# Ground Improvement-Based Protection of Transportation Infrastructure: Validation of PBEE via Centrifuge and Numerical Modeling

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# Presentation Outline

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    - Sand-Cement Columns Mixing and Strength
    - Geogrids 3D-Printing and Strength
    - Test Procedure
    - Ground Motions

3. Test Results
    - Kinematic Response
    - Performance Metrics

# Introduction

- Rocking shallow footings supporting bridge columns are capable of:
  - Providing energy dissipation when soil capacity is mobilized
  - Re-centering themselves during shaking
  - Preventing damage to structural components, where dynamic loads are concentrated when the foundation is too stiff
- However, concerns regarding structural compatibility issues arising from a flexible foundation have limited the adoption of rocking footings
- This study will implement ground improvement techniques to address these concerns while maintaining all the benefits of a rocking footing

# Rocking Footing Concept

- Plastic hinge develops in the foundation soils instead of the column, reducing damage to the superstructure:

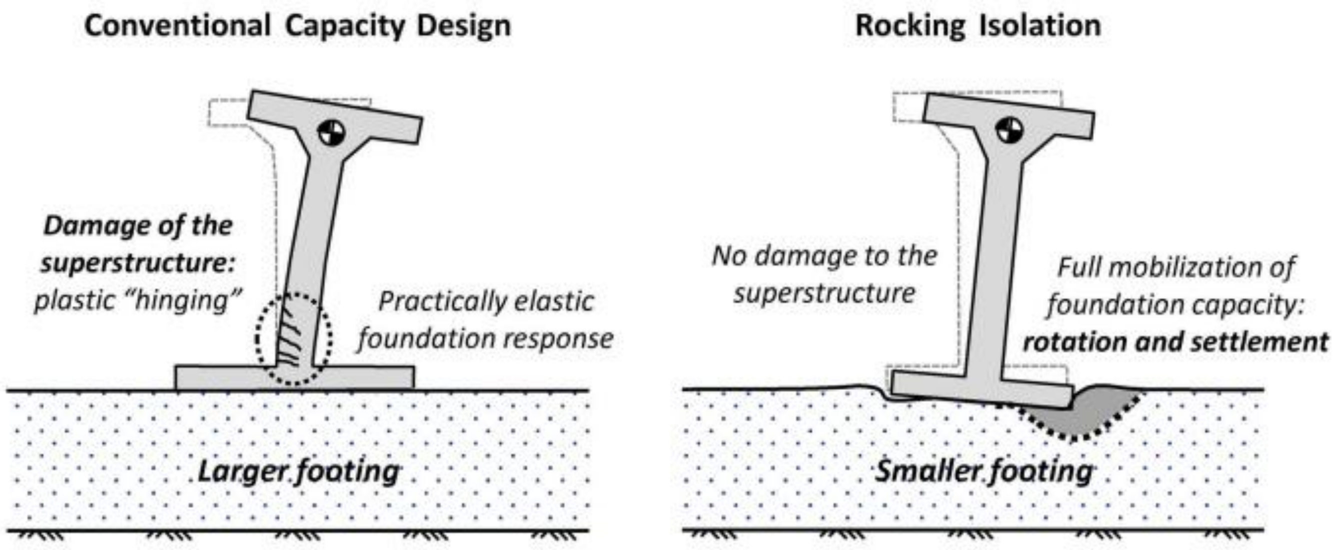


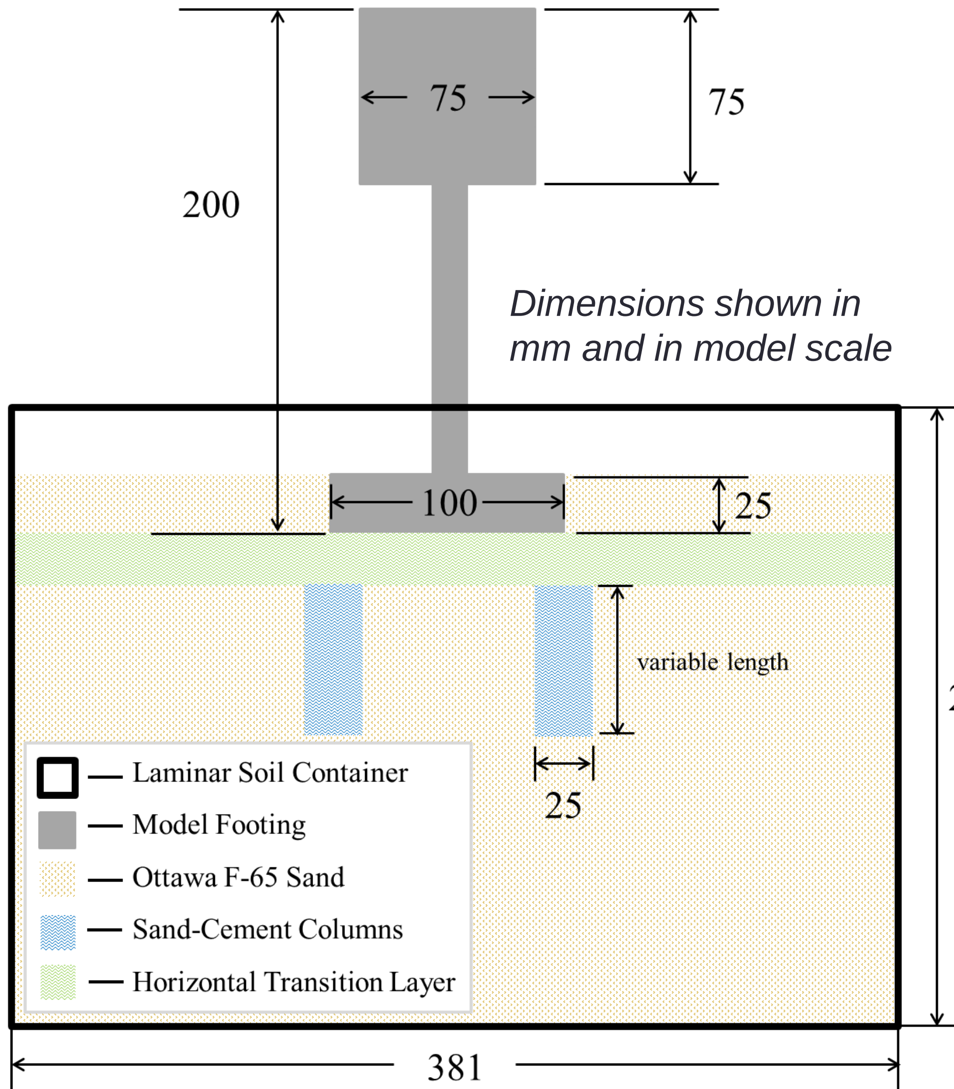

**FIGURE 1 | Conventional capacity design vs. rocking isolation**. While in the first case the plastic hinge develops in the superstructure, in a rocking-isolated system the foundation capacity is fully mobilized to protect the superstructure, at the cost of foundation rotation and settlement.

