Scaled Shake Table Tests of Free-Standing Structures with Varying Interface Geometry

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MOTIVATION

Critical structures, such as nuclear waste repositories, must be designed to withstand extremely rare earthquakes. However, records of such earthquakes are highly uncertain due to a lack of observations or recordings.

Precariously Balanced Rocks (PBRs)

- Naturally eroded into precarious or fragile configurations
- Existence of PBR formations is indicative of the upper bound ground motion that could have occurred at the rock's site over the rock's lifetime (Brune 1996)

Figure 1: Representative PBR

BACKGROUND

The "Rocking Problem"

- PBRs are a freestanding structure, likely to rock and overturn during an earthquake
- 2D rectangular projection to model structure excited into rocking

Equation of Motion & Restitution

$$(I + mR^2)\ddot{\theta} = mRcos(\alpha - |\theta|)\ddot{x}_g - sign(\theta)mRgsin(\alpha - |\theta|)$$

$$\dot{\theta}_{after} \,/\, \dot{\theta}_{before} = 1 - \frac{3}{2}\sin^2\alpha$$

- Non-linear with respect to geometry: slenderness, rotational inertia, radius
- Highly sensitive to small changes in geometry and input motion
- Piecewise with respect to direction of rocking: alternating centers of rotation
- Most common approach to modeling the response of PBRs and other freestanding structures, but PBRs have highly complex geometries that may not be accurately represented by simplistic model
- Original Derivation: Housner 1963

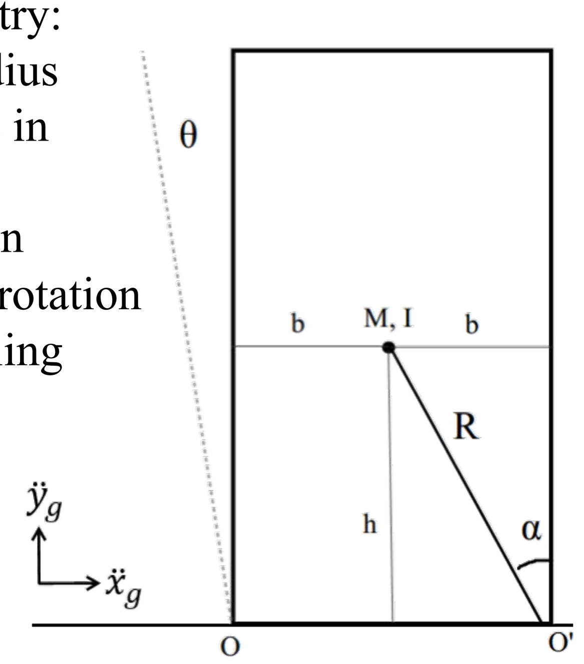

Figure 2: 2D rocking block

OBJECTIVE

Determine impact of geometric variations in the three-dimensional footprint and contact area of freestanding structures on their seismic response and the rate of overturning, through:

- Scaled shake table tests
- Systematic variation of footprint, while 2D projection is consistent

EXPERIMENTAL PROGRAM

Approach

Scaled shake table tests are conducted to evaluate the impact of varying three-dimensional footprint geometry on the rate of overturning

