

NHERI@UTEXAS EXPERIMENTAL FACILITY: LARGE-SCALE MOBILE SHAKERS FOR NATURAL-HAZARDS FIELD STUDIES

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Abstract

The vision of the Natural Hazards Engineering Research Infrastructure (NHERI) Program supported by the U.S. National Science Foundation (NSF) is to "transform how future civil infrastructure will be designed and how existing civil infrastructure might be rehabilitated" by enabling "research and education that can contribute knowledge and innovation for civil infrastructure, over its lifespan, to be multi-hazard, resilient and sustainable". The NSF-funded NHERI@UTexas is contributing unique, large-scale, hydraulically-controllable mobile shakers and associated instrumentation to study and develop novel, in-situ testing methods that can be used to both evaluate the needs of existing infrastructure and optimize the design of future infrastructure. The ability to test existing infrastructure under actual field conditions bridges the gap in the transformative tools needed for the next frontier of resilient and sustainable natural hazards research. Three key areas of investigation that NHERI@UTexas is targeting are: (1) performing deeper, more accurate, and higher resolution 2D/3D subsurface geotechnical imaging, (2) characterizing the nonlinear dynamic response and liquefaction resistance of complex geomaterials in situ, and (3) developing rapid, in-situ methods for nondestructive structural evaluation and soil-foundation-structure interaction (SFSI) studies. On-going, new, and future projects in these areas are discussed.

Keywords: mobile shakers; subsurface imaging; soil-structure interaction; in-situ liquefaction tests; in-situ nonlinear tests

1. Introduction

The Natural Hazards Engineering Research Infrastructure (NHERI) [1] is the next generation of the US National Science Foundation (NSF) support for a natural hazards engineering research large facility, replacing the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). NEES was established by NSF as a distributed, shared-used, national research infrastructure for earthquake engineering. A facility construction phase during 2000 – 2004 was followed by the operations phase of this infrastructure to support research, innovation, and education activities from October, 2004 through September, 2014. The new NHERI facilities consists of: (1) a Network Coordination Office (NCO), (2) a Computational Modeling and Simulation Center (SimCenter), (3) a Post-Disaster, Rapid Response Research (RAPID) Facility, (4) a Cyberinfrastructure named DesignSafe CI (https://www.designsafe-ci.org/), and (5) seven Experimental Facilities (EF). NHERI@UTexas is one of the seven experimental facilities, and this EF specializes in large-scale, mobile, field shakers.

Established under the NEES program as NEES@UTexas, NHERI@UTexas was renamed on January 1st, 2016 under the NHERI program. One of the key features of NEES and now NHERI 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 was operated as a 50% shared-use facility. In the past 12 years, NEES@UTexas has participated in 30 shared-use projects and numerous non-shared-used projects. All data collected on shared-used projects are available to the public in the "Data Depot" on the DesignSafe CI website (www.designsafe-ci.org). These data are formally published with a Digital Object Identifier (DOI) and the use of these data in other work can be cited using this DOI and the citation language. The data files can be downloaded for subsequent analysis or they may be analyzed in the cloud using tools such as the



newly implemented Jupyter Notebook. A Jupyter Notebook is a web application that runs on the DesignSafe web portal and allows users to create and share documents containing rich text, live code for data analyses, and plots of results. More information about NHERI@UTexas and the NHERI program can be found at https://www.designsafe-ci.org.

2. Overview of NHERI@UTexas

NHERI@UTexas equipment resources were primarily established with funding from the National Science Foundation (NSF) under the original George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program. These equipment resources have served the earthquake engineering community for over 10 years under the name of NEES@UTexas. All equipment operated by NEES@UTexas is now part of NHERI@UTexas. This equipment includes: (1) five, large, hydraulically-controlled shakers that can be used as mobile, wide-band dynamic sources for excitation of geotechnical and structural systems, (2) a tractor-trailer rig used to transport the four largest shakers, (3) a field supply truck for refueling and field maintenance of the mobile shakers, (4) an instrumentation van that houses state-of-the-art data acquisition systems and electrical power generation capabilities, (5) a field instrumentation trailer that has air-conditioned work space and electrical power generation systems and a wide range of numerous sensors that are used to measure vibrational motions and pore water pressures.