*Tsatsis & Anastasopoulos (2015)*

# Scope of Centrifuge Tests (N = 25 g)

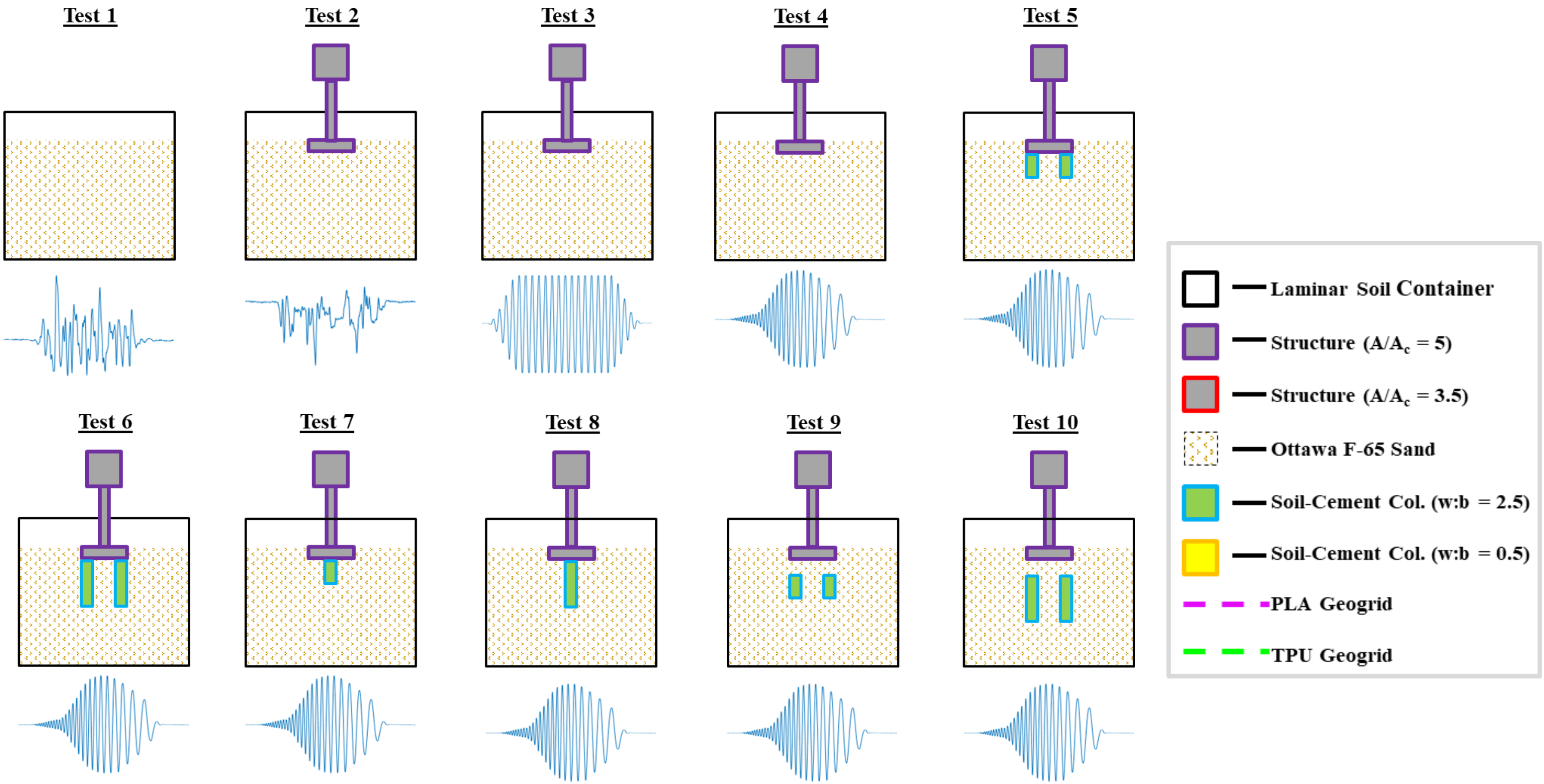
- Two test series performed:

1. Heavily loaded footing ($A/A_c$ = 5) supported by weaker sand-cement columns
2. Very heavily loaded footing ($A/A_c$ = 3.5) supported by stronger sand-cement columns or 3D-printed geogrids