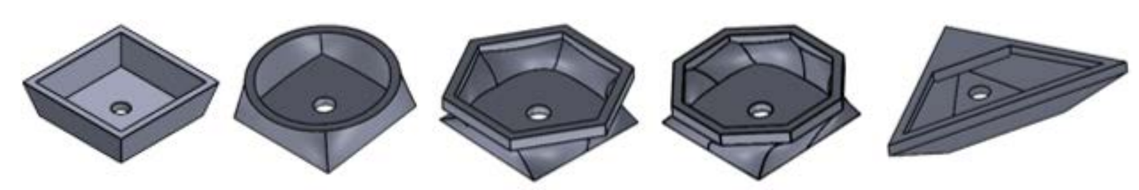

Figure 3: Model footprints with varying geometry

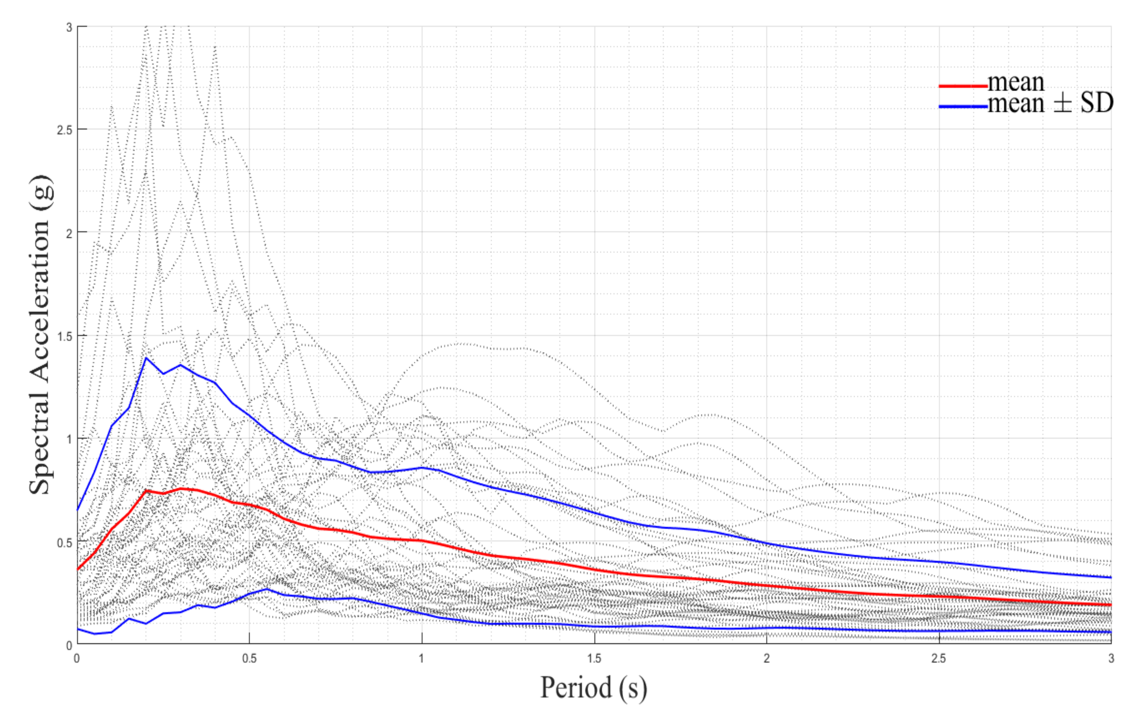

Figure 4: Elastic response spectra for 50 input motions

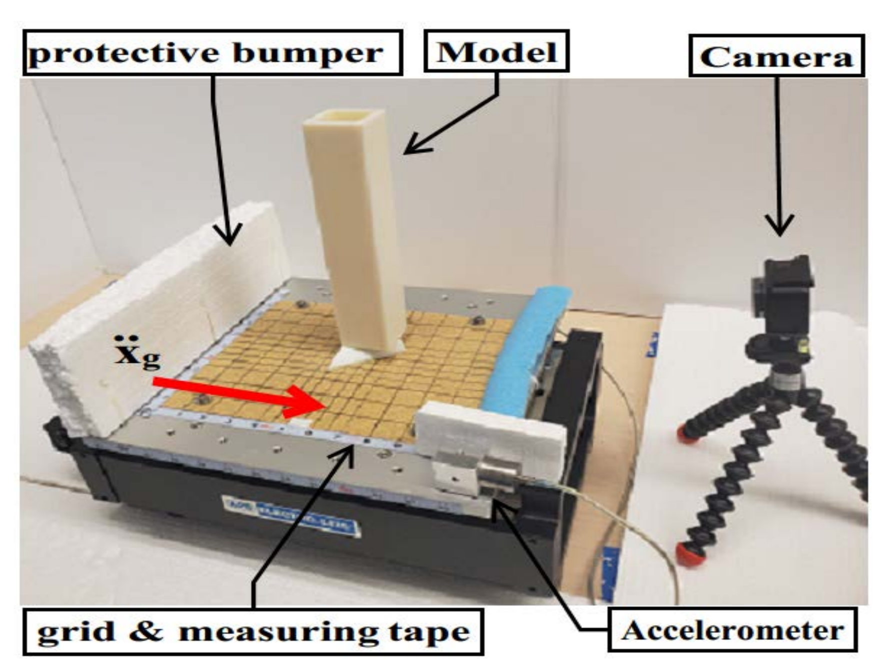

Figure 5: Test instrumentation and setup

Structural Models

- Single rectangular tower of 10 in. x 2 in. x 2 in. was 3D printed with rigid material
- 5 footprints were modeled and printed to maintain consistent 2D projections (see Figure 3)
- Each model consisted of the same tower with unique footprint bolted to the base

Input Motions

- Large quantity of motions necessary due to the known sensitivity of rocking problem
- 50 recorded near-fault earthquake motions obtained from PEER NGA Database, with selection targeting a large range of PGV/PGA