The five mobile shakers offer a wide range in force and frequency generation capabilities. For ease in identifying and referring to the shakers, they have been given the following names: (1) T-Rex, (2) Liquidator, (3) Raptor, (4) Rattler, and (5) Thumper (see photographs in Fig. 1). The two heaviest shakers are T-Rex (29,000 kg) and Liquidator (32,800 kg). T-Rex (Fig. 1a) 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, the operator simply pushes a button in the driver's cab. The shaking system is housed on an off-road, all-wheel-drive vehicle. The theoretical force outputs of T-Rex in the vertical and both horizontal directions are shown in Fig. 2a and 2b, respectively. The maximum force output is about 267 kN in the vertical mode and about 134 kN in each horizontal mode. T-Rex also has the capability of pushing cone penetrometers and other custom-made vibration and/or pressure-sensing instrumentation into the ground using a hydraulic ram located at the rear of the vehicle. These overall capabilities make T-Rex unique in the world.

The second large shaker is Liquidator (Fig. 1b). Liquidator is a custom-built, shaker that was designed specifically for low-frequency, large-motion operation. There is no other shaker like Liquidator in the world. It can be changed from the vertical mode to the cross-line horizontal (shear) mode at the manufacturer's facilities (IVI in Tulsa, OK) in about two working days. The theoretical force outputs of Liquidator are shown in Fig. 2. The maximum force output in both modes is about 89 kN down to a frequency of 1.3 Hz. We have recently developed a new Liquidator testing configuration that allows the entire off-road mobile platform to be lifted off the ground and oscillated in the vertical mode at frequencies between approximately 0.3 - 1.0 Hz. This modified configuration allows Liquidator to generate peak dynamic forces up to 89 kN down to 0.7 Hz. Below 0.7 Hz, the force level decreases but is still substantial to about 0.3 Hz. This modification is a remarkable and completely unique capability that has significant implications for deep (1 km or more), active-source subsurface imaging. Like T-Rex, Liquidator is also mounted on an off-road vehicle.

The two, intermediate-level shakers, based on force-generation characteristics and vehicle weight, are Raptor and Rattler. Raptor is a 1982 International Paystar model Y-1100 vertical shaker (Fig. 1c). 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. The maximum vertical force output is about 120 kN. Raptor is ideal for situations where the force output of Thumper (discussed below) is not sufficient for the desired testing application and the 3-mode shaking capabilities and/or higher force output of T-Rex is not required. The other intermediate-level shaker is Rattler (Fig. 1d). Rattler is a horizontal (shear-wave) vibrator that is a 1980 Mertz Model 13-609 mounted on an off-road vehicle. The theoretical performance of Rattler is shown in Fig. 2b. It has a frequency-force response which is nearly identical to T-Rex in the shear mode. One benefit of having two shear-wave vibrators (T-Rex and Rattler) is that they can be parked side-by-side with their force outputs synchronized to be in phase so that a larger area of high shear strains can be created. Thus, an instrumented portion of soil



beneath the two shakers can be excited in a condition closer to plane-strain for in-situ liquefaction and nonlinear soil testing. A similar arrangement can be created in the vertical shaking mode with T-Rex and Raptor. In addition, T-Rex and Rattler can be located next to each other but positioned to permit 2D, horizontal shaking of the ground surface. T-Rex, Liquidator, and Rattler must be transported to and from test sites on the 26-wheel, tractor-trailer rig shown in Fig. 1f. The large size of the tractor-trailer rig, called the Big Rig, is required because both T-Rex and Liquidator create "over-load" situations. Also, due to regulations in some states, Raptor has to be transported with the tractor-trailer rig.

Thumper is the smallest shaker and is built on an International model 4300 truck. Thumper has a moderate force output, which makes it ideal for testing in urban areas. A photograph of Thumper is presented in Fig. 1e, and its theoretical vertical and horizontal frequency-force outputs are shown in Fig. 2. The maximum force output of Thumper is about 27 kN. The direction of shaking with this machine can be changed from vertical to horizontal in about two hours at the test site. T-Rex, Liquidator, and Thumper are also equipped with hydraulic take-off connections that permit each truck to power other hydraulic equipment in the field. For example, T-Rex or Liquidator could be used to power linear hydraulic actuators for in-situ, push-apart, structural testing of piles and drilled piers. Furthermore, the hydraulic shakers mounted on T-Rex, Liquidator, and Thumper can also be removed and attached on a structure. The shakers can then be powered at some stand-off distance by the hydraulic take-off and electronics from the associated mobile platform/truck.

