Large Mobile Shakers for Natural Hazard Field Studies to Develop Resilient and Sustainable Infrastructure (Award CMMI-1520808, 2016-2020)

NHERI Experimental Facility, NHERI@UTexas

Principal Investigator:
Dr. Kenneth H. Stokoe, II, P.E., NAE

UT Austin, Dept. of Civil, Architectural, and Environmental Engineering (CAEE)

Co-Principal Investigators:
Dr. Brady R. Cox, P.E. and Dr. Patricia Clayton

UT Austin, CAEE

Stiffness-based Ground Improvement Monitoring Workshop

Co-hosted by Prof. Arash Khosravifar at Portland State University, and Prof. Ed Kavazanjian at the Center for Bio-mediated and Bio-inspired Geotechnics (CBBG) at Arizona State University

Portland, OR, September 11-12, 2019
NHERI@UTexas - Building 46

NEES@UTexas mobile shakers

50 ft by 200 ft parking area available for NHERI@UTexas

50 ft by 65 ft storage building of NHERI@UTexas

Ferguson Structural Engineering Laboratory

North
T-Rex (Tri-axial Shaker)
- Off-road buggy; weight = 64,000 lbs
- Three vibrational orientations
- Shear mode Peak Force = 30,000 lbs
- Vertical mode Peak Force = 60,000 lbs

Liquidator (Low Frequency Shaker)
- Off-road buggy; weight = 72,000 lbs
- Two vibrational orientations
- Shear mode Peak Force = 20,000 lbs
- Vertical mode Peak Force = 20,000 lbs

Thumper (Urban Shaker)
- International 4300 truck; weight = 24,800 lbs
- Three vibrational orientations
- Shear mode Peak Force = 6,000 lbs
- Vertical mode Peak Force = 6,000 lbs

Raptor (Mid-Size Shaker)
- Highway legal truck; weight = 41,200 lbs
- Vertical mode Peak Force = 27,000 lbs

Rattler (Horizontal Shaker)
- Off-road truck; weight = 54,500 lbs
- Shear mode Peak Force = 30,000 lbs

Big-Rig
- 26 wheeler tractor-trailer rig for shipping T-Rex, Liquidator, and Rattler

Field-Support Truck
- Carries diesel fuel for T-Rex and Liquidator
- Acts as a working platform for maintenance

Instrumentation Van & Trailer
- Cargo van with air-conditioned workspace
- Trailer with added work and storage spaces

Hydraulic Cylinder with Adjustable Platform
- Platform mounted at the rear of T-Rex
- Pushing and retrieving subsurface sensors
Instrumentation – Data Acquisition (DAQ)

72-channel VXI DAQ
- 24 bit digitizer
- Up to 50 kHz sampling rate
- Real-time frequency domain capabilities

136 channels of DAQ

64-channel Data Physics DAQ
- 24 bit digitizer
- Up to 200 kHz sampling rate
- Real-time frequency domain capabilities
Instrumentation – Sensors

109, 1-Hz Geophones
- 85 vertical & 24 horizontal
- 15,000 ft of cable

10, Nanometrics Broadband Seismometer Stations
- 3-component, GPS synchronized
- 120-sec period Trillium Compact seismometers
- Flat response 0.01 to 100 Hz
- Taurus digitizers (24 bits)
- Structural and Geotechnical applications
Instrumentation – CPT and Liquefaction Sensors

Cone Penetrometers
- Standard CPT
- Seismic CPT
- 4 different cones

Motion Sensors
- Tri-axial MEMS accelerometers
- 2D or 3D geophones

Liquefaction Sensors
- Custom built
- Pore water pressure transducers

Direct-Push Sensors

Adjustable platform for the CPT hydraulic cylinder
Additional Instrumentation Resources

- **IRIS/PASSCAL**

Free to NSF-funded projects
*PI pays for shipping & travel expenses*

- (35) 3D accelerometers
- Digitizers
- Field support
- and more...
Proof-of-Capability Workshops

• Each test aligned with one of three main areas in our Science Plan:

  (1) Subsurface Imaging (2D/3D)
   (St. Louis, MO; November 11, 2016)

  (2) In-situ Liquefaction/Nonlinear Testing
   (Portland, OR; June 24, 2016)

  (3) Structural Health Monitoring/SFSI
   (Brunswick, NJ; August 3-4, 2017)
Proof-of-Capability Workshops cont...

