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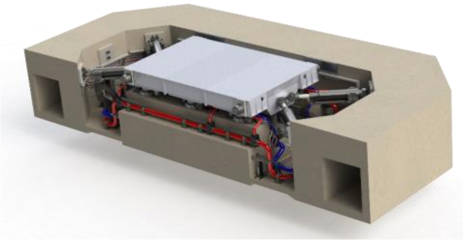
# *Geotechnical Earthquake Engineering: List of Open Issues, Scope of Problems, and Example Uses of Facilities to Address Scientific Needs*


***John S. McCartney, UC San Diego***

***NHERI@UC San Diego User Training Workshop***

***December 15-16, 2022***
***University of California, San Diego***

# Presentation Overview

- Role of large-scale shake table testing in geotechnical earthquake engineering
  - Motivation
  - Need for Scaling
- Geotechnical testing with LHPOST6 at NHERI@UC San Diego
  - Available geotechnical containers (soil boxes)
  - Soil management plans
  - Other geotechnical testing resources at UC San Diego
- Examples of past geotechnical projects at NHERI@UC San Diego
- Open issues and future research challenges that can be evaluated using LHPOST6

## *Role of large-scale shake table testing in geotechnical earthquake engineering*

# Motivation

- Large-scale shake-table tests used in combination with large soil boxes and reasonably sized foundation and structural models are needed to complement centrifuge tests to validate computational models of soil-foundation-structure systems
- Large-scale shake table tests can be used to study the full-scale performance of near-surface embedded structures (such as energy vaults, pipelines, and shallow tunnels), as well as bridge abutments, earth retaining walls, levees, embankments, and stability of cut and fill slopes in hillside construction
- LHPOST6 is particularly suitable for studying phenomena that cannot be considered at laboratory- or centrifuge-scales, including liquefaction of gravels, efficacy of conventional or bio-mediated soil improvement, behavior of materials with large particle sizes like tire derived aggregate (TDA), and liquefaction-induced lateral spread
- LHPOST6 tests can help study soil-structure interaction problems as well as studying the effects of seismic deformations of saturated and unsaturated soils on shallow and deep foundations
- Testing on LHPOST6 can support the testing of underground pipelines or utilities subject to liquefaction loads, lateral soil spreading, or fault crossing demands

# *Role of 6DOF Capabilities of LHPOST6 in Geotechnical Problems*

- The 6-DOF capabilities of the LHPOST6 provide new opportunities for studying geotechnical applications under realistic 3-D ground motions
- As the stiffness and shear strength of soils depend on self-weight, vertical accelerations may lead to changes in soil properties during earthquake shaking, the effects of which are poorly understood in 2-D or 3-D site analyses
- At some sites, the vertical component of an earthquake motion may exceed the horizontal at short periods
- Element-scale studies have shown that deformations during 2-D horizontal shaking are underestimated when using methods based on unidirectional shaking
- One of the few studies on 1-g shake table tests on small samples of sand under 3-D motions was performed by Pyke et al. [1975]
  - Shaking in the vertical direction alone with acceleration amplitudes of less than about 1g did not notably affect the volumetric contraction of soils
  - Combined vertical-horizontal shaking led to greater settlements than those from horizontal shaking alone

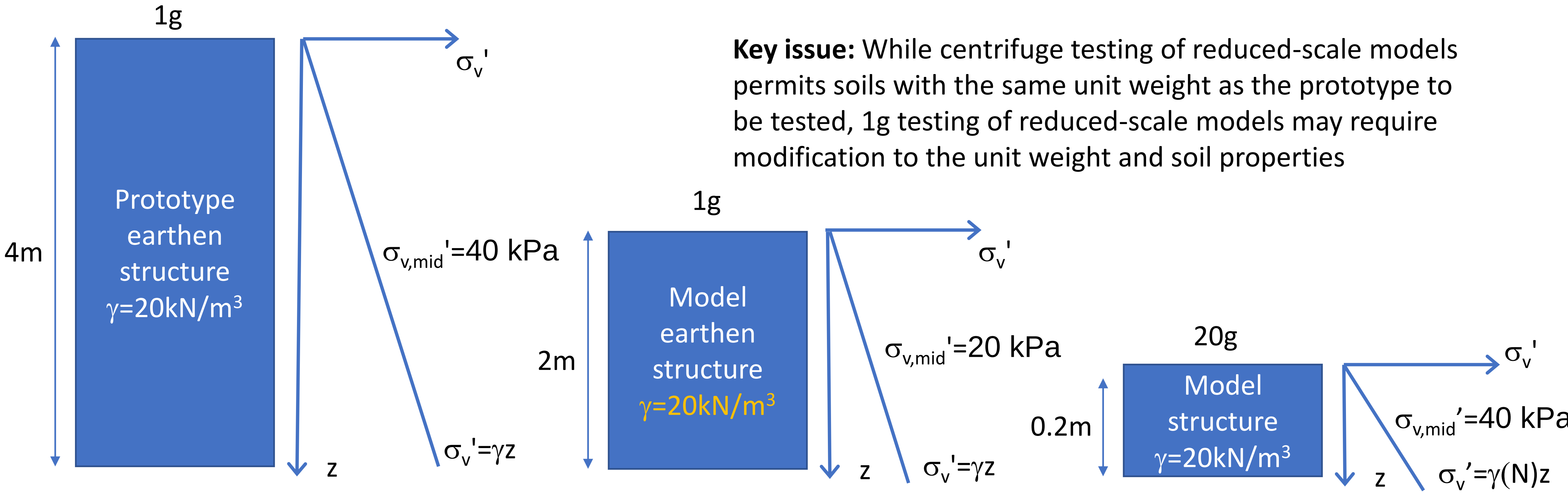
# *Centrifuge vs. 1g Testing*

- Seismic testing of geostructures in the ***centrifuge*** permits construction of multiple specimens with different configurations to understand the impacts of different geometric variables or design features
- Centrifuge testing often uses transparent soil boxes or even transparent soils to visualize soil-structure interaction mechanisms, which may not be as straightforward to implement on the LHPOST6
- Testing of geostructures in the ***large soil boxes on the LHPOST6*** permits use of actual geotechnical construction procedures for compacting soils, consideration of foundation installation effects, consideration of actual ground improvement techniques, and use of actual geosynthetic reinforcements
- Large-scale testing permits incorporation of large instrumentation like earth pressure cells, dieletric sensors, and settlement plates
- Use of the large soil boxes available at the LHPOST6 may also help minimize near-field and boundary effects encountered when applying in-situ shear wave velocity tomography techniques that may be encountered in centrifuge-scale experiments
- There are opportunities for collaboration with the NHERI@UC Davis EF or other centrifuge facilities
  - Different types of data may be obtained from centrifuge and 1-g shake table testing that may complement each other and creating natural avenues for collaboration
  - Use of the modeling of models for validation of scaling relationships
  - Perform multiple simplified parametric-study type experiments in the centrifuge, then consider the effects of full-scale construction features like those permitted in LHPOST6

# Importance of Scaling in Shake Table Testing

- Soil dynamic properties are controlled by the stress-state dependent effective stress
- When a full-scale geotechnical system or when a phenomenon (liquefaction, seismic compression, etc.) is tested on the shake table, no scaling is required
- However, when testing a model at 1g with a geometry that is N times smaller than a prototype, the self-weight is still proportional to the height of the soil layer

**Key issue:** While centrifuge testing of reduced-scale models permits soils with the same unit weight as the prototype to be tested, 1g testing of reduced-scale models may require modification to the unit weight and soil properties



- Numerical simulations are often used to extrapolate measurements from reduced-scale tests to large scale tests, but the use of similitude relationships is preferred to convert model scale measurements to prototype scale

<u>Basis of scaling in the centrifuge</u>:

Let $\sigma^* = \sigma_m / \sigma_p = 1$ (soil properties depend on σ')

Let $L^* = L_m/L_p = 1/N$ (definition of scale factor, N)

Let $\rho^* = \rho_m / \rho_p = 1$ (same materials)

And because $[\sigma] = [\rho][g][L]$ [x] = units of x

$\sigma^* = \rho^* g^* L^*$

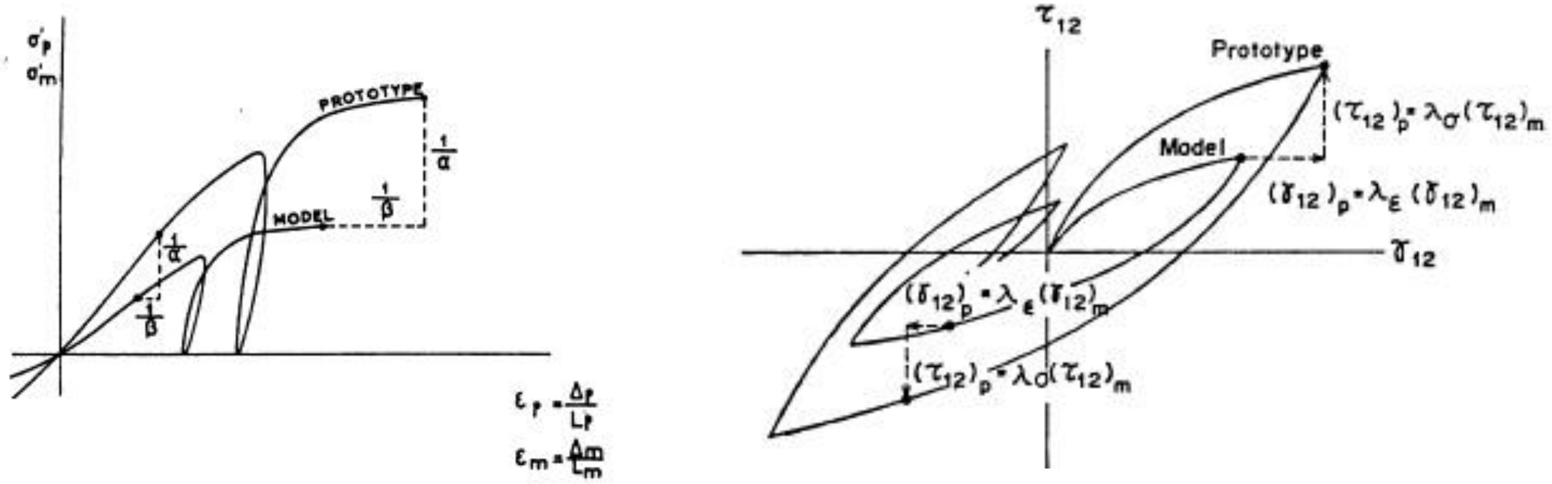
$1 = (1)(g^*)(L^*) \rightarrow g^* = 1/L^* = N$

$\sigma' = 1$ is important because strength, stiffness, dilatancy, and void ratio of soil have nonlinear dependence on effective stress. Modeling similarity is enhanced by stress similarity

| Parameter | Model/Prototype |
|---|---|
| Pressure, stress | 1 |
| Density | 1 |
| Length | 1/N |
| Gravity | N |
| Time (diffusion) | $1/N^2$ |
| Time (dynamics) | 1/N |
| Force | $1/N^2$ |
| Velocity | 1 |
| Frequency | N |
| Acceleration | N |
| Stiffness | 1/N |

(Kutter, 1995, Recent Advances in Centrifuge Modeling of Seismic Shaking )

- Shear strength and stiffness of soils depend on the effective stress
  - Shear strength is typically linearly related to the effective stress
  - Stiffness is nonlinearly related to the effective stress
- The stress-strain curve may change as a function of effective stress (peak values may not occur at the same strain)
- Scaling relationships are thus required to design a reduced scale model so that results can be extrapolated from model to prototype




Monotonic and cyclic stress-strain relationships for model and prototype
(Rocha 1957; Roscoe 1968)