Field-support vehicles and some of the instrumentation available at NHERI@UTexas are shown in Fig. 3. The first field-support vehicle is a supply truck (see Fig. 3a) that carries diesel fuel for T-Rex, Liquidator, Raptor and Rattler. It also carries spare parts and provides a working platform for maintenance. The second vehicle is an



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



c. Single-axis, vertical shaker called Raptor



e. Urban, three-axis shaker called Thumper



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



d. Single-axis, horizontal shaker called Rattler



f. Tractor-trailer rig, called the Big Rig, with T-Rex

Fig. 1. Photographs of the five mobile shakers and tractor-trailer rig available at NHERI@UTexas.



Fig. 2. Theoretical force outputs of the five mobile shakers in: (a) the vertical mode and (b) the horizontal mode.



e. Data Physics Analyzers setup as 3 Separated Units

f. Trillium Compact Seismometers and Taurus Digitizers

Fig. 3. Photographs of the field supply truck, mobile instrumentation trailer and some associated instrumentation available at NHERI@UTexas.

b. Air-conditioned work space in instrumentation trailer





instrumentation van that is a customized Ford cargo van (not shown in Fig. 3). This vehicle provides airconditioned workspace for personnel, DAC systems, and electrical power. The third support vehicle is a 2.4 m by 4.8 m instrumentation trailer with storage space, air-conditioned workspace and electrical power. A photograph of the instrumentation trailer is shown in Fig. 3a. A photograph of the air-conditioned workspace of the instrumentation trailer is presented in Fig. 3b.

A significant amount of field instrumentation is also part of the NHERI@UTexas equipment facility. This instrumentation includes: (1) two main data acquisition systems (discussed below), (2) 85, 1-Hz vertical geophones (Fig. 3c), (3) 24, 1-Hz horizontal geophones, (4) 6, high-capacity dynamic load cells, (5) 18, triaxial MEMS accelerometers, (6) cone penetrometer test (CPT) and seismic CPT equipment, and (7) 12, 120-seconds Trillium Compact broadband seismometers (see Fig. 3f). The CPT equipment was manufactured by Fugro, Inc. There are four electrical cones, with two of them having a base area of 10 cm² and the other cones having base areas of 5 cm² and 15 cm². A photograph of the CPT equipment in use on the back of T-Rex is presented in Fig. 3d.

The two main data acquisition systems are: (1) a 64-channel Data Physics spectrum analyzer system, and (2) 10, 3-channel Nanometrics Taurus digitizers (30 total channels). The Data Physics system uses a Microsoft Windows-based software named SignalCal 730 that generates input signals (sinusoidal, stepped-sine, white noise, frequency sweeps, etc.) to drive the mobile shakers and record output signals from various sensors. The Data Physics system actually consists of three dynamic signal analyzers, which can be used individually as two, 16-channel units and one, 32-channel unit, or can be linked together as a single 64-channel system. Fig. 3e shows the setup of the Data Physics Analyzers as 3 separate units with different sampling rates during an in-situ liquefaction test. All sensors are connected to the Data Physics spectrum analyzers by electrical cables. These analyzers have the capacity to record data for long periods of time (hours) at a high sampling rate (up to 200,000 samples per second). Furthermore, the control software, provided by Data Physics Inc., can be used to perform real-time frequency domain calculations and display auto power spectra, transfer functions, coherency and phase plots for reviewing and analyzing data in the field.

It is not practical for field experiments that utilize widely spread sensors (hundreds of meters to a km apart) to have all sensors connected with electrical cables. Passive surface wave testing and topographic amplification studies represent such experiments that will likely be conducted by researchers using the NHERI@UTexas facilities. In these cases, the Nanometrics Taurus digitizers and Trillium seismometers can be used. The 10, solar-powered Taurus digitizers are self-sustaining recording stations, each with three recording channels. They are designed for long-term deployments such as aftershock monitoring, but can also be used for any type of data acquisition where individual, GPS-synchronized digitizers are required. Although the Nanometrics Taurus digitizers are predominantly used with the Trillium Compact broadband seismometers, other types of sensors can also be connected to the system to monitor strain or displacements of buildings and bridges. Fig. 3f shows a photograph of the Trillium Compact seismometers and Taurus digitizers during a huddle-type calibration test.