• Marketing to broaden the user base
  – Familiarize potential users with NHERI@UTexas capabilities
  – Invite all interested parties (Gov/Academia/Industry)
  – Data and metadata posted to NHERI DesignSafe-CI (open access)
  – Generate preliminary proposal data
  – Opportunities for piggy-back projects

Thumper at levee testing workshop

Liquefaction testing workshop
Example Field Studies of the Natural and Built Environments Using Large Mobile Shakers

Eight projects illustrating the use of the unique resources of NHERI@UTexas that include:

(a) shallow to very-deep noninvasive surface wave testing,
(b) deep downhole testing,
(c) parametric studies of linear and nonlinear shear stiffnesses,
(d) liquefaction testing, and
(e) dynamic and cyclic structural testing.
1. Shallow, Noninvasive, Active-Source, Surface-Wave (SASW) Testing of a Dam Spillway on Rock

Key Parameters:
1. Frequency range: 500 to 5 Hz
2. Frequency range varies with receiver spacing:
   - shorter = 7.25 m: 500 to 5 Hz
   - longer = 22.5 m: 350 to 5 Hz
3. Approx. 100 frequency steps in each sweep.
Examples of SASW Testing in the Dam Spillway Area

(a) Multiple source-receiver position; Common-middle-receiver-geometry

(b) Shorter source-receiver positions

(c) Longer source-receiver positions
Locations of 22 SASW Testing Arrays; Profiling Depths from 2 to 25 m
Example SASW Testing Results at One Location in the Dam Spillway Area
Example Measurements and Resulting $V_S$ Profile

(b) Composite dispersion curve using sledge hammer and Thumper as sources

(b) Forward Modeling to fit the experimental dispersion curve with a global theoretical dispersion curve

(c) $V_S$ profile determined from forward modeling
2. Deep (> 300 m) $V_S$ Profiling on Top of Yucca Mountain, NV, using Liquidator as the Active, Low-Frequency Source

(a) Map of Nevada

(b) Liquidator shaking on Yucca Mountain

(c) Generating surface waves up to 900 m long
SASW Testing in the Exploration Site Facility (ESF) Tunnel in Yucca Mountain

(a) SASW testing locations at Yucca Mountain

(b) SASW testing within the tunnel

(c) Complexity in the rock structure
Comparison of Two Groups of $V_S$ Profiles Determined in Two Different Areas at the Yucca Mountain Site (with comparisons of $V_S$ measured in the tunnels)

(a) Nine “Softer Sites in Group 1

(b) Eight “Stiffer” Sites in Group 2
3. Very-Deep (> 500 m) $V_s$ Profiling at a Greenfield Site in Georgia, USA, using Liquidator as the Low-Frequency Source

Site map showing the 5 SASW arrays
Initial SASW Profiling with Liquidator in the Normal Operating Mode at the Greenfield Site

(a) Normal operating mode

(b) Typical profiling depth
Special Low-Frequency Operating Mode with Liquidator at the Greenfield Site

(a) Liquidator shaking in the modified mode where the 25-kg body of Liquidator moves up and down

(b) Extended low-frequency shaking range
Active-Source, Very-Deep $V_S$ Profiling

(a) Normal operating mode and typical profiling depth

$\lambda_{\text{max}} + \frac{N_F}{4} = 910 \text{ m}$

$\lambda_{\text{max}} / 2 = 610 \text{ m}$

$V_S$ estimated from near-field data at SASW#3

(b) Improved profiling depth

$\lambda_{\text{max}} + \frac{N_F}{4} = 910 \text{ m}$
4. Very-Deep (> 500 m) Profiling using Combined Active-Source and Passive-Source, Surface-Wave Methods
Reliable 1-D $V_S$ Profiles to Record Depths

**Inversion Process**

- Analysis took weeks for each site
- Millions of models searched via Monte-Carlo/Neighborhood algorithms
- Hours of computer time followed by user scrutiny, model adjustment, repeat inversion

![Graph showing shear wave velocity (m/s) vs depth (m) with sigma[ln(Vs)] and uncertainty quantified.](Image)
5. Deep Downhole Seismic Testing using T-Rex as an Active Source to Generate Controlled-Waveform P and S Waves

(a) Generalized field arrangement using T-Rex

(b) Example sinusoidal P waveforms at 158 m

(c) Example sinusoidal P waveforms at 293 m
Example Analysis of P Waveforms, Resulting $V_S$ and $V_P$ Profiles and Geologic Profile

(a) Filtered P waveforms and reference travel-time “picks”, Brts, on each depth axis