# Scaling for 1g Shake Table Testing

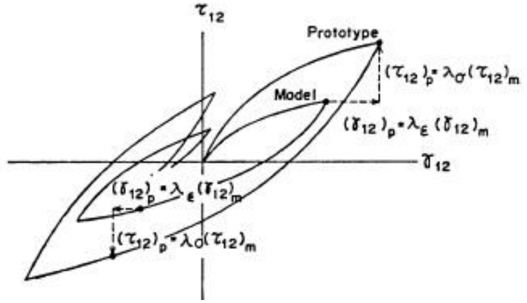
- Appropriate similitude relationships are needed for the design of reduced-scale model so that experimental results from reduced scale 1g shaking table tests can be extrapolated to full-scale conditions
- Most widely used set of 1g similitude relationships - Iai (1989)
- Basis: equilibrium and mass balance of soil, structures, and pore water
  - Assumption: scaled stress-strain relationships for soil are independent of confining stress if appropriate scaling factors are selected
  - Three independent scaling factors:
    - Geometry scaling factor $\lambda$ – most important for reduced scale model design
    - Density scaling factor $\lambda_r$ – typically assumed to be 1 for the same soil
    - Strain scaling factor $\lambda_e$ – can be determined using shear wave velocity measurements, typically assumed to be 1
  - Applicability: applicable to deformation analysis prior to failure, not applicable to the ultimate state of stability due to large deformations or loss of soil contact

# Scaling for 1g Shake Table Testing

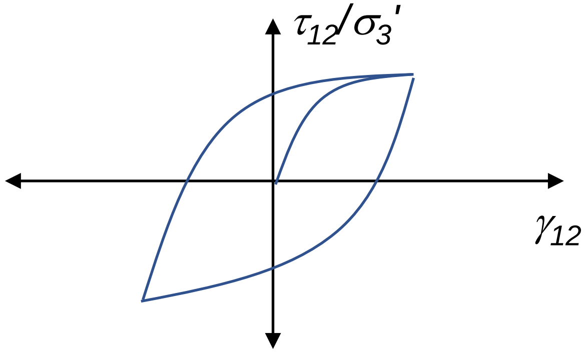
- 1g similitude relationships from Iai (1989)

| Variable | Scaling factor | $\lambda_\rho = 1$ $\lambda_\varepsilon = 1$ | $\lambda = 2$ |
|---|---|---|---|
| Length | $\lambda$ | $\lambda$ | 2 |
| Density | $\lambda_\rho$ | 1 | 1 |
| Strain | $\lambda_\varepsilon$ | 1 | 1 |
| Mass | $\lambda^3\lambda_\rho$ | $\lambda^3$ | 8 |
| Acceleration | 1 | 1 | 1 |
| Velocity | $(\lambda\lambda_\varepsilon)^{1/2}$ | $\lambda^{1/2}$ | 1.414 |
| Stress | $\lambda\lambda_\rho$ | $\lambda$ | 2 |
| Modulus | $\lambda\lambda_\rho/\lambda_\varepsilon$ | $\lambda$ | 2 |
| Stiffness | $\lambda^2\lambda_\rho/\lambda_\varepsilon$ | $\lambda^2$ | 4 |
| Force | $\lambda^3\lambda_\rho$ | $\lambda^3$ | 8 |
| Time | $(\lambda\lambda_\varepsilon)^{1/2}$ | $\lambda^{1/2}$ | 1.414 |
| Frequency | $(\lambda\lambda_\varepsilon)^{-1/2}$ | $\lambda^{-1/2}$ | 0.707 |

**Goal**: Choose soil conditions to have a similar normalized stress-strain response in model and prototype for $\lambda_\varepsilon = 1$




Original stress-strain relationships for soil in the model and prototype (Rocha 1957)

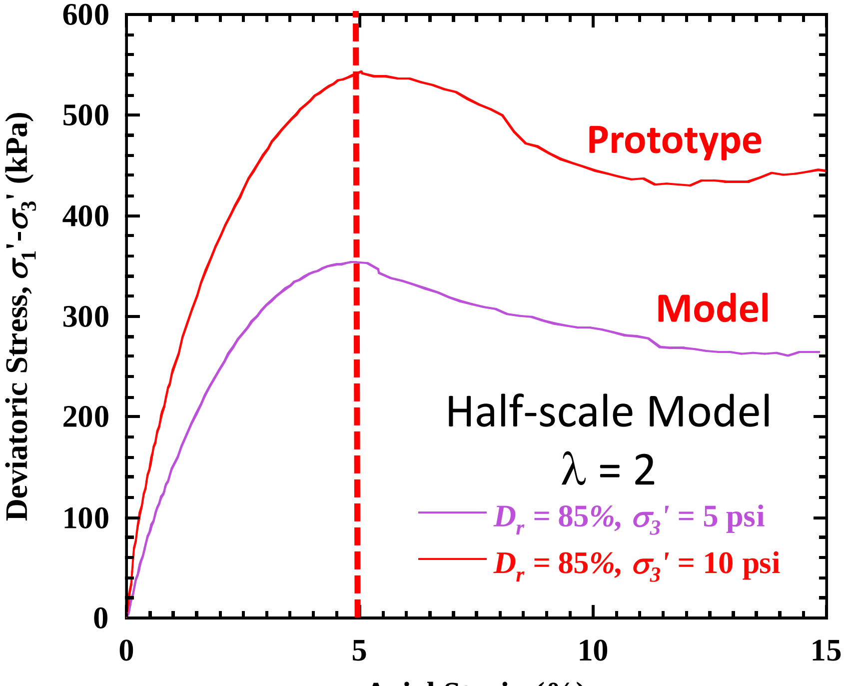



Normalized stress-strain relationships for soil in the model and prototype for $\lambda_\varepsilon=1$

# Scaling Example

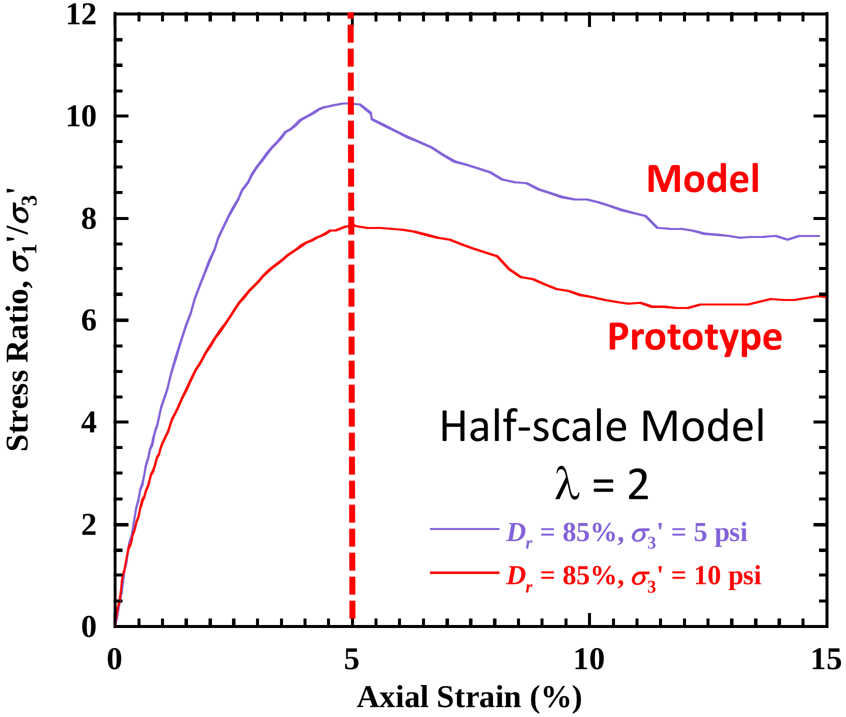
- Zheng et al. (2017): ½ Scale Testing of MSE Bridge Abutments
- Relative density ($D_r$) for prototype structures = 85% (RC = 96%)

**Peak stresses occur at approximately same axial strain (5%), which indicates that the assumption of $\lambda_\varepsilon = 1$ is valid**



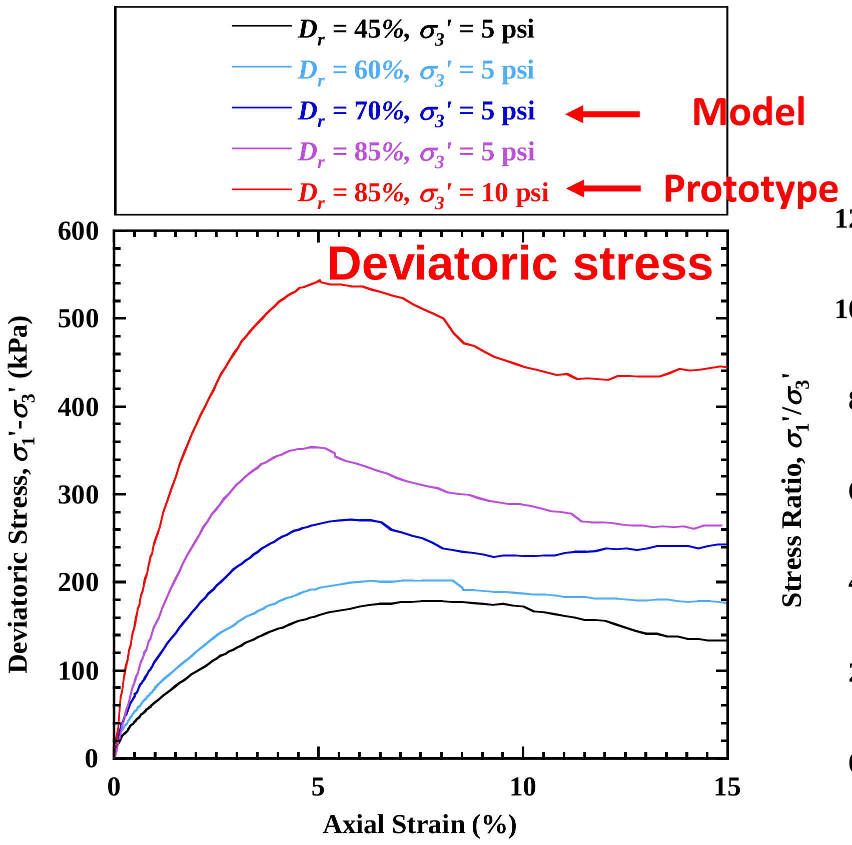

**Deviator stress**

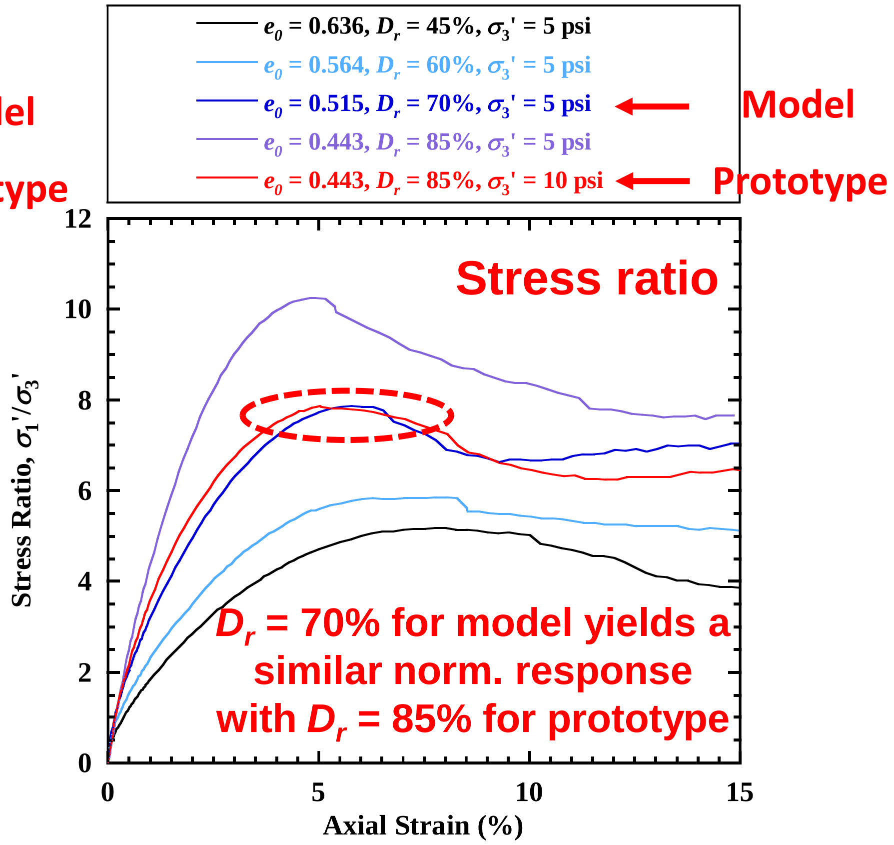
**However, due to the nonlinear effects of confining stress on shear strength and stiffness, the normalized curves are not similar for model and prototype for same $D_r$**