3. Key Areas of Investigation

The *science plan of NHERI@UTexas* is guided by three main challenges. These three main challenges are: (1) performing deeper, more accurate, higher resolution, 2D/3D subsurface geotechnical imaging, (2) characterizing the nonlinear dynamic response and liquefaction resistance of complex geomaterials in situ, and (3) developing rapid, in-situ methods for non-destructive structural evaluation and soil-foundation-structure interaction (SFSI) studies. As examples of how NHERI@UTexas is important in addressing these challenges, six research projects, that utilized NEES@UTexas facility, are discussed below. These six projects includes: (1) two NSF-funded RAPID awards that helped build a resilient Christchurch, (2) an NSF-funded CAREER award and an NSF-funded NEES research project that focused on continuous 2D/3D in-situ profiling for anomaly detection, (3) an industrial research project that focused on evaluating the nonlinear dynamic response of complex geomaterials in situ, and (4) an NSF-funded research project that focused on soil-foundation-structure interaction. Details of these projects are presented below.



3.1 NEES@UTexas: Helping to Build a Resilient Christchurch

In 2010-2011, the city of Christchurch, New Zealand was devastated by a series of powerful earthquakes, the most destructive being the 22 February 2011 Mw6.2 Christchurch Earthquake. During this event, the seismic demands imposed on the built environment at many locations in the city were higher than engineering design levels, causing severe structural damage and collapse, especially within the central business district (CBD). Ultimately, the Christchurch Earthquake resulted in 181 casualties, thousands of injuries, and widespread soil liquefaction that caused billions of dollars of damage to buildings, homes, lifelines and other infrastructure. The entire CBD was cordoned-off following this event and remained closed to the public for more than 1.5 years, while an estimated 2400 structures were being demolished. Additionally, more than 7000 homes were ultimately "red zoned" by the government, forcing residents to abandon their properties after repeated soil liquefaction damage to structures and lifelines led them to conclude that land repair would be prolonged and uneconomical. While it is hard to quantify all economic factors, most estimate the Christchurch earthquakes resulted in approximately \$40 billion NZD in damage (roughly 20% of the entire New Zealand GDP), which equates to approximately \$115,000 per citizen of the city. These statistics are shocking, considering that New Zealand seismic design standards are on par with countries such as the U.S. and Japan. Clearly, the "old Christchurch" was not resilient or sustainable under the demands of earthquake hazards. The research equipment of NHERI, then operated as NEES@UTexas equipment, was called upon following these earthquakes for help with in-situ testing and research needed for building a "new and resilient Christchurch".

In 2012 and 2013, two RAPID awards involving the NEES@UTexas equipment for research projects in New Zealand were funded by NSF. As part of this research, NEES@UTexas mobilized approximately \$1.5 million of equipment to New Zealand, including: (a) the large, mobile, triaxial shaker called T-Rex, (b) 10, Nanometrics 3-component, 120-sec broadband seismometers with Taurus digitizers, (c) 30, 1-Hz vertical geophones, (d) 48, 4.5-Hz vertical geophones, (e) several different data acquisition systems comprising approximately 100 channels, and (f) more than 100 custom-built, push-in vibration sensors and pore pressure transducers. The first Christchurch RAPID project focused on characterizing the liquefaction resistance of fine sands in situ. These were two key challenges that had to be addressed before a "new and resilient Christchurch" could be established. These two projects are discussed in more depth below.

3.1.1 Improved Site-Specific Subsurface Models for Ground Motion Predictions; Deep Profiling in Christchurch

In earthquake engineering, the need to develop reliable, site-specific subsurface models with accompanying dynamic material properties cannot be overstated. Subsurface materials nearly always play a critical role in the areal extent and severity of damage associated with earthquakes. However, these materials are the least investigated, most variable, and least controlled of all materials in the built environment. All forms of ground motion prediction, from rudimentary to complex, rely on some knowledge of the subsurface small-strain shear modulus (G_{max}) /shear wave velocity (Vs) profile. The more accurately this information is known, the more accurately we can estimate the amplitude and frequency content of future seismic ground motions can be estimated. Without a good subsurface Vs model, these attempts are futile.