(b) Composite $V_S$ and $V_P$ Profiles

(c) Geologic Profile
6. Parametric Field Studies of Linear and Nonlinear Stiffnesses

(a) Surface footing or shaker base plate as the loading platen (Park, 2010)

(b) Drilled shaft as the loading platen (Kurtulus and Stokoe, 2007)
Test Pit in Cemented Alluvium
Linear and Nonlinear Steady-State Dynamic Tests: Yucca Mountain

(a) Small-to-moderate shaking with Thumper

(b) Moderate-to-large shaking with T-Rex
Static Load Level: ~1814 Kg
(Average in-situ vertical stress is estimated as ~0.3 MPa)

Excitation Frequency: 130 Hz

Shear Modulus, G/\max\quad \text{MPa}

Lab

Field

-3
-2
-1
0
10
10
10
10

1.0
0.8
0.6
0.4
0.2
0.0 Normalized Shear Modulus, G/G_{max}

Experiments

G/\max

Field

Uncemented Gravel
(Menq, 2003)
(C_u = 50, \sigma_v = 0.3 MPa, K_O = 0.5)

Laboratory

(uncemented)

Field

Approx. 3 times

Steady-State Testing Using Thumper

-3
-2
-1
0
10
10
10
10

Shearing Strain, \%
7. In-Situ Liquefaction Testing Using T-Rex as the Controlled Source to Shake an Embedded Array of Sensors
Staged Testing: 24-hr Process of Sensor Installation and Staged Loading with T-Rex at the Natural Soil Test Panel

(a) Install Sensors, Vertical Static Loading, and Demobilization

(b) Staged, Horizontal Shaking with T-Rex
Liquefaction Testing of a Natural Soil Test Panel in Christchurch, NZ; pore pressure ratio, $r_u$, versus time and shear strain, $\gamma$, versus time for 100 cycles in Stage 5 loading.

Notes: $r_u = u_{\text{excess}}/\sigma_v'$; CSR = $\tau/\sigma_v'$; $G = \tau/\gamma \rightarrow \tau = G(\gamma)$
Example $r_u$ - Log $\gamma$ Relationship Estimated for Loose Sand and New Approach to Increasing Maximum Strain

Extrapolation based on the Dobry et al., 1982 $r_u$ – log $\gamma$ model

Data from previous slide

N = 30 Cycles

(a) Measured and extrapolated $r_u$ -log $\gamma$ relationship

(b) New approach using two shakers to increase the largest strain levels
8. Investigating the Dynamic and Slow-Cyclic Responses of Scaled-Structural Systems in the Field

(a) Sinusoidal excitation of Bridge Bent #2 created by attaching the shaker from Thumper

(b) Slow pull-over testing of Bridge Bent #1 using T-Rex and Liquidator

Bridge Bent #2 after shaking

Bridge Bent #1 during pull-over test
Most Recent Dynamic Loading of a Full-Scale Bridge in the Field Using T-Rex

Preparing to dynamically load a two-span bridge over Interstate Highway I-195 in Trenton, NJ. Bridge deck was loaded longitudinally and laterally and the motions were large and easily seen. Shared-use project was performed for Professors Nenad Gucunski, Franke Moon, and John DeVitis from Rutgers University.
A new era in field testing, primarily in the geotechnical environment, is now possible with the large mobile shakers of NHERI@UTexas. This type of testing is also available to most researchers around the world because of the shared-use policy of the U.S. National Science Foundation.

The large mobile shakers can be used to apply all types of controlled dynamic loads on the ground surface, to systems embedded in the ground, and to the above-ground portion of structures with ground-supported foundations.

Hopefully the range in these examples will stimulate new ideas in you and other colleagues. We hope to have the opportunity to assist you in developing an improved understanding and new knowledge of the natural and built environments.
Additional Information

- Dr. Kenneth Stokoe (PI) k.stokoe@mail.utexas.edu
- Dr. Brady Cox (co-PI) brcox@utexas.edu
- Dr. Patricia Clayton (co-PI) clayton@utexas.edu
- Dr. Farnyuh Menq (Operations Manager) fymenq@utexas.edu

- NHERI@UTexas website at www.designsafe-ci.org for Webinar slides & budgetary information are posted
Special Thank you!

• National Science Foundation for the financial support to develop and operate the NHERI@UTexas Equipment under grants CMS-0086605, CMS-0402490, and CMMI-1520808.