**Stress ratio**

- Typical relative density ($D_r$) for prototype structures = 85% (RC = 96%)
- Target relative density ($D_r$) for model specimens = **70%** (RC = 92%)



# Scaling Example

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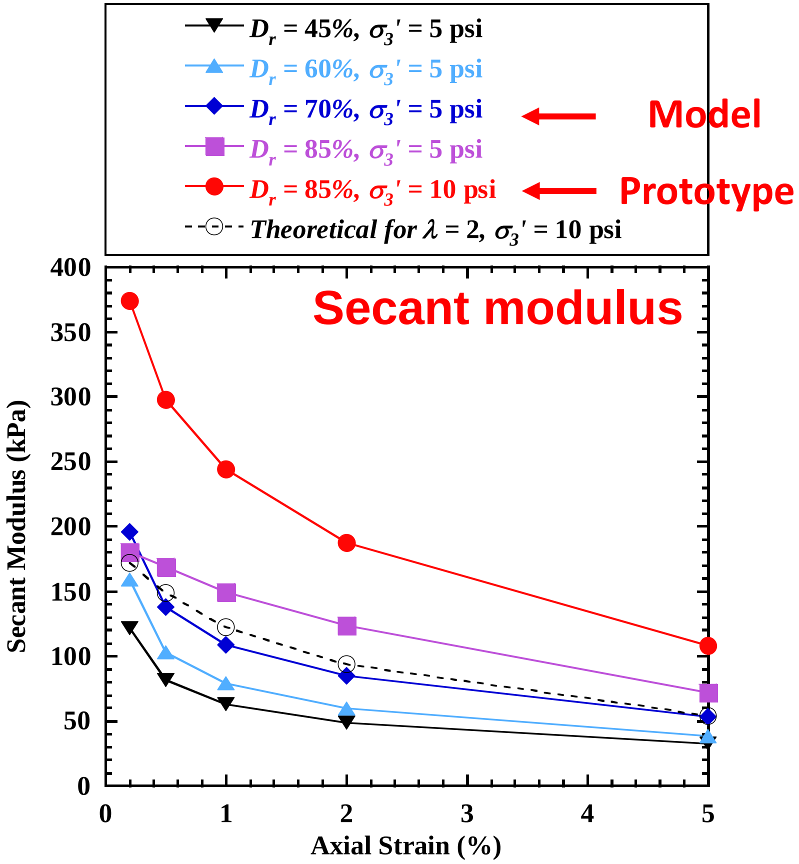



**Theoretically-scaled secant modulus as a function of strain is consistent with the target relative density**

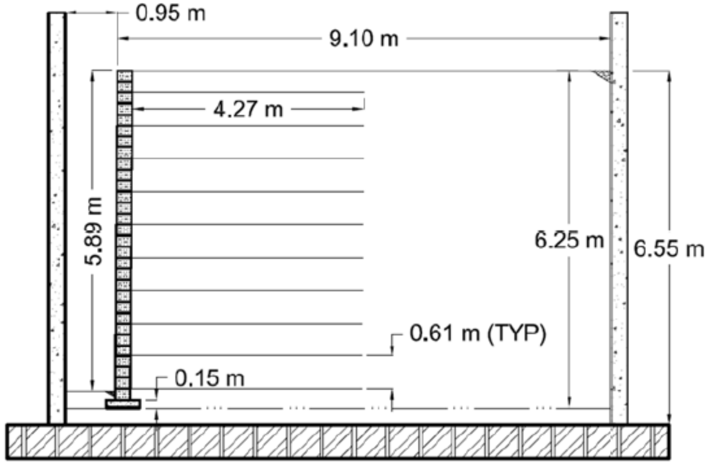
**Total unit weights for $w_c$ = 5% are close for both prototype and model relative densities for this soil:**
**$\gamma$ = 113 pcf for $D_r$ = 70%**
**$\gamma$ = 119 pcf for $D_r$ = 85%**
**So assumption of $\lambda_\rho$ = 1 is reasonable**

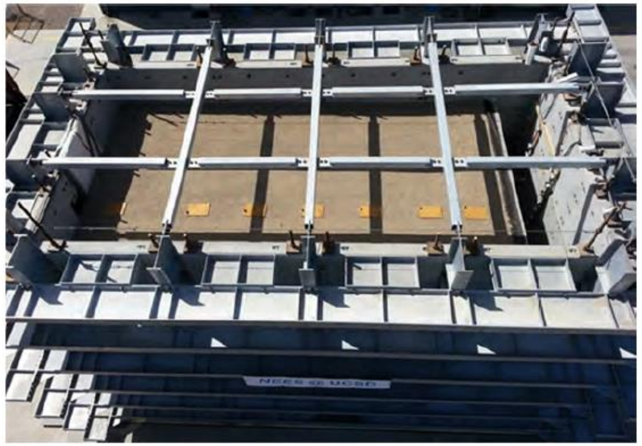
# *Geotechnical testing with LHPOST6 at NHERI@UC San Diego*

- Laminar Soil Box
  - Currently equipped to perform 1D horizontal shaking tests
  - Could be adapted with minor adjustments to accommodate vertical shaking, but must be refurbished to accommodate 2D horizontal shaking tests


**Length of 6.7 m (22 ft), width of 3 m (9.6 ft) and height of 4.7 m (15.2 ft)**

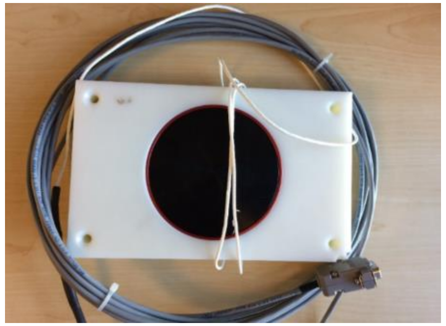
- Rigid soil box
  - Most appropriate for plane strain testing (MSE walls, cantilever retaining walls, embankments, strip footings, etc.)



- Wide range of sensors
  - Linear potentiometers, string potentiometers, earth pressure cells, accelerometers, settlement plates, tilt meters, temperature, etc.
  - Specialized sensors and measurements can be created by UCSD faculty (fiber optic, water content, resistivity, digital image correlation, etc.)

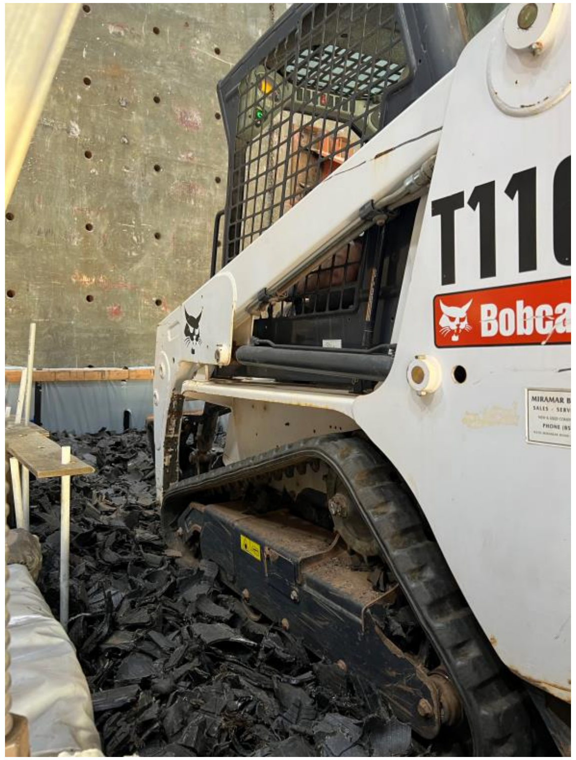


# Soil Management

- Soil boxes require a significant volume of soil
- Safe storage of soil is necessary to avoid contamination of the soil (so that it can be reused) and to protect the hydraulic actuators
- Bottom drop rigid hopper boxes are being explored, which can be carried with a forklift and stacked in a strategic location


- Construction equipment
  - Bobcat, front end loader, forklift, crane (available on recharge)
  - Vibratory compactor, whacker packer



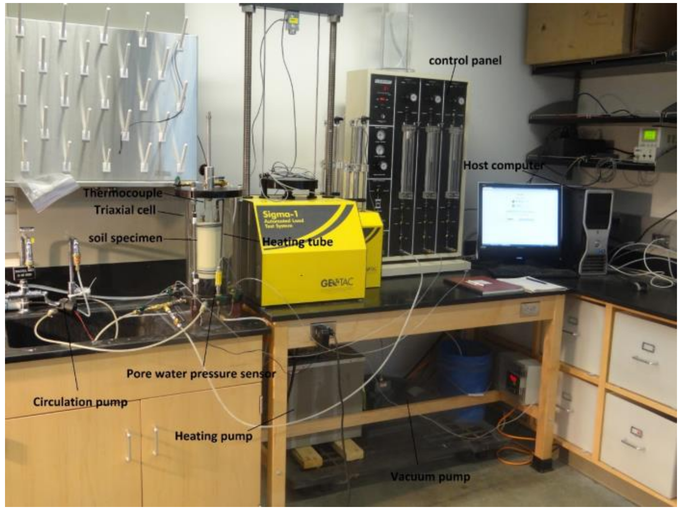


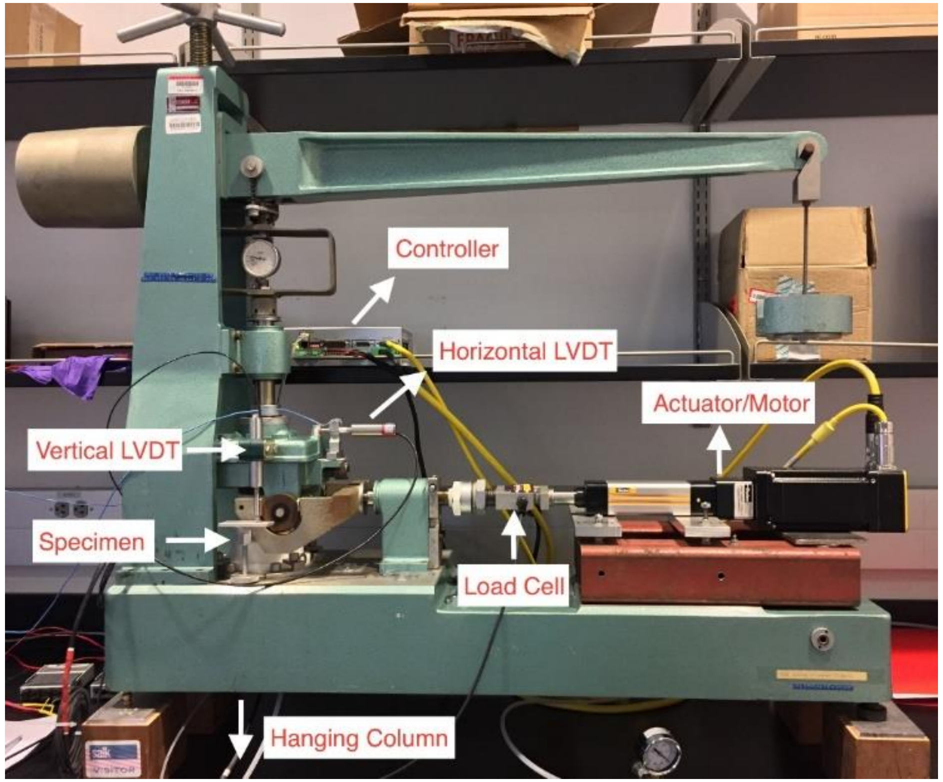


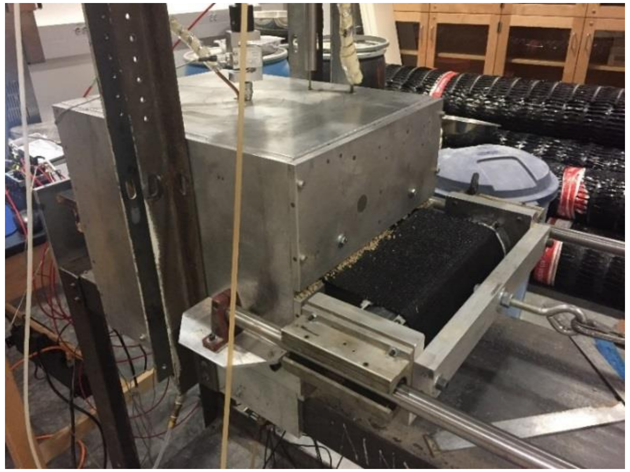
- Two 9 m-deep soil pits for foundation testing
  - Reaction mass, actuators, hydraulic pump and accumulators
  - Available for use by NHERI shake table researchers
  - New user must budget to remove previous test