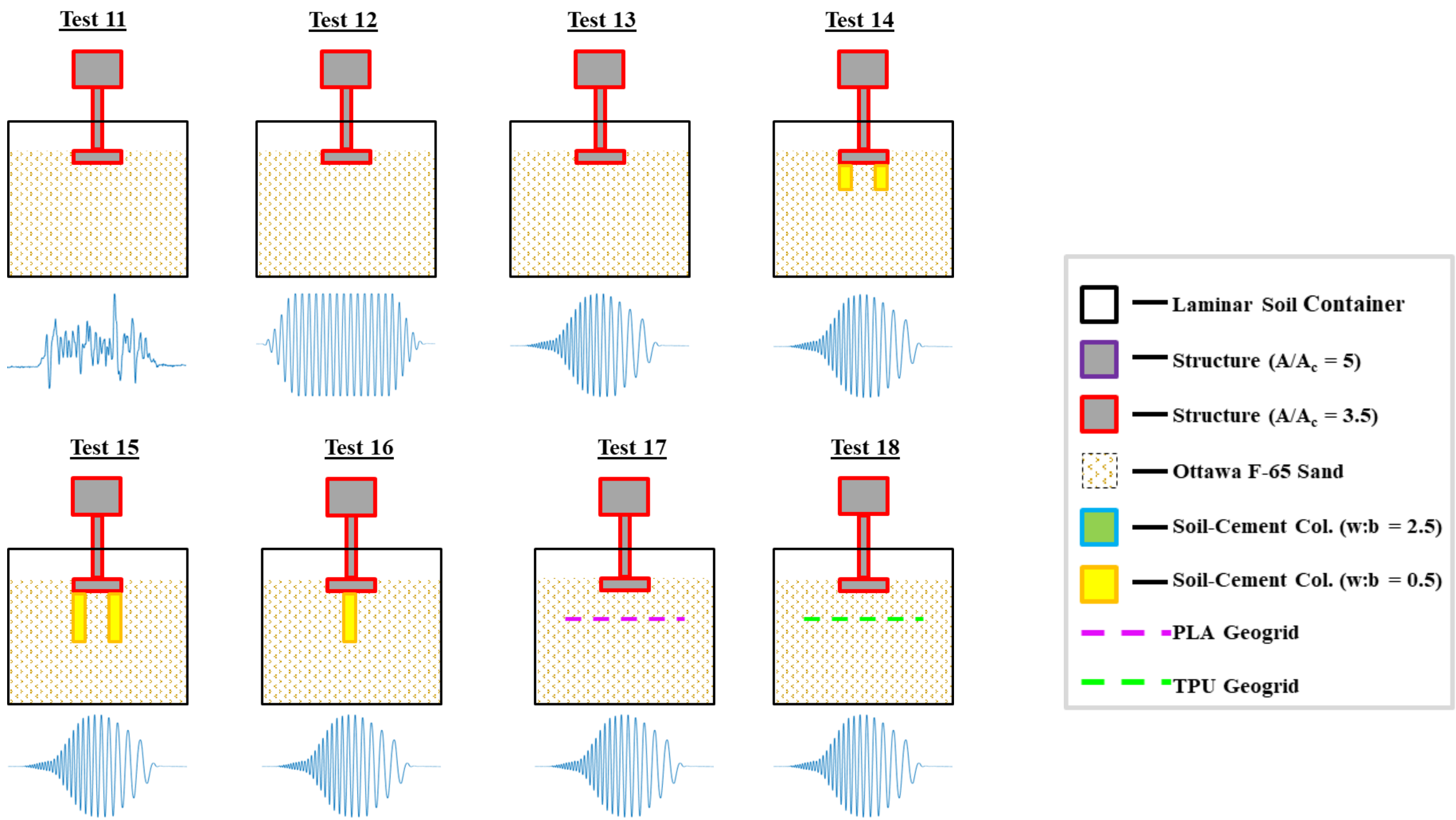
# Test Schematics: Series 1

- Heavily loaded footing ($A/A_c$ = 5) supported by weaker sand-cement columns



# Test Schematics: Series 2

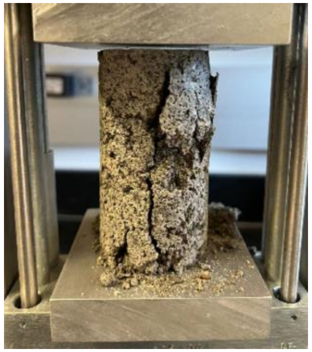
- Very heavily loaded footing ($A/A_c$ = 3.5) supported by stronger sand-cement columns or 3D-printed geogrids



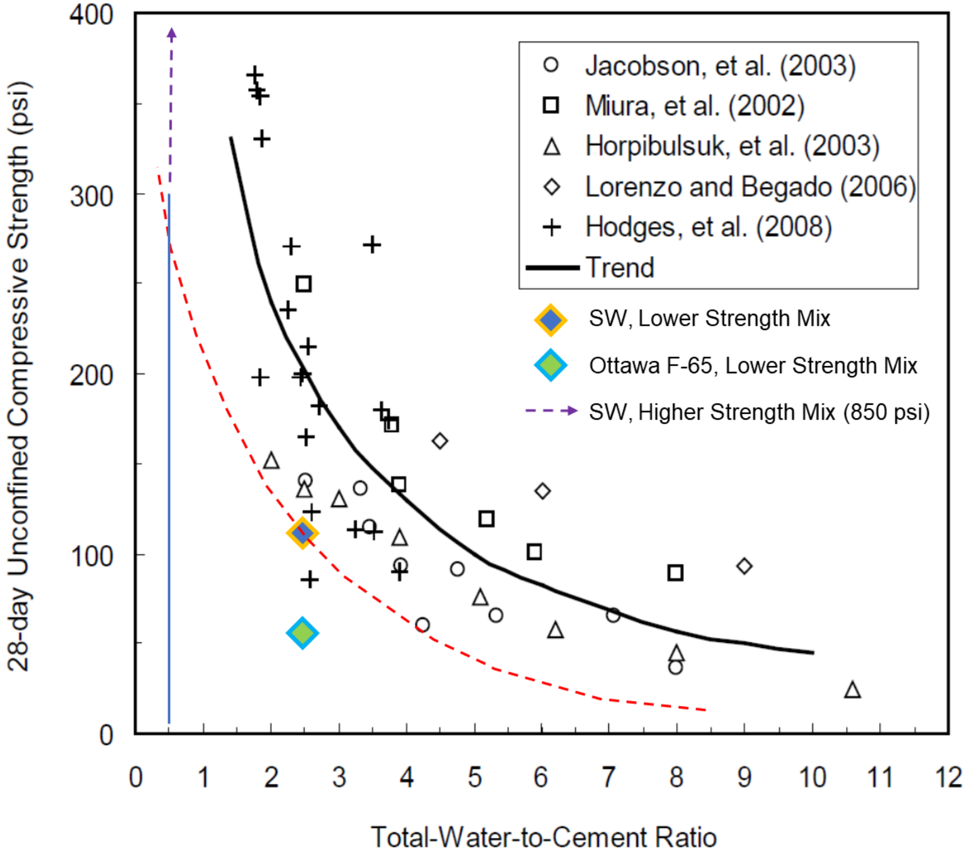
# Cement-Mixed Columns

**w:b = 2.5**

**w:b = 0.5**

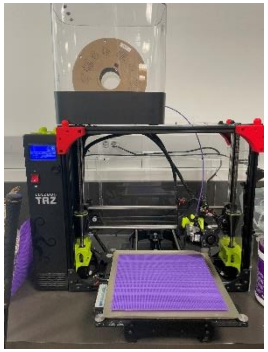


- Low strength (w:b = 2.5) columns are more typical for a GI application, but often exhibited crushing following rocking footing tests during Series 1
- Thus high strength (w:b = 0.5) columns were mixed and used during Series 2
- Ottawa F-65 sand exhibited propensity to segregate during mixing, so well-graded sand (SW) was used instead