The deep profiling with the NEES@UTexas equipment in Christchurch is an excellent example of the important of this work. The ground motions recorded during the Christchurch Earthquake significantly exceeded design levels at many locations in the city. While higher-than-expected, short-period ground motions were not a surprise, given the closer-than-expected fault rupture, higher-than-expected long-period ground motions could not be explained, and were postulated as potentially the result of site effects (1D amplification), basin-edge effects (2D/3D amplification) and/or rupture directivity effects [2]. Detailed back-analyses aimed at reproducing the recorded ground motions were hampered by the lack of information on the Vs structure of the deep interlayered sand and gravel deposits of the Canterbury basin. Therefore, confidence in predicting more robust, future design ground motions from forward-analyses was lacking.

The unique equipment resources of NEES@UTexas (now NHERI@UTexas) were mobilized to Christchurch with the goal of performing ultra-deep (>400m), non-intrusive Vs profiling to aid in developing a 3D velocity model of the Canterbury basin [3]. The combined large, active-source and ambient-wavefield surface



wave testing program had never been applied before. It involved deploying (refer to Fig. 4): (a) circular receiver arrays (up to 400-m diameter) to record low-frequency ambient/microtremor waves with specialized 120-s period Nanometrics seismometers, and (b) linear receiver arrays (up to 230-m long) to record waves generated actively



Fig. 4. Configuration for combined active-source (T-Rex) and ambient-wavefield surface wave testing used for deep (500-1000m) Vs profiling in Christchurch, New Zealand [4].

with the large, mobile shaker called T-Rex. Extensive datasets were collected at 15 sites over a period of approximately 30 days. This unique equipment, coupled with advanced signal processing and data analysis techniques, allowed 500- to 1000m deep Vs profiles to be developed at each site, with accompanying estimates of uncertainty [4] [5]. These ultra-deep Vs profiles revealed subsurface structure, including a very strong, deep impedance contrast, that played a significant role in the long-period amplification observed in the recorded ground motions. This information could not have been obtained economically in any other way. However, there is still much future work to do in refining and validating these methods. Furthermore, as these combined large, active-source and ambient-wavefield techniques have been

employed only sparingly in the U.S., much work remains to study the Vs structure beneath cities in high seismicity areas underlain by deep sedimentary deposits, such as Los Angeles, Seattle, Salt Lake City, Memphis and Charleston.

3.1.2 Characterizing the in-situ liquefaction resistance of fine sands in Christchurch

In addition to surface wave measurements, T-Rex has also been used to study soil liquefaction using in-situ, staged, dynamic loading methods at Christchurch. Since liquefiable soils are loose and saturated, it is necessary to push the sensors into place using the hydraulic ram on the back of T-Rex [6]. This in-situ testing methodology was utilized in Christchurch, New Zealand to investigate shallow ground improvement methods that could inhibit liquefaction triggering beneath new or repaired residential structures. The 2010-2011 Canterbury earthquakes caused repeated, widespread and severe liquefaction throughout the suburbs of Christchurch. There was a great need to investigate simple, cost-effective ground improvement methods for increasing the resilience of residential construction during future earthquakes. As such, a series of full-scale field tests of various shallow ground improvement methods was initiated using T-Rex [7]. This effort was sanctioned by four New Zealand authorities [Earthquake Commission (EQC), Housing New Zealand (HNZ), Canterbury Earthquake Recovery Authority (CERA), and Ministry of Business Innovation and Employment (MBIE)] and partially funded by NSF.

The four ground improvement methods selected by New Zealand authorities for the test trials were: (1) Rapid Impact Compaction (RIC), also known as dynamic compaction, (2) Rammed Aggregate Piers (RAP), (3) Low-Mobility Grouting, also known as compaction grouting, and (4) construction of one or two rows of horizontal beams beneath the residential structure using in-situ soil mixing. The relative effectiveness of these ground improvement methods to inhibit liquefaction triggering was evaluated by shaking the ground and monitoring the subsurface movements and dynamic pore water pressures within the improved zones using the embedded sensor array [7]. Specifically, in-situ measurements of shear strain and pore water pressure ratio (r_u) were made within each of the four ground improvement zones, and within an unimproved (natural soil) zone, at three separate test sites in the city. As seen in Fig. 5a, T-Rex was used to perform staged loading directly on the ground surface, without the need to construct a separate loading foundation. The tendency for the ground improvement zones to strain and buildup pore pressure under dynamic loading was evaluated relative to the natural soil at each test site. Example records of the build-up in excess pore water pressure ratio ($r_u = u_{excess}/\sigma'_v$) with number of cycles of



(a) T-Rex was used to performing staged-loading tests on unimproved (natural) and improved ground conditions.