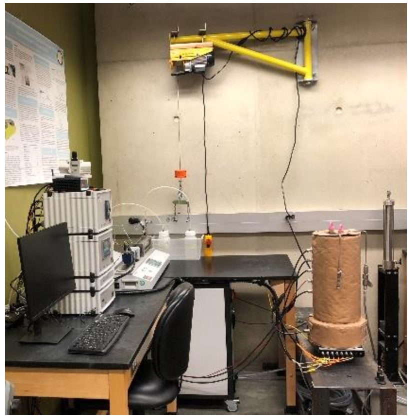
# Other Geotechnical Equipment at UCSD

- Standard geotechnical testing/characterization equipment
- Specialty equipment (large scale direct/simple shear, geosynthetic pullout, triaxial cells, cyclic simple shear, unsaturated soil testing)

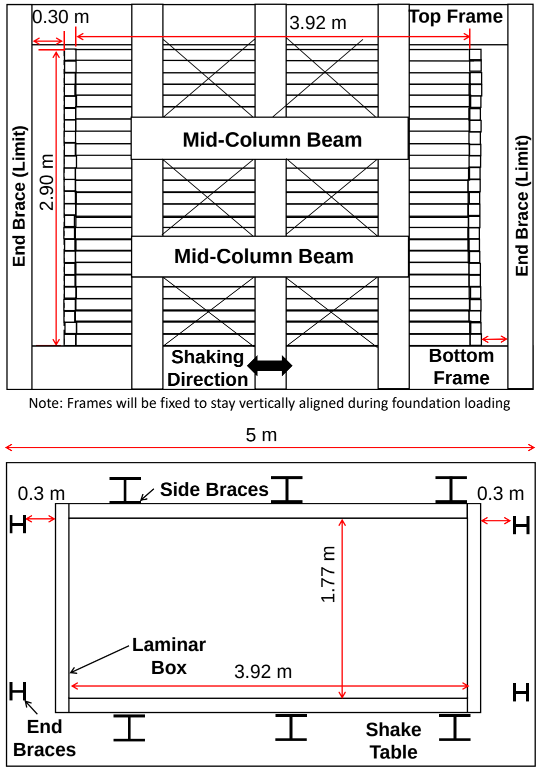


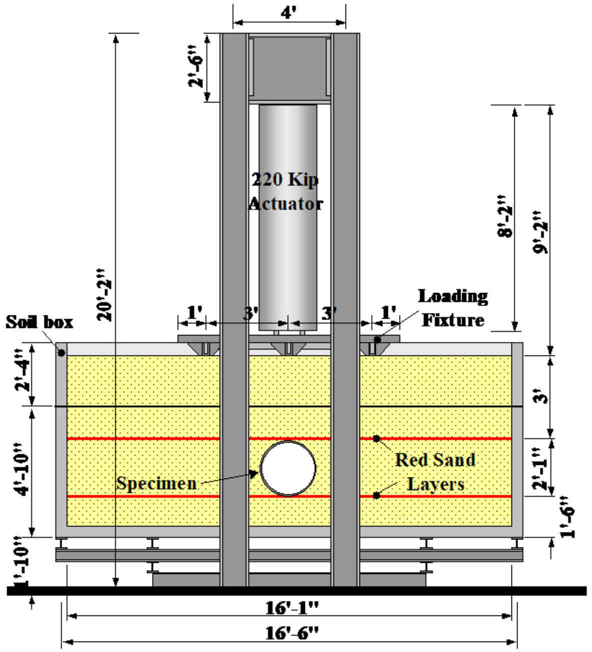





- Smaller laminar container and smaller rigid container
  - Typically used on the Powell lab shake table, but can be used on LHPOST6

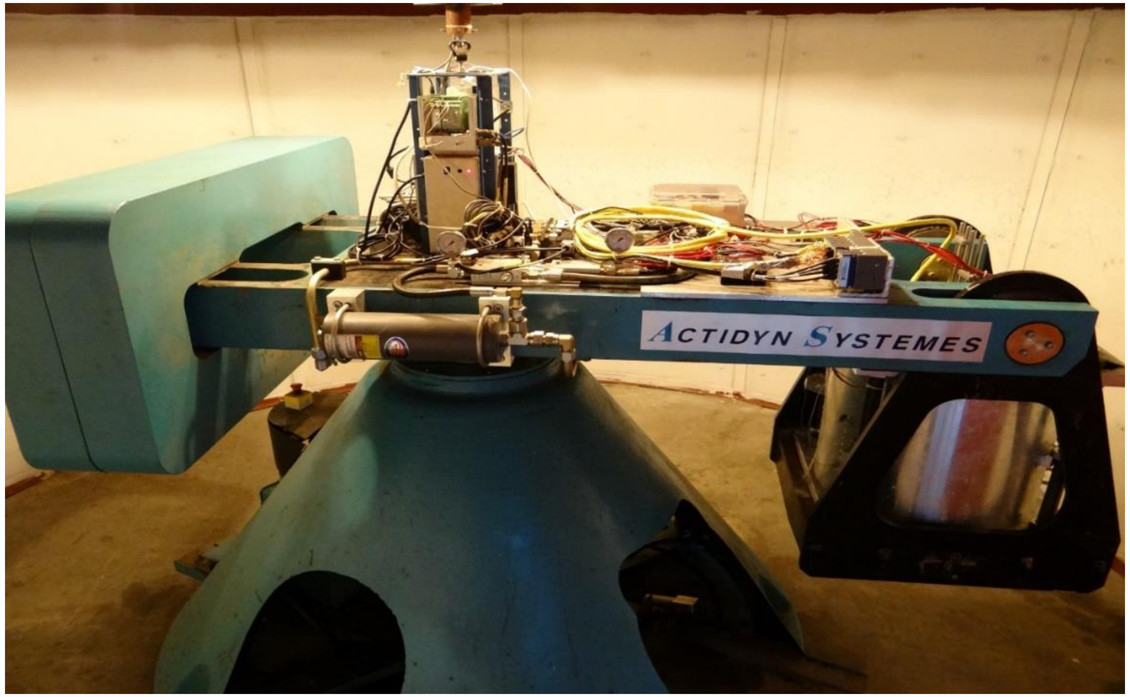



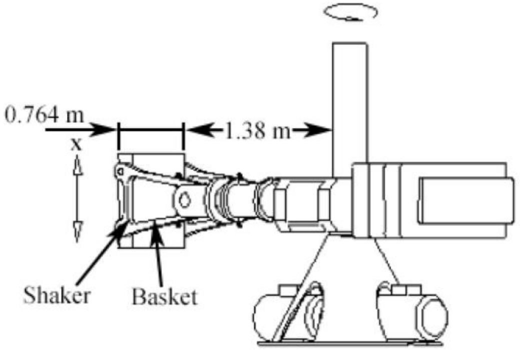


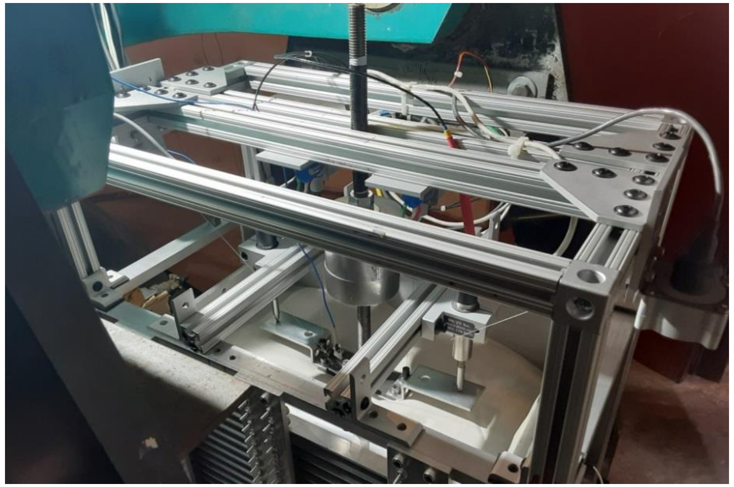



Rigid container for footing/pipeline testing with transparent acrylic side walls

- Geotechnical centrifuge
  - 50 g-ton capacity, max. payload mass of 500 kg, footprint of 0.6 m by 0.7 m
  - Containers for foundation loading
  - Shake table and laminar container

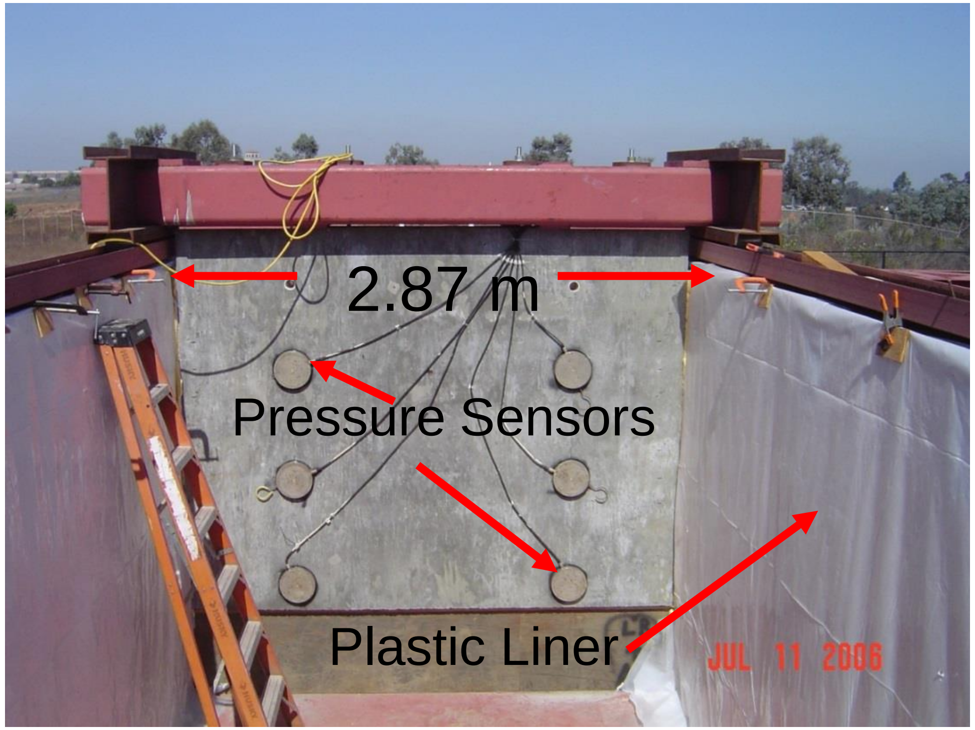


## *Examples of past geotechnical projects performed at NHERI@UC San Diego*

# • Rigid Retaining Wall: Elgamal


•Vertical test wall suspended from a supporting beam resting on rollers

•2.87 m wide plane-strain section configuration

•Soil container inside walls lined with 3 layers of smooth plastic

•Pairs of pressure sensors mounted at 3 depths

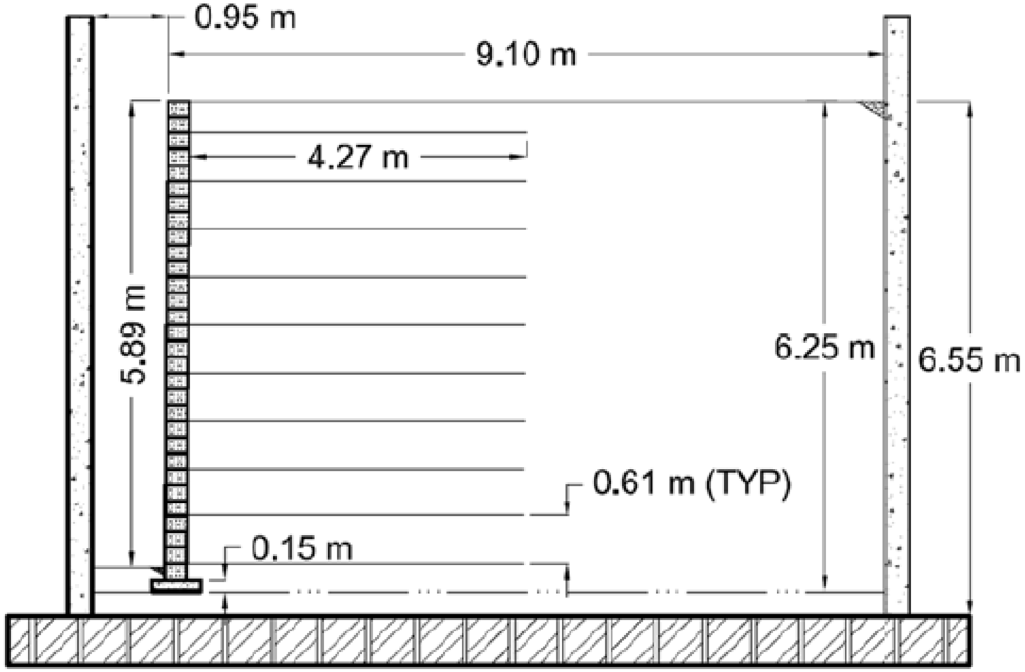
Well graded sand with 7% silt and up to 7% fine gravel (SW-SM) was used in all tests (($c$-$\phi$) that meets Caltrans structural backfill specifications