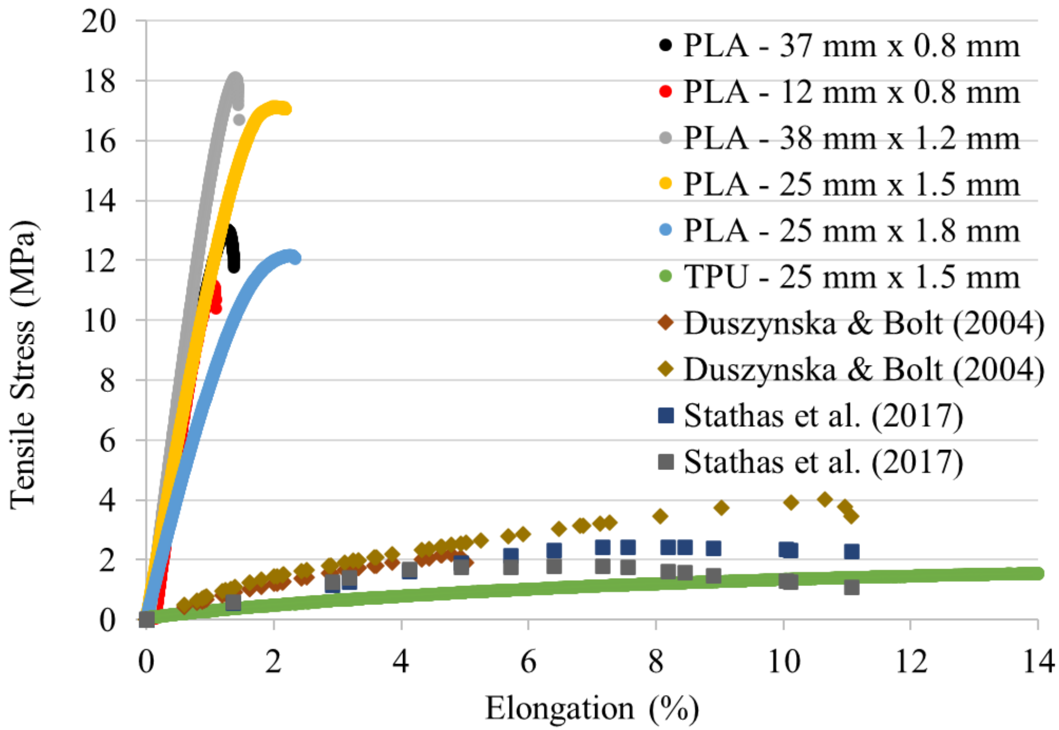

*FHWA Deep Mixing Manual*

# 3D-Printed Geogrids



- Biaxial geogrids printed with polylactic acid (PLA) and thermoplastic polyurethane (TPU) with 1 mm thick ribs and 2 mm wide square apertures, about 10x the mean grain size of Ottawa F-65 sand

- Strength and stiffness of printed geogrids are compared to commercial geogrids by Duszynska & Bolt (2004) and N = 10 g printed geogrids by Stathas et al. (2017); ultimately the thickness proved the most difficult dimension to scale accurately



# Test Procedure

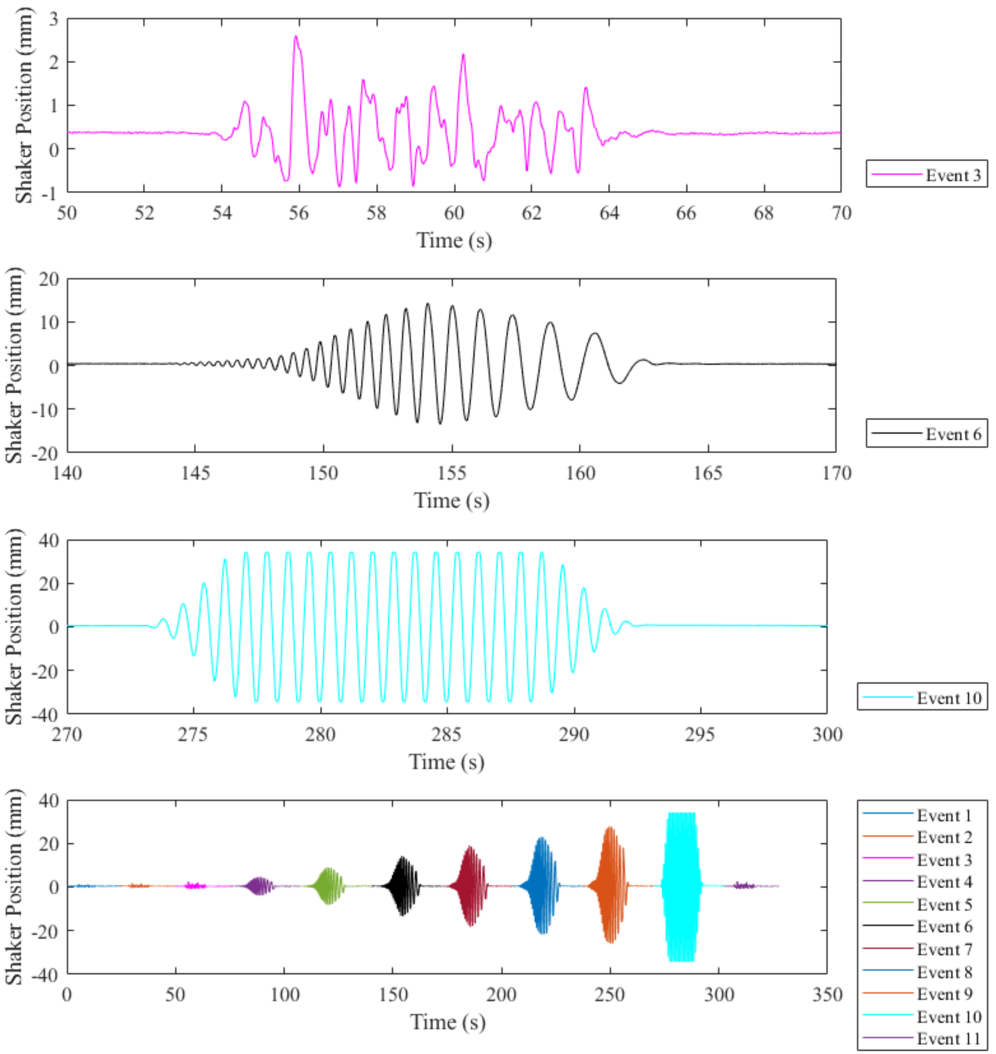
- Dry sand is pluviated through a pair of sieves to achieve uniform dispersion; relatively low drop height results in a ~50% $D_R$ deposit
- WD-40 is sprayed lightly around footing area, allowing for excavation and placement of sand-cement columns, and precluding sand from unnaturally falling into the gap which opens during rocking
- No structural connection between sand-cement columns and footing

# Shake Table Motions

- Each test was comprised of three motion types, sequentially increasing in amplitude:

1. white noise to characterize the rocking natural frequency of the structure ($f_{rock}$)
2. sine sweeps where the amplitude peaks at $f_{rock}$
3. harmonic with many high amplitude cycles at $f_{rock}$