(b) Example records of pore water pressure ratio and dynamic shear strain for 100 cycles of high-level shaking of natural soil.

Fig. 5. Staged in-situ testing with T-Rex was used to evaluate the mitigating effects of various ground improvements on liquefaction triggering in Christchurch, NZ.

shear strain (γ) at one natural soil site are shown in Fig. 5b. In each record, the controlled sinusoidal loading is 10 Hz for 10 seconds. Hence, the response of the loose, saturated sand to 100 cycles of shaking for each stage in the staged loading sequence is shown. The results from a complete set of staged loading tests are shown in Fig. 6 in



Fig. 6. Example of the pore water pressure ratio (r_u) versus shear strain (g) relationship determined after 50 cycles of shaking for each loading stage on an unimproved (natural) soil.

terms of $r_u - \log \gamma$. Shear strains ranging from 0.0028% to 0.19% were generated in situ by the staged T-Rex loading. No significant pore pressures were generated at cyclic shear strains less than about 0.01%, after which pore pressure build-up accelerated rapidly with increasing shear strain. The rapidly increasing value of r_u after $\gamma \sim 0.04\%$ clearly shows that the pore pressure ratio is rapidly approaching $r_u = 100\%$, which indicates complete soil liquefaction. While the in-situ tests did not reach 100% liquefaction, the trend of incipient soil liquefaction in the natural soil was observed, allowing comparisons to be made with tests conducted in zones of improved ground. As a result of these tests, the RIC and RAP methods were found to be effective at mitigating liquefaction triggering [7]. This research, aimed at rehabilitating a city devastated by earthquakes and increasing community resilience against future hazards,

could not have been completed without the in-situ testing resources of NHERI@UTexas.

3.2 Continuous 2D/3D In-Situ Profiling for Anomaly Detection

A major scientific and engineering breakthrough would be the ability to rapidly and non-intrusively image the subsurface in 2D/3D for the purpose of site characterization and anomaly detection. In this context, anomalies refer to any abnormality/irregularity such as cavities/voids, soft/weak zones, dipping layers, buried objects, etc. Consider for example the levee systems in the U.S., which consist of approximately 160,000 km of earth embankments constructed to protect cities, urban areas, and farmlands from flooding. The reliability of this levee system is largely unknown under the demands of natural hazards such as flooding/hurricane inundation and earthquakes, and the cost to repair or rehabilitate these levees is currently estimated to be \$100 billion [8]. The ability to rapidly and reliably profile levee systems in order to search for weak zones would greatly increase the resiliency of civil infrastructure, while simultaneously reducing the cost to do so. The NHERI@UTexas equipment can be used to help solve this 2D/3D imaging problem.

The primary goal of full waveform inversion (FWI) is reconstruction of the near-surface material profile of arbitrarily heterogeneous formations, in terms of the formation's spatially distributed elastic properties, using



Fig. 7. True 2D/3D imaging via full waveform inversion (FWI) using a dense configuration of receiver and source locations [9]

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> elastic waves as the probing agent [9]. FWI is a challenging data-fitting procedure based on full-wavefield modeling to extract quantitative information from all wave types in the seismograms [10]. FWI recorded requires both a densely spaced grid of and multiple excitation sensors locations from a broadband seismic source (refer to Fig. 7), both of which are provided as part of the proposed essentially equipment, mimicking multiple-input, multiple-output (MIMO) modal testing of structures. Two prior NSF-funded projects utilized

NEES@UTexas equipment for FWI research: (1) CAREER: Towards Near-Real-Time Site Characterization: Advanced Computational Methods and NEES-Based Validation Experiments; PI Loukas Kallivokas; January 1, 2004; and (2) NEESR-SG: High-fidelity Site Characterization by Experimentation, Field Observation, and Inversion-based Modeling; PI Jacobo Bielak; October 1, 2006). While significant progress was made during these projects, the goal of developing a rapid, non-intrusive, robust way of imaging the subsurface in 2D/3D for the purpose of site characterization and anomaly detection remains to be realized. Furthermore, FWI has the potential to reveal in-situ material damping, which has heretofore been the "holy grail" of in-situ site characterization. Just as in medical imaging, the potential for transformative impacts on the design and rehabilitation of civil infrastructure is enormous if rapid, continuous, 2D/3D in-situ profiling for anomaly detection can be achieved.

