameters are generally not available. As shown above, only three parameters are needed when using the trapezoidal approximation to estimate shear strains under the dynamically loaded area. The three parameters are: (1) shear force applied by the shaker, (2) equivalent loaded area, and (3) soil shear moduli. The applied shear force depends on the shaker characteristics and ground conditions as discussed earlier. The equivalent loaded area is based on a trapezoidal approximation as illustrated in Fig. 8. A vertical-to-horizontal ratio of 2-to-1 was found to produce reasonable estimations for the equivalent loaded areas. For the third parameter, shear modulus, a range of values should be estimated based on site conditions as discussed below.

As an example of estimating shear strains under the loaded area, considering the case of a footing or loading plate on uncemented sandy soils. The small-strain shear modulus of uncemented sandy and gravelly soils can be determined as (Menq, 2003):

$$G_{\max} = C_{G3} \times C_u^{b1} \times e^x \times \left( \sigma_o' / P_a \right)^{n_G} \tag{4}$$

where $C_{G3}$ =67.1 MPa (1400 ksf), $C_u$ = uniformity coefficient, b1 = - 0.20, e = void ratio, $\sigma_o'$ = effective confining pressure, $P_a$ = atmosphere pressure, x = -1- $(D_{50} / 20)^{0.75}$, $D_{50}$ = mean grain size in mm, and $n_G = 0.48 \times C_u^{0.09}$. Shear modulus (G) at larger strains ($\gamma$) can be determined using the modified hyperbolic model as (Darendeli, 2001):

$$G/G_{\max} = 1 / \left( 1 + (\gamma / \gamma_r)^a \right) \tag{5}$$

where $\gamma_r$ is the reference strain, and "a" is a curvature coefficient. For sandy and gravelly soil, Menq (2003) suggested that reference strain and the curvature coefficient can be determined as:

$$\gamma_r = 0.12 \times C_u^{-0.6} \times \left( \sigma_o' / P_a \right)^{0.5 \times C_u^{-0.15}} \text{ and,} \tag{6}$$

$$a = 0.86 + 0.1 \times \log (\sigma_o' / P_a). \tag{7}$$

With these four equations, the shear moduli of sandy (or gravelly) soils at different shear strains can be estimated. Fig. 12 shows the estimated theoretical shear strain range underneath the loading plate of T-Rex on an uncemented sandy soil at the maximum horizontal force output of 134 kN. The tested soil is assumed to have a uniformity coefficient of 1.5 and mean grain size of 0.5 mm, and the water table is near the ground surface. The upper and lower bounds of the estimated shear strain range are calculated from relative density of 30% and 95%, respectively. As shown in the figure, shear strain decreases with increasing depth, from 0.2% near the ground surface down to 0.004% at 6m deep.

It should be noted that, in the example above and in the other examples presented earlier, the trapezoidal approximation is a static approach and does not consider resonances in the shaker-soil-mass system. Shear strains induced in the field can be higher if tests are conducted near the resonant frequency of the shaker-soil-mass system. Induced shear strains can also be lower when testing at high frequencies where inertial forces are large.

## 7. Summary Conclusions

As demonstrated in the two projects presented in the article, nees@UTexas mobile shakers are effective in creating nonlinear shear strains in soil. A simple method using a trapezoidal approximation is suggested to estimate an equivalent area that is used to calculate shear strains at depths beneath the shakers. Base on field data from two projects, a vertical-to-horizontal ratio of 2-to-1 is suggested for determining the equivalent loaded area (Fig. 8). With this approximation, the estimated shear strains are about 2 times higher at shallow depths (depths ≤ 0.2 B) and about 0.5 time smaller at larger depths (depths ~ 1.6 B). Additional studies would be helpful to further validate this approach.

## Acknowledgements

The authors would like to thank the U. S. National Science Foundation for the financial support to develop and operate the nees@UTexas equipment site under grants CMS-0086605 and CMS-0402490. Financial support for the research projects was provided through the National Science Foundation under grant CMS-0421275, and through the U.S. Geological Survey (USGS) under award 01HQR0036. Thanks also goes to the staff at the University of Texas at Austin who assisted in the field work, including Mr. Cecil Hoffpauir, Mr. Andrew Valentine, and Mr. Christopher Stanton.

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