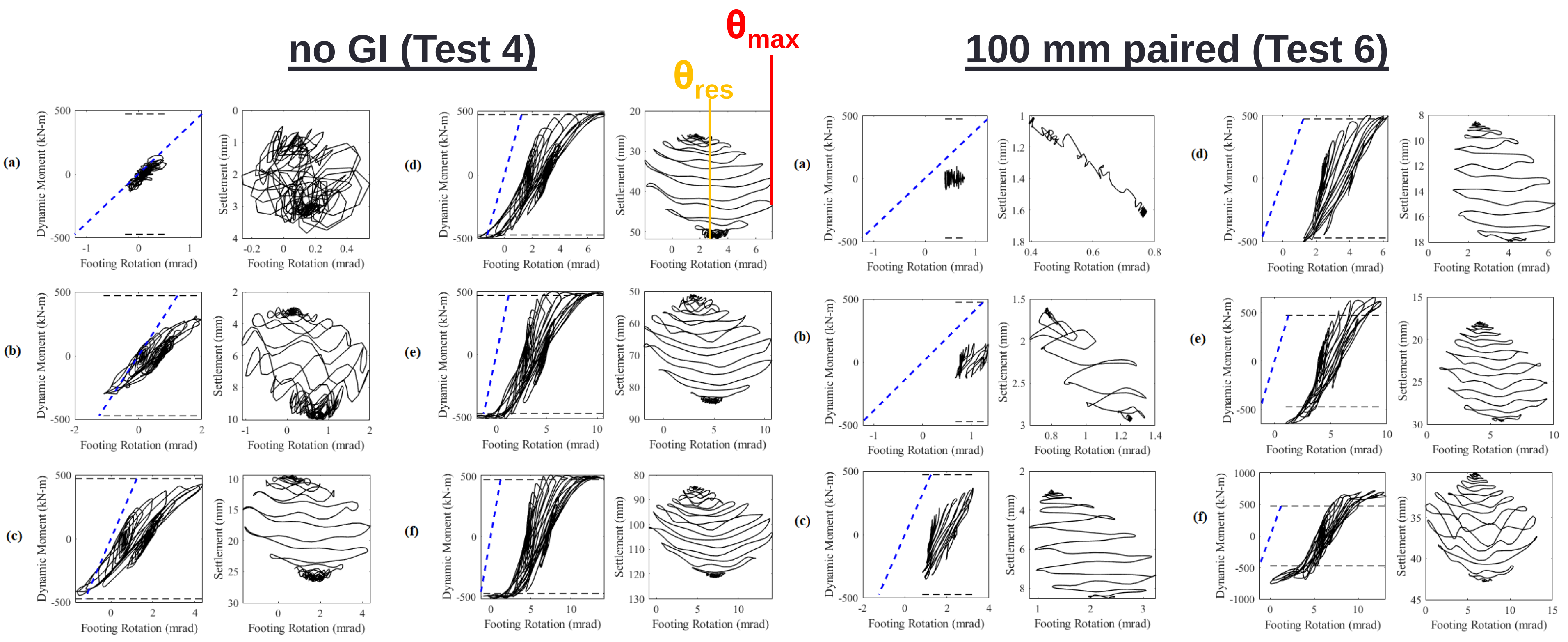
- Allows for assessments to be made regarding the performance of each ground improvement technique under low and high seismic demand



# Typical Kinematics during Rocking Test

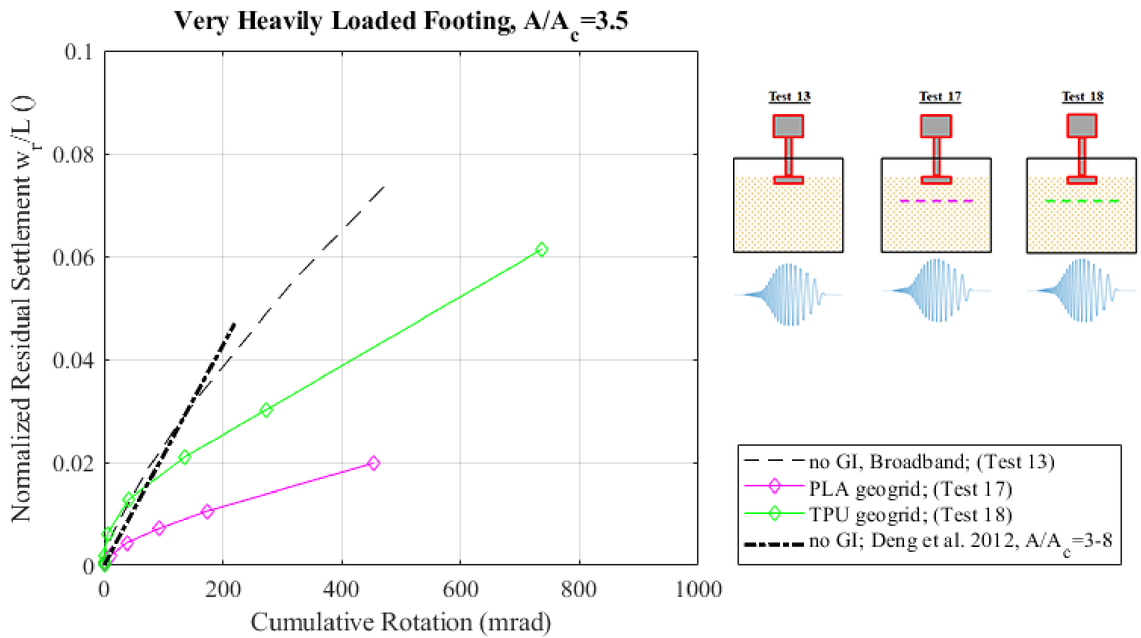
- Rapid accumulation of settlement during Test 4 once dynamic moments cause yielding in the soil