3.3 Characterizing the nonlinear dynamic response in situ of complex geomaterials – cemented alluvium

Natural geotechnical materials, soil and rock, represent a significant fraction of all materials that impact the performance of any country's infrastructure during earthquakes and other natural hazards. As noted earlier, these materials nearly always play a critical role in the areal extent and severity of damage associated with earthquakes. The role of geotechnical materials in hurricanes and floods is also important, and generally represented by a combination of compacted soils that form levees, dams or dikes over the underlying natural materials. A significant challenge to making our infrastructure resilient and sustainable is characterizing the nonlinear dynamic response of complex geomaterials in situ.

Nonlinear dynamic soil properties are required for predicting the response of geotechnical and structural systems to earthquake shaking. Specifically, the nonlinear dynamic soil properties required in these analyses are: (1) the variation of shear modulus (G) with shear strain (γ) and (2) the variation of material damping ratio in shear (D_s) with shear strain (γ). These relationships are typically expressed as G-log γ and D_s-log γ since the shear strains induced by large earthquakes can easily range over a factor of 1000 (from below 0.001% to above 1.0%). Presently, these dynamic soil properties are never measured in the field because of the challenges associated with generating a systematic, wide range of strains in situ. Therefore, the G-log γ relationships are normally estimated by combining large-strain nonlinear measurements from small-scale dynamic laboratory testing of intact or reconstituted soil specimens with limited, low-strain, field seismic testing used to evaluate the in-situ V_s profiles from which G_{max} values are calculated. Over the past few years, the NEES@UTexas mobile shakers have been used to develop a generalized staged-testing approach by which G-log γ relationships can be determined in situ. This type of staged, in-situ parametric testing is needed because many geotechnical materials cannot be readily, or cost-effectively, tested in the laboratory. These materials include: gravelly soils, cemented alluvium, loose sandy soils with nonplastic fines, municipal solid waste, and loose gravelly, sandy and silty soils prone to liquefaction. The generalized staged-testing approach involves creating an array of the appropriate sensors in the target material and shaking this material with some type of "loading platen". At this time, the loading platen at the ground surface has been either a concrete footing or the base plate of the mobile shaker (T-Rex), as illustrated in



Fig. 8. Field arrangements for staged testing with increasing dynamic load levels to evaluate nonlinear shear moduli

Fig. 8a [11], while a reinforced-concrete, drilled shaft with a diameter of about 0.3m has been used to excite deeper material, as illustrated in Fig. 8b [12].

One example illustrating in-situ staged dynamic testing of difficult-to-sample material is presented in Fig. 9. These tests were conducted to aid in the seismic design of the once-proposed Yucca Mountain nuclear waste repository. The material is cemented alluvium which has never before been tested in situ to evaluate G-log γ relationships. A 0.9-m diameter footing at the ground surface was the loading platen for shear (S) wave excitation using Thumper and then T-Rex as the source. The embedded array of sensors is composed of 3D velocity

transducers (geophones) located beneath the footing in a configuration shown schematically in Fig. 8a. The geophones were grouted in shallow, pre-drilled holes [11]. The results, in terms of G-log γ , are presented in Fig. 9b. These results represent the first time G-log γ data was measured in such a material under controlled in-situ conditions. The in-situ test results indicated the cemented alluvium was approximately 3 times stiffer than would have been anticipated using traditional laboratory-based methods. These finding are very significant and are only made possible because of the large, mobile hydraulic shakers. Other examples of this type of nonlinear testing include measurements in municipal solid waste [13].



Fig. 9. Staged loading tests of cemented alluvium at Yucca Mountain, NV [11]

3.4 Developing rapid, in-situ methods for non-destructive structural evaluation and soil-foundation-structure interaction (SFSI) studies.