• Yumei Wang, Oregon Department of Geology and Mineral Industries.
Example of Estimated Costs Associated with Using the NHERI@UTexas Equipment Facility on NSF-Funded Research Projects

| Step 1: Estimated total time needed for the testing | Estimated time required for testing | 30 hours | include shaking + relocating shaker |
|                                                  | Realistic estimation of required time | 60 hours  | * 2 for Try out * mistakes * DAO malfunction + others |
|                                                  | Total days of testing                | 10 days   | 6 hours of vibration each day |
|                                                  | Travel                               | 4 days    | 4 travel days to and from Austin + 4 * 0.5 days for |
|                                                  | week ends                            | 2 days    | UT personnel is required to take one day off |
|                                                  | Days in the field                    | 16 days   | |

<table>
<thead>
<tr>
<th>Step 2: Estimated equipment costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-Rex</td>
</tr>
<tr>
<td>Tractor-Trailer</td>
</tr>
<tr>
<td>Fuel-Supply Pickup Truck</td>
</tr>
<tr>
<td>Tracked</td>
</tr>
<tr>
<td>Recording equipment</td>
</tr>
<tr>
<td>Instrumentation Trailer</td>
</tr>
<tr>
<td>Total equipment cost</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 3: Estimated travel cost</th>
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</thead>
<tbody>
<tr>
<td>Total Travel</td>
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</table>

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<tr>
<th>Step 4: Estimated other cost</th>
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</thead>
<tbody>
<tr>
<td>Material and supply</td>
</tr>
<tr>
<td>Mobile phone service in the field</td>
</tr>
<tr>
<td>Site liability insurance**</td>
</tr>
<tr>
<td>Total Others</td>
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</tbody>
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<thead>
<tr>
<th>Step 5: Estimated total cost</th>
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</thead>
<tbody>
<tr>
<td>Total direct cost</td>
</tr>
<tr>
<td>Indirect cost (55% overhead)</td>
</tr>
<tr>
<td>Total Cost</td>
</tr>
</tbody>
</table>

Budget worksheet posted on DesignSafe-CI

NSF user pays only for fuel for truck(s), truck shipment, and personnel travel

$22,134 (for this example)
Example of Estimated Costs Associated with Using the NHERI@UTexas Equipment Facility on non-NSF-Funded Research Projects

<table>
<thead>
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<th>Step 1: Estimated total time needed for the testing</th>
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<tr>
<td>Estimated time required for testing: 30 hours include shaking + relocating shaker</td>
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<tr>
<td>Realistic estimation of required time: 60 hours, *2 for Try out mistakes + DAQ malfunction + others</td>
</tr>
<tr>
<td>Total days of testing: 10 days 6 hours of vibration each day</td>
</tr>
<tr>
<td>Travel: 4 days 4 travel days to and from Austin + 4 * 0.5 days from site</td>
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<tr>
<td>Weekends: 2 days UT personnel is required to take one day off for every 2 days of work</td>
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<tr>
<td>Days in the field: 16 days</td>
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<tr>
<th>Step 2: Estimated equipment costs</th>
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<tbody>
<tr>
<td>Equipment</td>
</tr>
<tr>
<td>T-Rex</td>
</tr>
<tr>
<td>Vibrator (Big Rig)</td>
</tr>
<tr>
<td>Fuel-Supply Pickup Truck</td>
</tr>
<tr>
<td>Recording equipment</td>
</tr>
<tr>
<td>Instrumentation trailer</td>
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<table>
<thead>
<tr>
<th>Total Equipment</th>
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<tbody>
<tr>
<td>$144,834</td>
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<th>Step 3: Estimated travel costs</th>
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<td>Material and supply</td>
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<td>Mobile phone service in the field</td>
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<tr>
<td>Site liability insurance</td>
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<table>
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<tr>
<th>Total Others</th>
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<tbody>
<tr>
<td>$3,600</td>
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<table>
<thead>
<tr>
<th>Step 4: Estimated other costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 technicians</td>
</tr>
<tr>
<td>1 engineer</td>
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<table>
<thead>
<tr>
<th>Total Personnel</th>
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<tbody>
<tr>
<td>$58,370</td>
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<table>
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<tr>
<th>Step 6: Estimated total cost</th>
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</thead>
<tbody>
<tr>
<td>Total direct cost</td>
</tr>
<tr>
<td>Indirect cost (55% overhead)</td>
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Non-NSF user pays for truck fuel and shipment, personnel travel & overtime + equipment usage fees

$144,834 (6.5x more for this example)