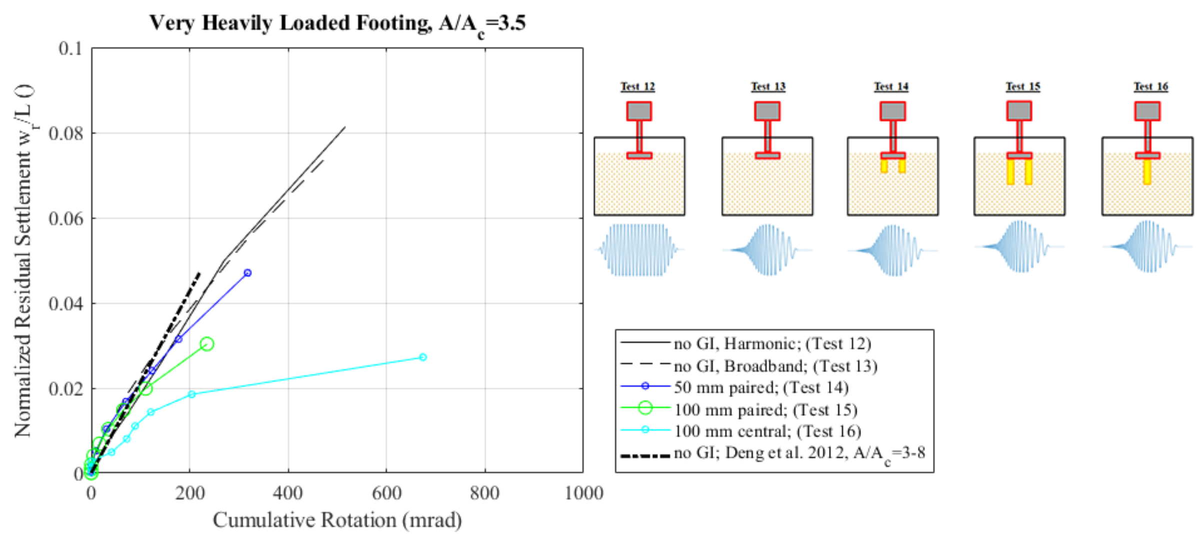
- Stiffness and moment capacity both increased during Test 6, and as a result, settlement is only ⅓ that of Test 4



# Settlement

- Baseline cases without ground improvement match trend reported by Deng et al. (2012) based on many tests
- Similar trends observed for each structure
- Longer paired columns reduce settlement more than all other strategies, except the longer central column; however ...



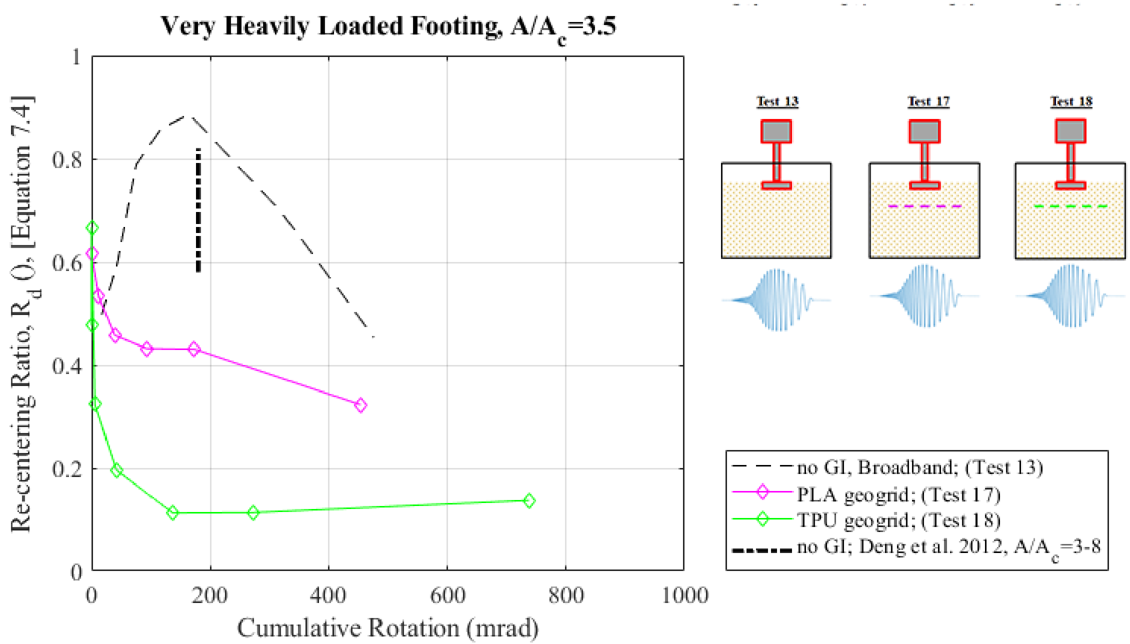



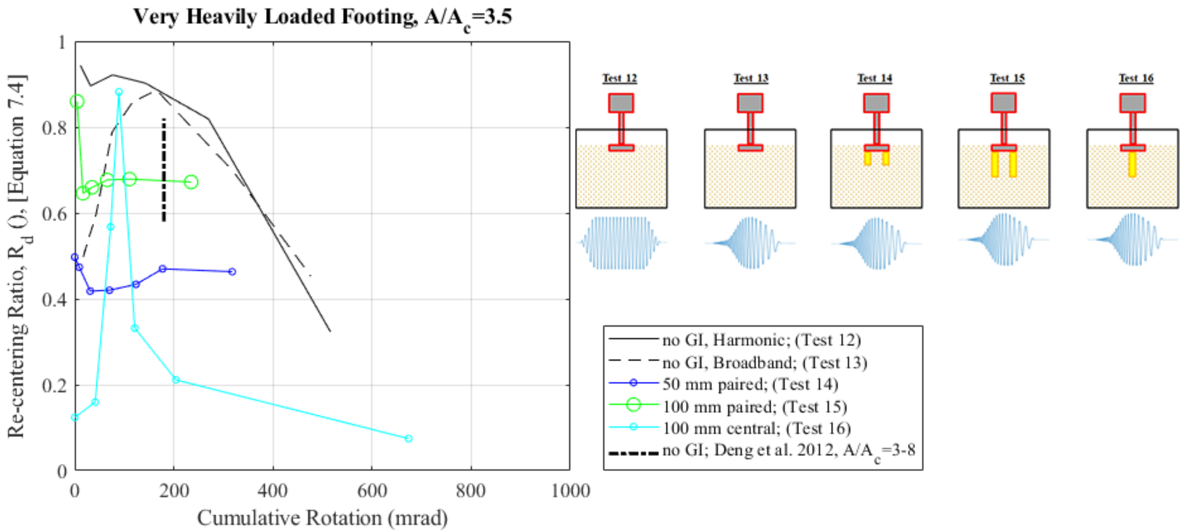
# Re-centering

- $R_d = 1 - \frac{\theta_{res}}{\theta_{max}}$

- Central columns exhibit poor re-centering; reminiscent of an inverted pendulum equally likely to tip to either side

- Paired columns provide more stable configuration, providing re-centering at high seismic demand