The mobile field testing equipment of NHERI@UTexas can also be used to help answer critical structural engineering research questions, under realistic conditions, that have not been addressed previously. The vast majority of structural engineering experimental research comprises quasi-static, pseudo-dynamic, or shake table testing of structural specimens that have idealized boundary conditions (e.g., fixed foundation and/or assumed stationary inflection points at actuator loading locations). While these types of tests are ideal for characterizing performance of structural components under lateral loading, they neglect the complex soil-foundation-structure



interaction (SFSI) that can critically impact performance of complete civil infrastructure systems. Experimental research that addresses SFSI often involves small-scale structural models (with model-to-prototype scales on the order of 1:30 to 1:100) in containers of perfectly uniform soil excited on a shake table or in a centrifuge. These small-scale specimens are not representative of actual construction methods or structural materials and only consider a limited range of "perfect" soil conditions. While scaled and idealized laboratory experimental research programs provide important findings for understanding structural behavior, the next frontier of natural hazards research requires that engineers and researchers translate laboratory simplifications into practical applications for complex structure-foundation-soil systems, requiring in-situ testing and validation of realistic civil infrastructure systems in a range of soil conditions that can only be provided by the mobile NHERI@UTexas equipment.



(a) Indirect and direct shaking of SFSI specimen constructed in the field

(b) Remove shakers to test structures inaccessible to trucks

(c) Quasi-static field tests using winches on T-Rex and Liquidator

Fig. 10. Examples of structural testing versatility with the mobile shakers

The NSF-funded project entitled "Collaborative Research: Demonstration of NEES for Studying Soil-Foundation-Structure Interaction" (CMMI-0324326, PI: S. Wood,), which used the NEES@UTexas equipment, is a perfect example of the range of methods in which the mobile shakers can be used to study SFSI. In this study, two ¹/₄-scale bridge bents were constructed in an open field. The shakers were used to excite the structures both indirectly, through the soil with T-Rex, and directly with Thumper by removing one of the shakers from the mobile platforms and attaching it directly to the bents (see Fig. 10a). The shakers, which are typically attached to the mobile platforms, are designed to be removable (as demonstrated schematically in Fig. 10b), such that they can be used to excite a structure from locations that may not be directly accessible to the truck. Hydraulic pumps, which are often an integral part of the mobile platform, can be connected to the remote shakers via hoses. Alternatively, the hydraulic pumps on the mobile platforms can be used to power hydraulic equipment other than the shakers (e.g., linear actuators), offering a versatile range of loading options in the field. Results from these tests included identification of resonant frequencies and mode shapes in the structure-foundation-soil system during elastic and inelastic response [15]. The trucks were also used to conduct a quasi-static cyclic test in the field. High-strength cables connected to winches on T-Rex and Liquidator were attached to the bridge bent to pull the specimen backand-forth, to deformations well beyond what can be generated by the shakers (shown schematically for singledirection loading in Fig. 10c). This quasi-static testing was used to determine the nonlinear hysteretic response of the bridge bent up to complete collapse (shown in Fig. 10c), including damage near the foundation-soil interface, which would not have been observed in traditional, idealized laboratory quasi-static testing. While this testing program was a successful demonstration of using the mobile shakers to better understand SFSI effects, further insitu field testing of complex systems is necessary to better address research needs related to structure-foundationsoil system behavior and in-situ structural dynamic evaluations.

4. Summary

The NEES@UTexas equipment site was established and operated with support from NSF through the NEES program from 2000 to 2014. Unique field equipment at NEES@UTexas was transferred to the NHERI@UTexas equipment facility when this facility was awarded support from NSF through the NHERI program on January 1st, 2016. Testing capabilities available at NHERI@UTexas include: five, large, hydraulically-controlled shakers, a tractor-trailer rig used to transport the four largest shakers, field-support vehicles, an extensive collection of field



instrumentation, and a wide range of numerous sensors that are used to measure vibrational motions and pore water pressures. A key aspect of NHERI@UTexas is that this facility functions as a shared-use facility, and all individuals with NSF-supported grants can utilize the NHERI@UTexas equipment facility in their research. Further, the facility is available for non-NSF funded projects with UT personnel during 25% of the operational time that is not funded by NSF. Examples of the uses of this unique equipment in the NEES program and in industrial research are given to illustrate the types of transformative research that can be accomplished.

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