95% relative compaction (around OMC) Verified by nuclear gauge measurements

- Rigid Retaining Wall Testing: Elgamal


- Test wall pushed into the backfill using 4 hydraulic jacks
- Jacks were connected through a manifold system to allow independent control
- Reaction was measured by 4 load cells mounted behind the jacks

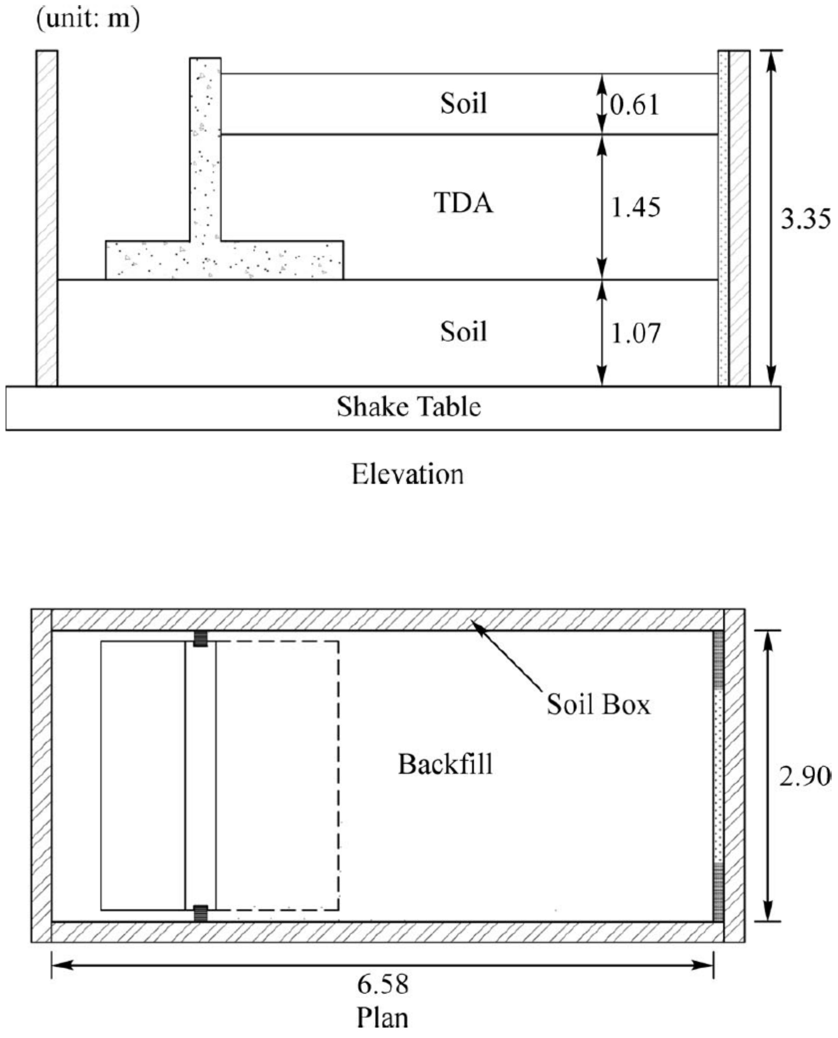
- Deformation Response of a Full-Scale Geosynthetic-Reinforced Retaining Wall

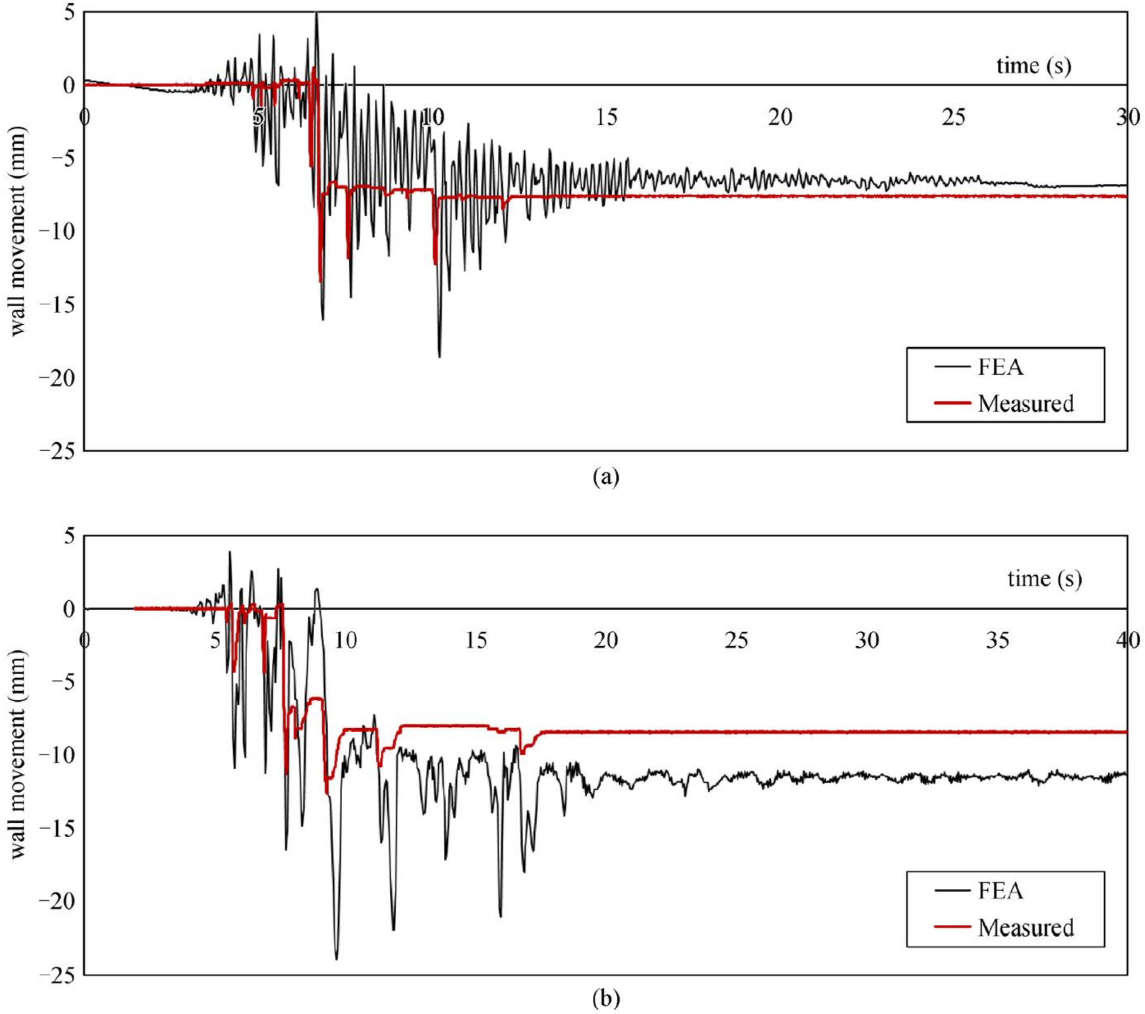


- Shake Table Test of Large-Scale Bridge Columns Supported on Rocking Shallow Foundations: Bruce Kutter UC Davis

- Antonellis et al. (2015) carried out shake-table testing of two 1:3 scale bridge piers with shallow foundations designed to rock
- The test specimens were placed inside the large confinement soil box described in [Fox et al. 2015], which was partially filled with poorly graded medium sand and water
- Because of the uni-directional limitation of the LHPOST at the time, one of the test units was aligned with the direction of the shake table excitation, whereas the other was rotated 30 degrees
- While this provided multi-directional input to the specimens, the obvious correlation of the pair of translational input motions was present, which is no longer an issue with LHPOST6

- TDA Cantilever Retaining Wall, Dawn Cheng UC Davis



- Impact of lateral spread on pile foundations: Elgamal with support from Caltrans


- Racking Response of Reinforced Concrete Cut and Cover Tunnel (Caltrans/Bay Area Rapid Transit) and Spillway Retaining Wall Shake Table Test Program (US Bureau of Reclamation), Ahmed Elgamal
  - Used internal instrumentation to understand soil-structure interaction mechanisms of the tunnel reinforced concrete liner configuration and for use of field soil materials and construction procedures
  - Based on the recorded experimental data sets, computational studies were performed to further assess the involved soil-structure-interaction mechanisms

- Rapid: Large-Scale Shake Table Test to Quantify Seismic Response of Helical Piles in Dry Sands (CMMI-1624153), Amy Cerato, OU

- The first study on the kinematic and inertial behavior of full-scale single helical piles in a dense sand bed was evaluated as a payload project led by Amy Cerato of the University of Oklahoma, resulting in a large number of journal publications focused on damping effects of individual piles and pile groups
- The data from this project is being used to both update building codes and minimum damping attributes for slender piles and to calibrate numerical simulations