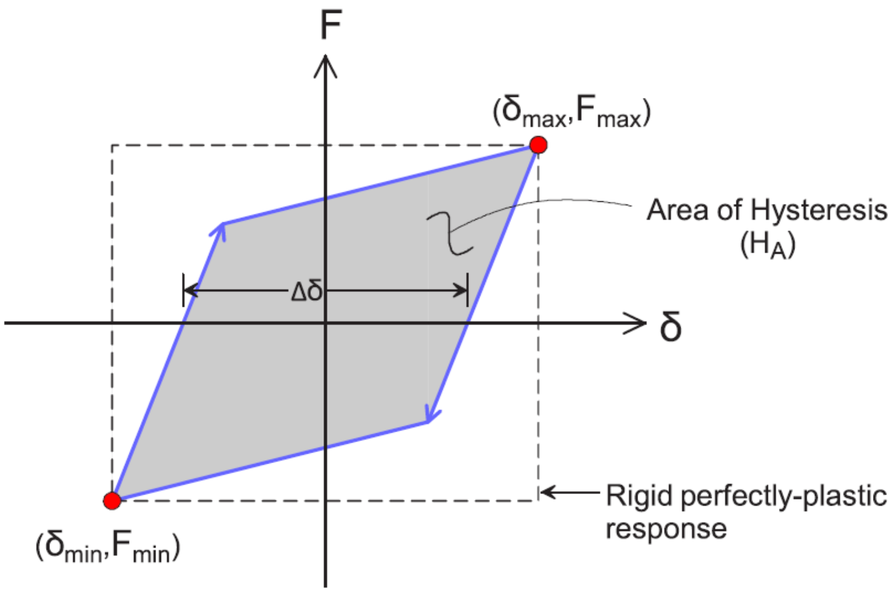



# Correlation Diagram

- Re-centering and energy dissipation may be examined via a correlation diagram readily extensible to a variety of seismic force-resisting members

- These ratios are defined based on the shape of one unload-reload cycle

- For the present application, axial force and displacement are replaced by overturning moment and footing rotation

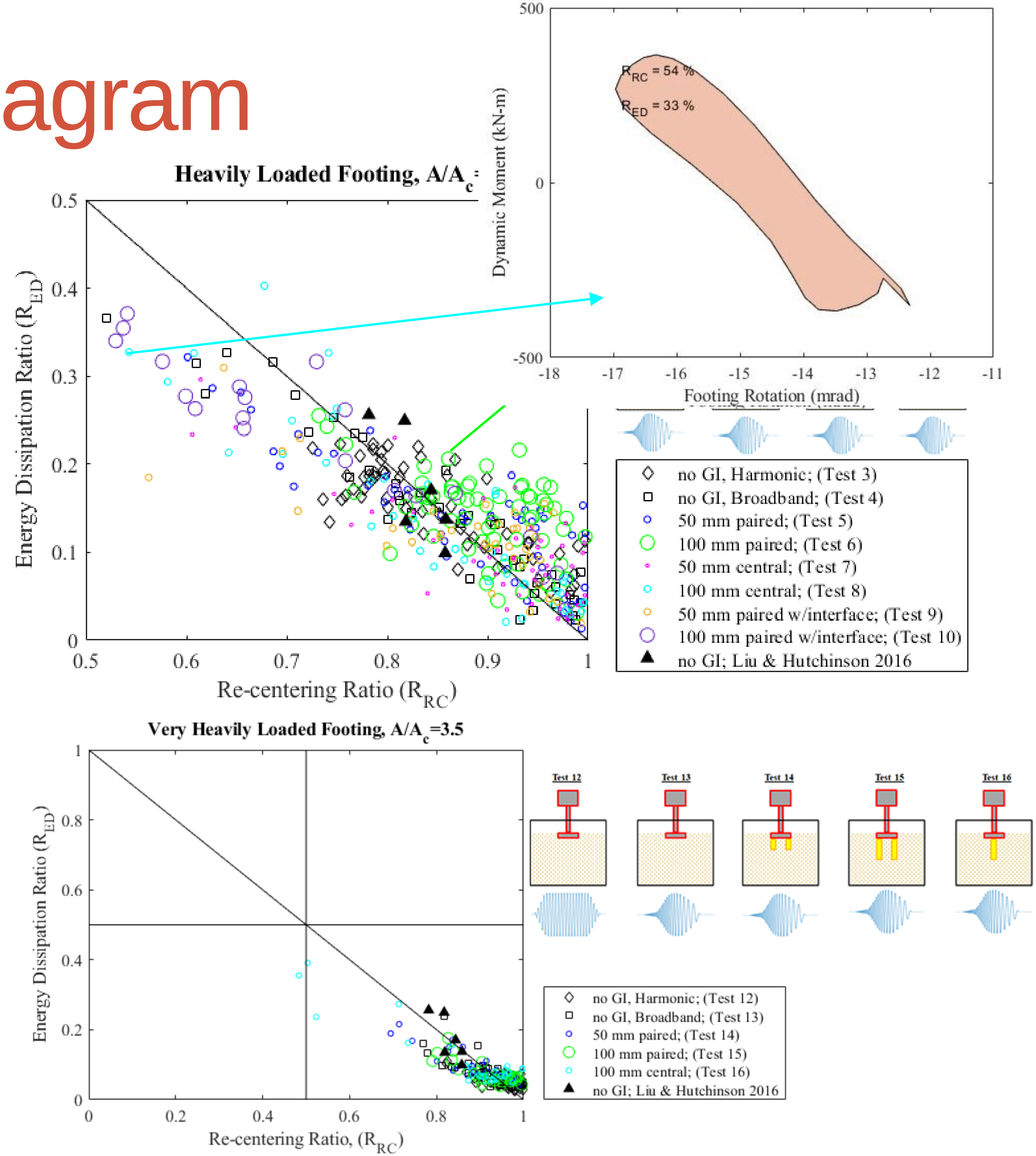



$$R_{ED} = \frac{H_A}{(F_{max} - F_{min}) \times (\delta_{max} - \delta_{min})}$$

$$R_{RC} = 1 - \frac{\Delta\delta}{(\delta_{max} - \delta_{min})}$$

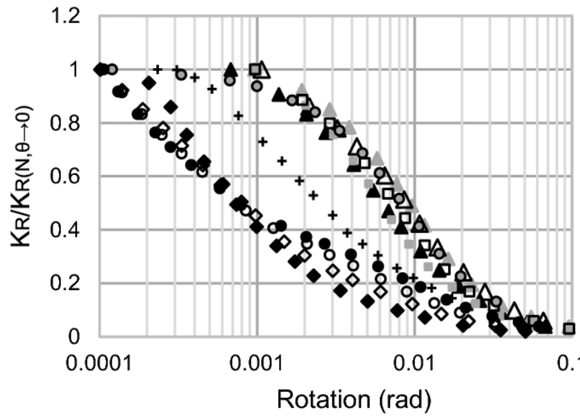
# Correlation Diagram

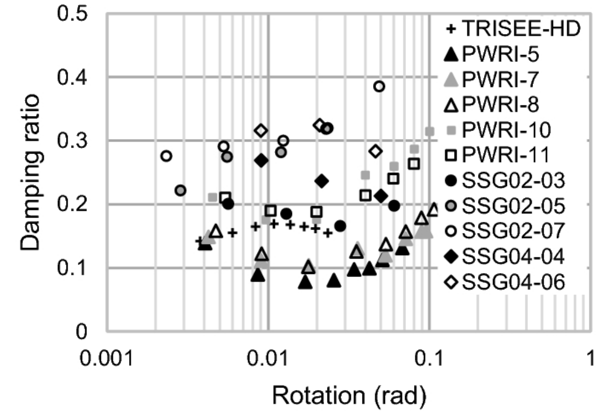
- All load cycles fall within the re-centering prone quadrant; to be expected for a rocking footing, which feels the pull of gravity drawing it back to center as it rocks
- As energy dissipation increases, re-centering performance inevitably decreases (nearly a -1:1 relationship)