## *Open issues and future research challenges that can be evaluated using LHPOST6*

# Soil-Structure Interaction Testing

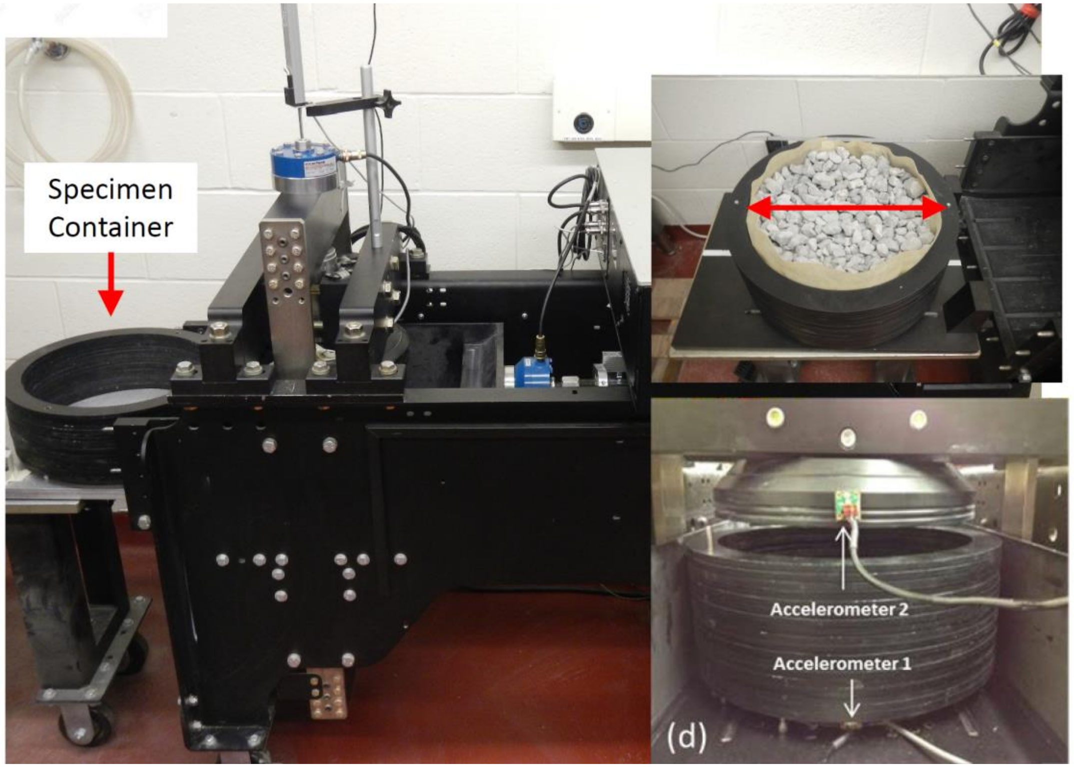
- Verification Studies under Tri-axial Excitation:
  - Computational models of the complete soil-foundation-structure system would be used to obtain the **total translational and rotational motion** of the foundation which would then be **applied at the base of the structure placed on the shake table**, followed by comparison of the model and the resulting experimental response
  - This would extend the current design practice of including only translational components (in the absence of SSI)
  - Such tests will also open an avenue for **blind prediction contests and discussions about the models** used to augment knowledge in the community
- Laminar and Rigid Soil Box Studies under Tri-axial Translational Excitation:
  - Full-scale or scaled models of structures will be supported on soils placed in either the 1D laminar or rigid soil boxes available at the facility
  - The soil box will be subjected to tri-axial translational base motions to better simulate the seismic input excitation
  - Such tests could be used to **study the nonlinear response of soils, the response of partially saturated soils, alternative backfill materials, and the nonlinear interaction between foundations, structures, and the soil contribution of radiation damping to the apparent damping in the structure** could also be studied using this approach
  - The effects of the coupling through the soil on the seismic response of adjacent structures (i.e., structure-soil-structure interaction), a topic of importance in the **urban environment and in farms of storage tanks and wind turbines**, could also be investigated through this approach
  - **Liquefaction, seismic-induced settlements and lateral soil spreading** in urban areas have accounted for a large percentage of the damage to the built environment in cities stricken by a strong earthquake, such as in the 2010 and 2011 Christchurch, New Zealand earthquake swarm
- Hybrid Tests:
  - These will be ambitious tests in which the soil will be modeled in the computer and the foundation input motion (i.e., the response of the foundation to seismic waves), and the compliance matrix i.e., the response of the foundation to external forces) will be obtained numerically
  - Potential to study the nonlinear seismic response of structures in the presence of soil-structure interaction, and the torsional response of structures

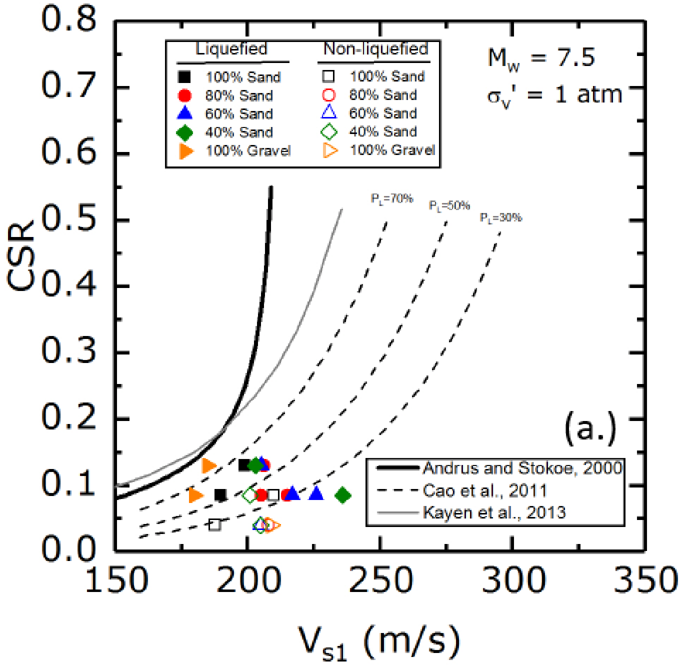
- Gravel liquefaction

Nikolaou et al. GEER (2014)

2016 Kaikoura EQ

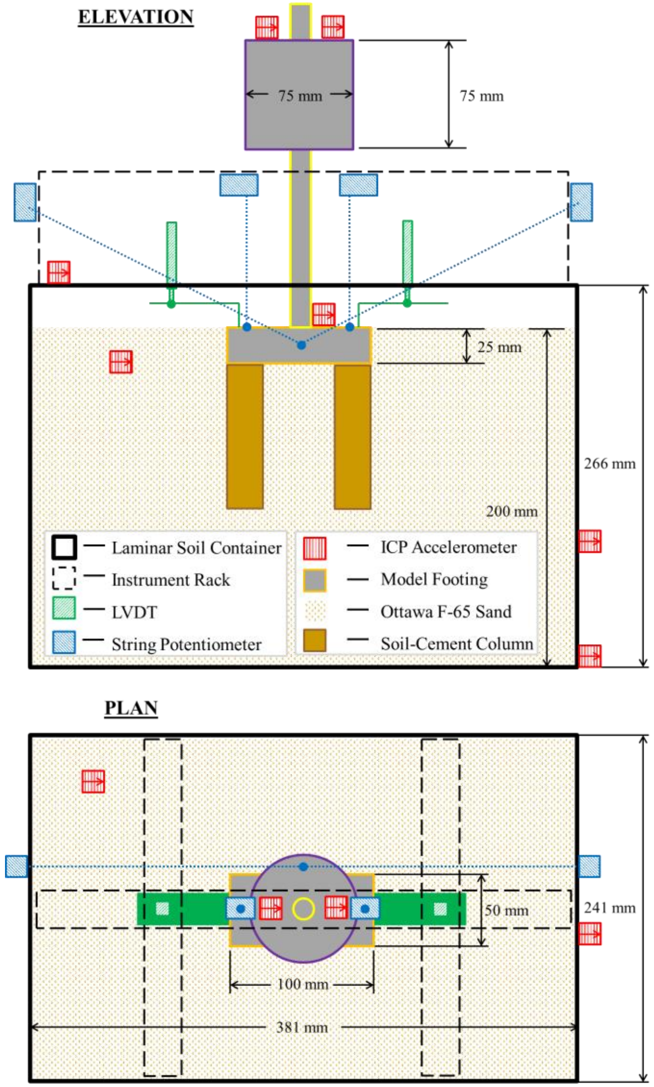
Cubrinovski et al. (2018)



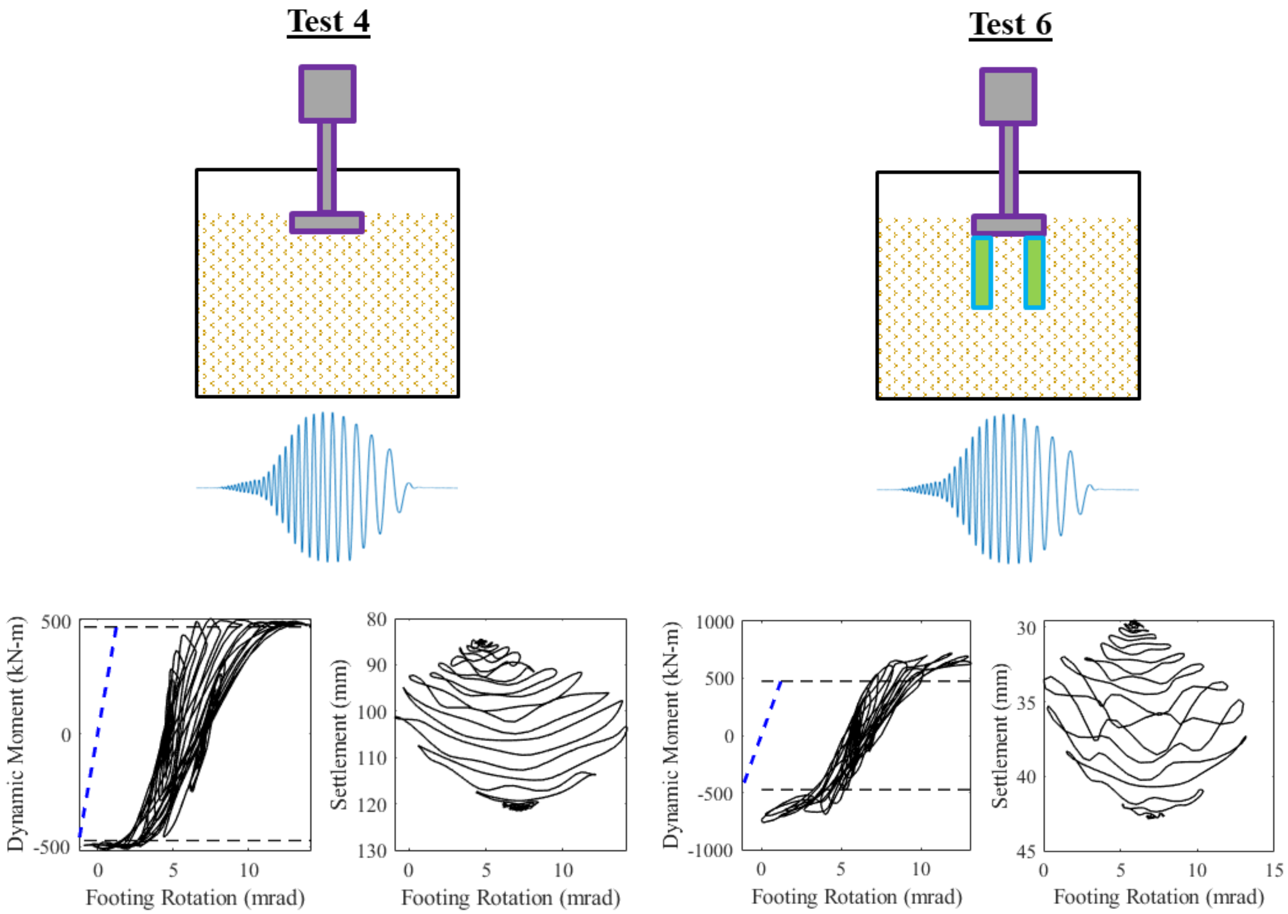




Images from Adda Athanasopoulos-Zekkos 2020 PEER Workshop Presentation

- Rocking foundations on ground-improved soils

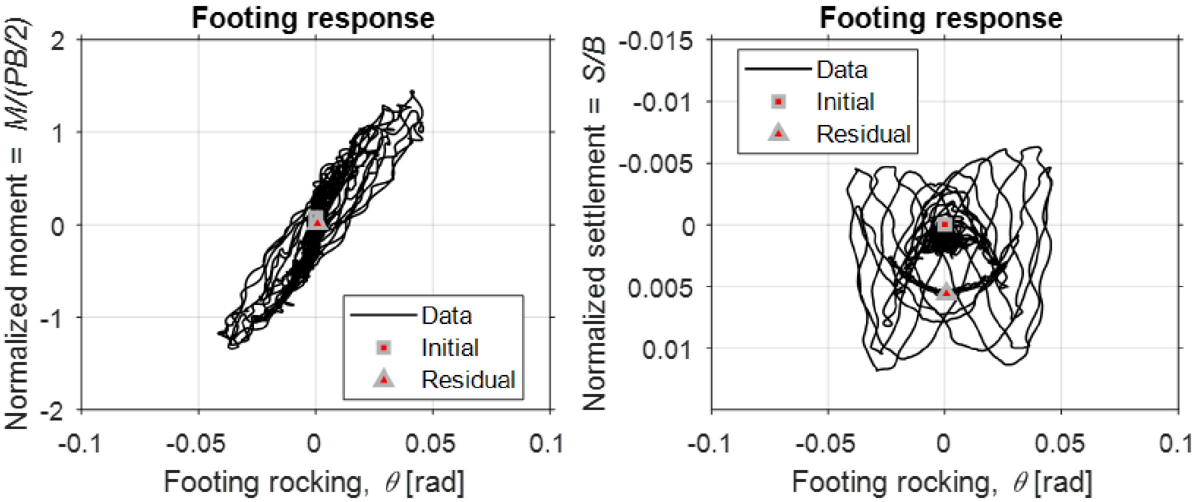



Newgard et al. (2022)



- Rocking foundations on tire-derived aggregate (TDA)

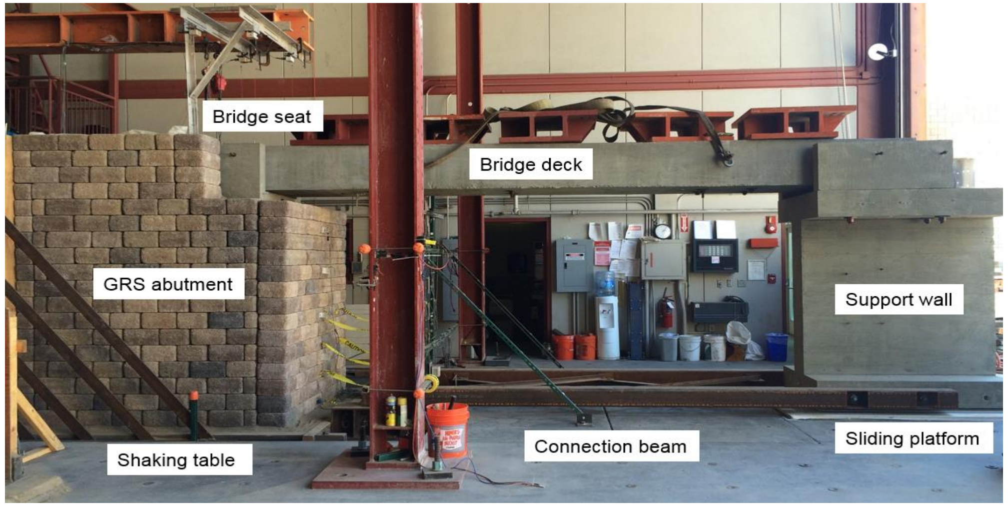
**Issues**:
- Permanent settlements
- Recentering
- Moment capacity

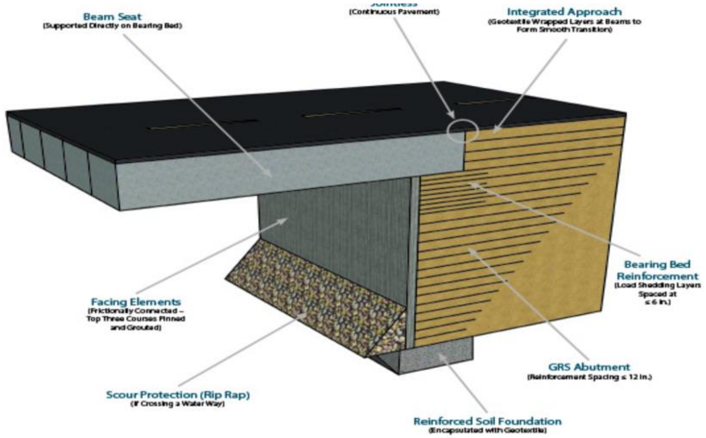



Yarahuaman and McCartney (2022)

# Open Issues

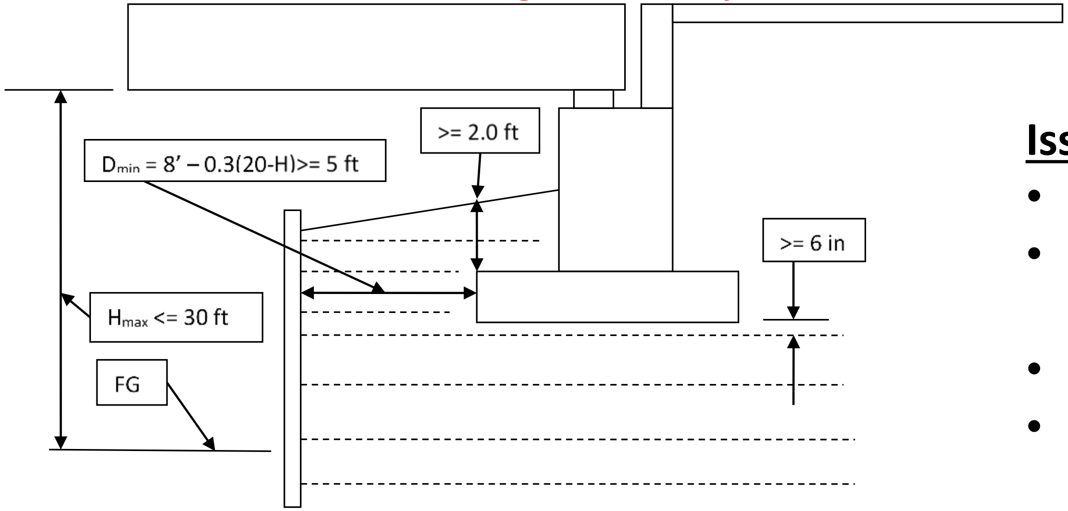
- Seismic Response of GRS-IBS Walls




Jointless integrated approach

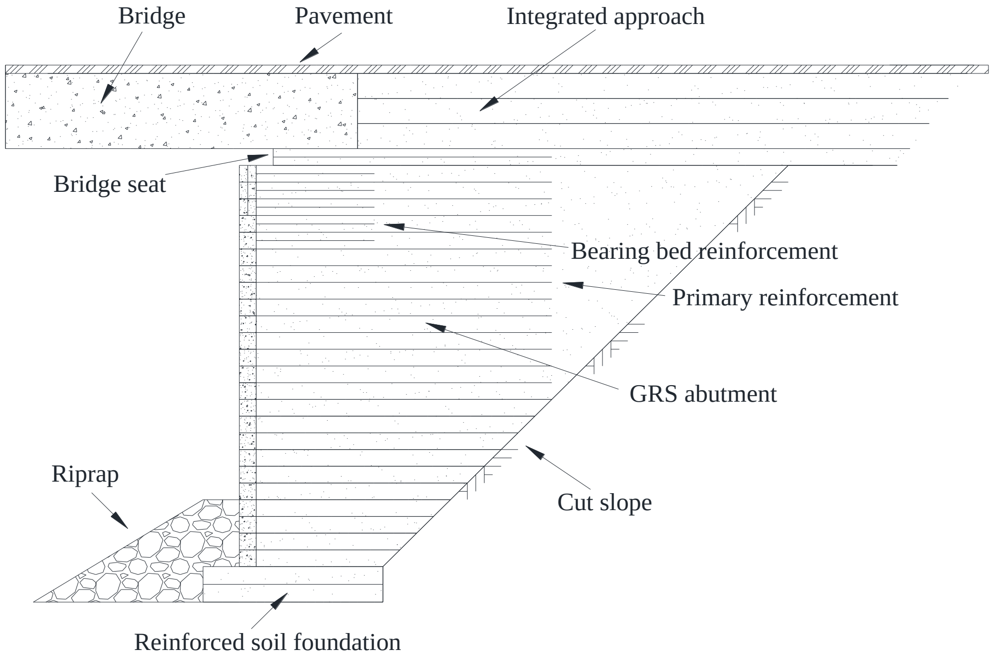
Bridge seat with joint




MSE Bridge Abutment

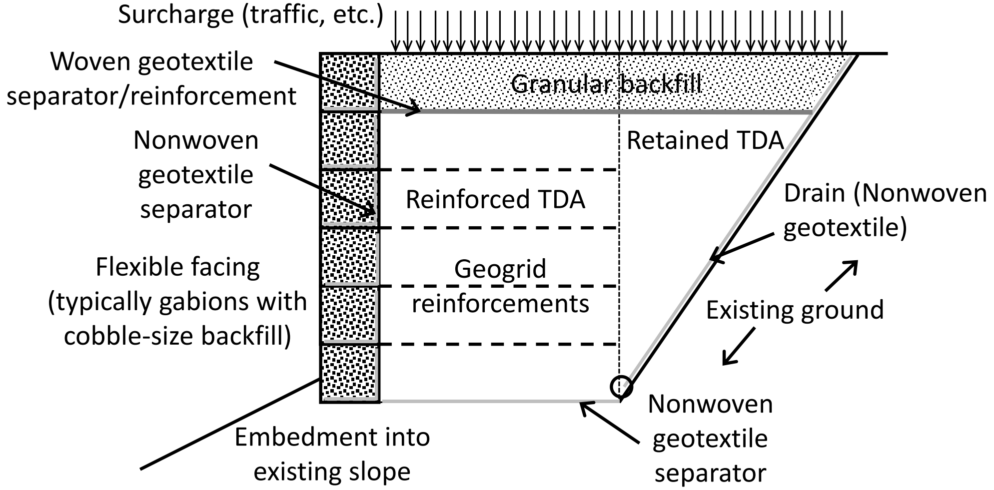
**Issues**:

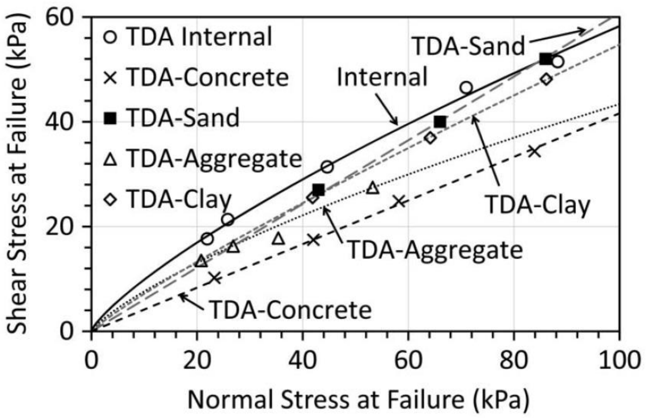
- Impact forces
- Reinforcement strains
- Deck settlements
- Facing deformations

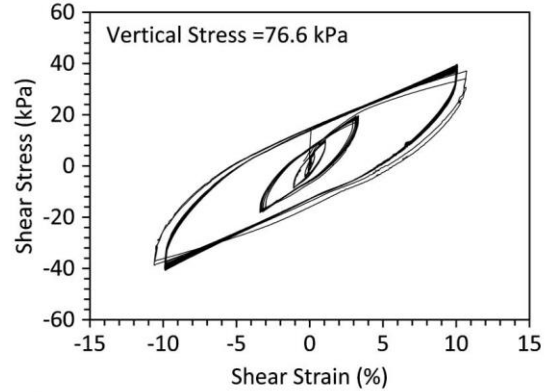


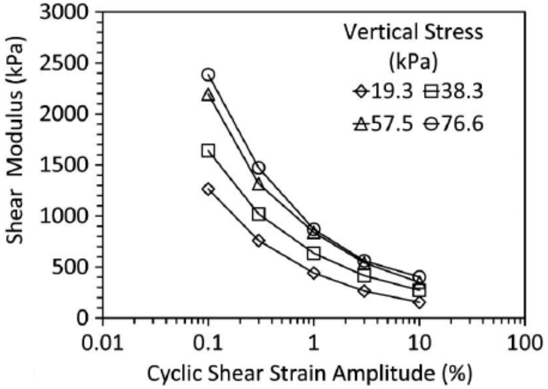

GRS-IBS Abutment

- MSTDA Walls



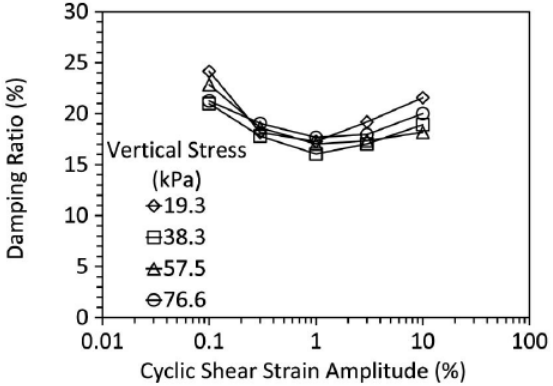





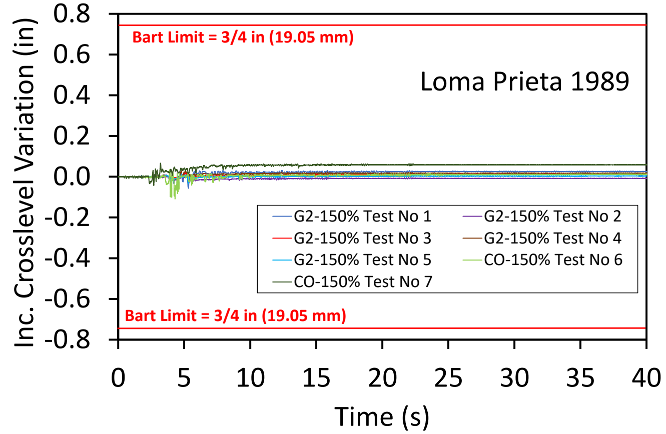
MSTDA Wall Constructed near Montecito, CA in 2019