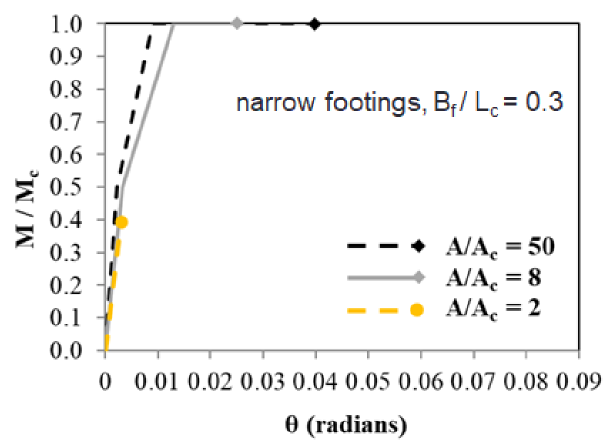
# Further Data Analysis

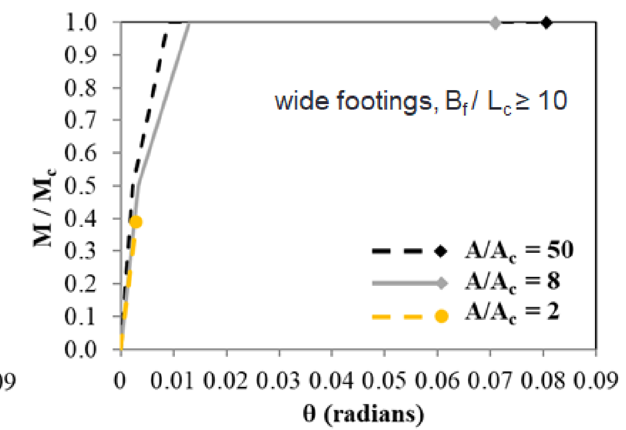
- Tracking rocking stiffness degradation as a function of either maximum rotation or cumulative rotation



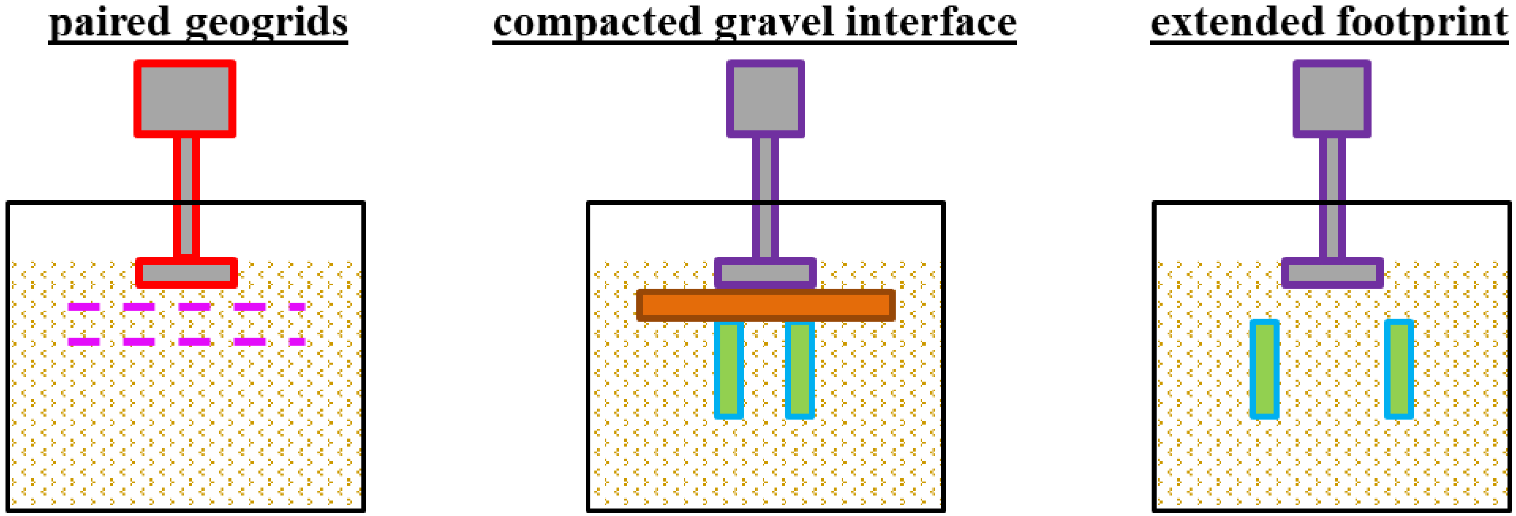

- Developing moment-rotation curves (based on settlement and re-centering) available to designers for each GI strategy



# Potential Strategies

- Additional near-surface reinforcement consistent with findings by Tsatsis & Anastasopoulos (2015) that a compacted crust of only 1B thickness was sufficient to reduce settlement by about ⅓ from no GI



# Conclusions

- Long paired columns provide the greatest reduction in settlement and preservation of re-centering and energy dissipation
- Footing behaves akin to an inverted pendulum when supported by a single central column and exhibits poor re-centering
- It is not recommended to incorporate ground improvement solely at a depth greater than 0.5B below bottom of footing, because the interface layer of sand is liable to experience increased yielding as a result
- 3D-printed geogrids scaled to N = 25 g bounded load-displacement characteristics of commercial products, and stiff (PLA) geogrid was more effective at reducing settlement than flexible (TPU) geogrid

# Project Notes

- PEER draft report is completed with everything presented here today (and much more)!
- Possibility to perform a few more tests; relatively easy to run tests at the UCSD centrifuge
- Feedback welcome on presentation of results to maximize utility to engineering community and design engineers

# Thank you!

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