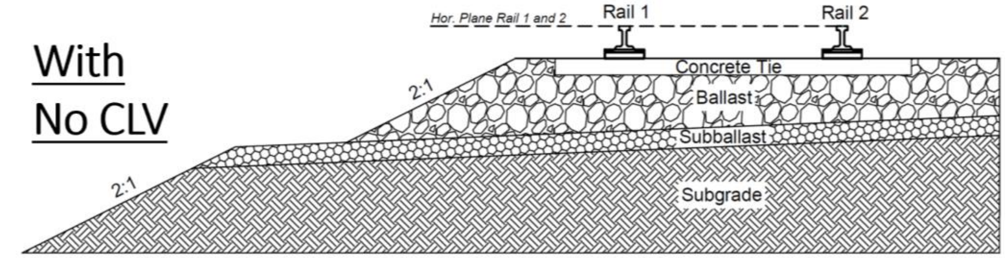
# • Seismic deformation of embankments

- During earthquakes, the rails in a ballasted track embankment may settle differentially, leading to **Cross-Level Variation (CLV)**
- Movements of the embankment slope face may lead to more settlements for outer rail (**Rail 1**) than inner rail (**Rail 2**)
- CLV used by BART as the criteria for track uniformity and permitted train speed
- After an earthquake, CLV may lead to a change in track class and train speed, or complete disruption of track operations

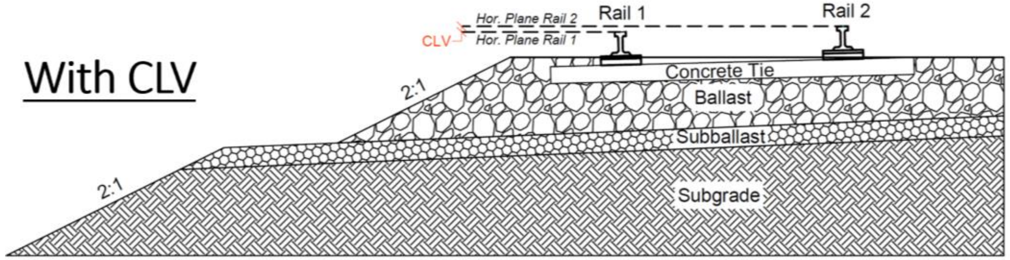
| Class of Track | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Maximum Allowable Operating Speed (mph) | 10 | 27 | 44 | 60 | 80 |
| Crosslevel Variation (in) | 2 | 1 3/4 | 1 1/4 | 1 | 3/4 |

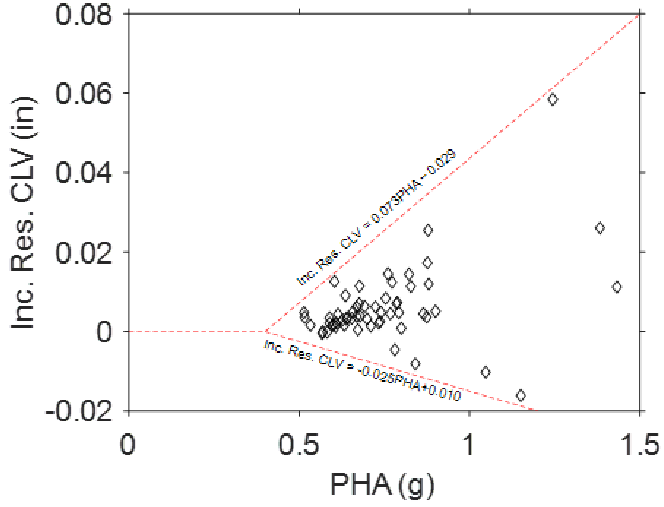



With No CLV



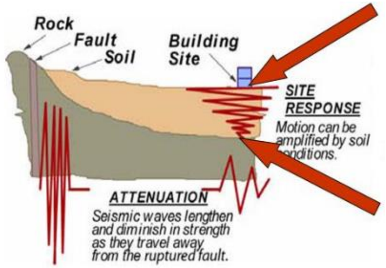

With CLV

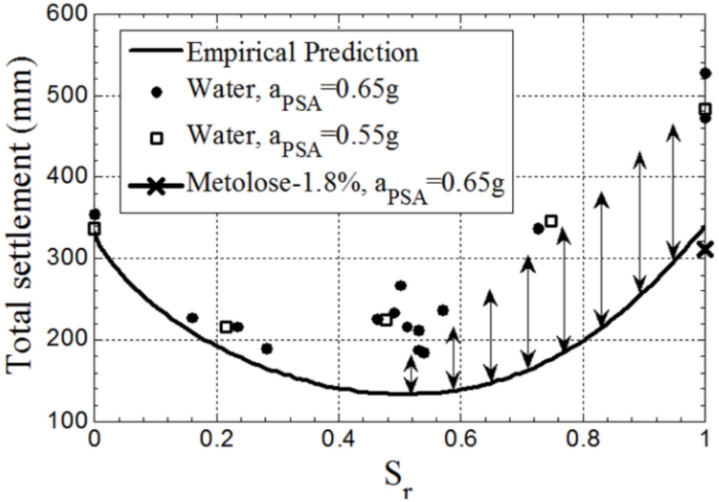


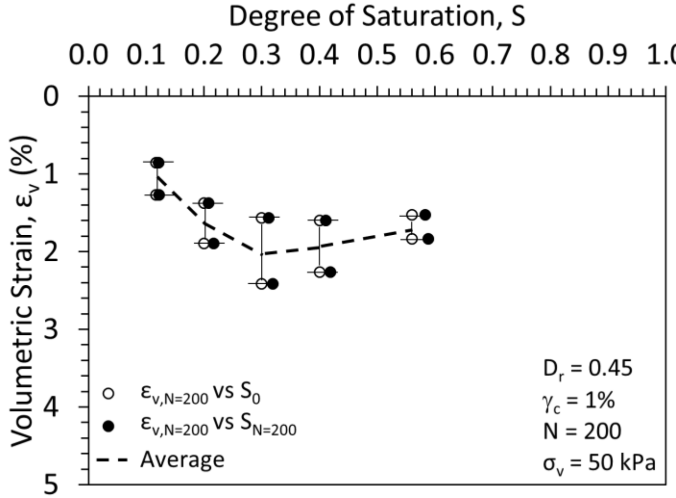

Relationship between incremental CLV with the PHA measured at Rail 1

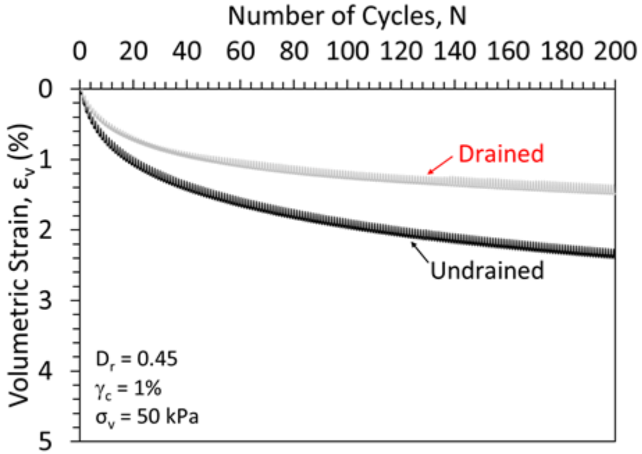
- Seismic compression of unsaturated backfill soils

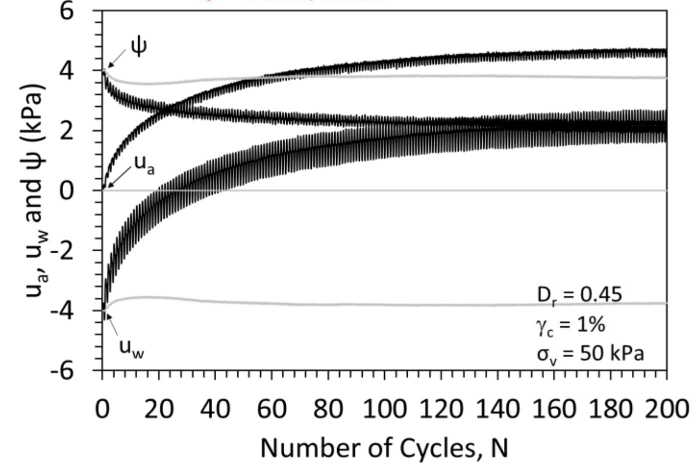


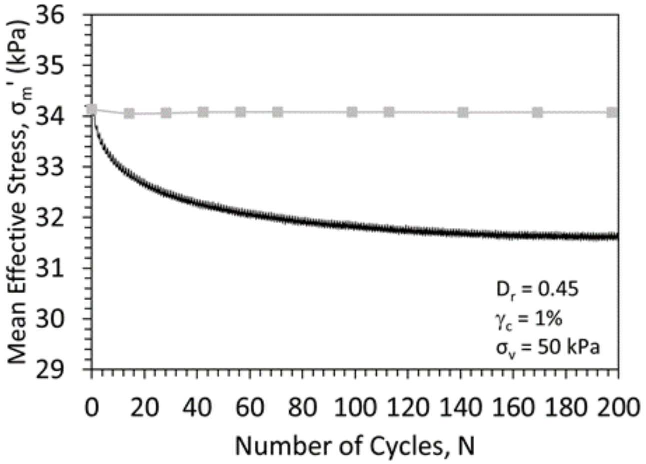



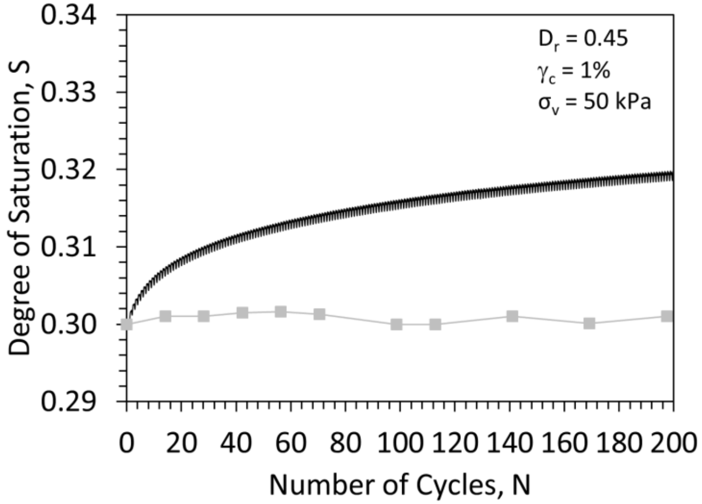

Ghayoomi et al. (2013)




Rong and McCartney (2022)

# ***Final Comments***

# Final Comments

- LHPOST6 is an appropriate testing facility for a range of geotechnical and soil-structure interaction problems
  - Full-scale performance of near-surface embedded structures (such as energy vaults, pipelines, and shallow tunnels), as well as bridge abutments, earth retaining walls, levees, embankments, and stability of cut and fill slopes in hillside construction
  - Phenomena that cannot be considered at laboratory- or centrifuge-scales, including liquefaction of gravels, efficacy of conventional or bio-mediated soil improvement, behavior of materials with large particle sizes like tire derived aggregate (TDA), and liquefaction-induced lateral spread
  - Soil-structure interaction problems considering effects of seismic deformations of saturated and unsaturated soils on shallow and deep foundations
  - Underground pipelines or utilities subject to liquefaction loads, lateral soil spreading, or fault crossing demands
- LHPOST6 tests on geotechnical structures can compliment centrifuge testing and numerical simulations