- Each motion scaled to 4 PGA bins to achieve a wide range of intensities with distribution across matrix of PGV/PGA and PGA values, which correlate with rocking demands
- Response spectra for the 50 unscaled motions included in Figure 4

Test Setup

- Unidirectional shake table
- 200 individual tests (motions) for 5 models
- Acceleration of the shake table recorded
- Sandpaper fixed to table platen to encourage rocking responses
- Grid used to quantify displacements
- Observation of response mode and overturning recorded manually and by video for each test

RESULTS

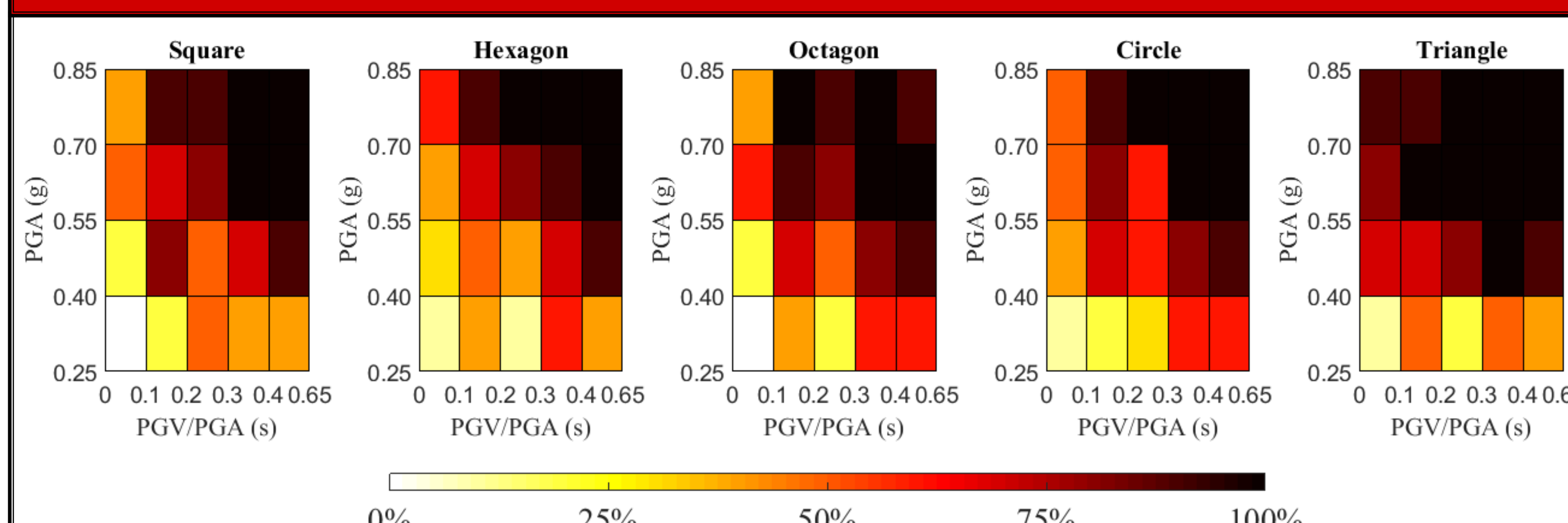

Figure 6: Colormaps illustrating the rate of overturning by footprint geometry

RESULTS

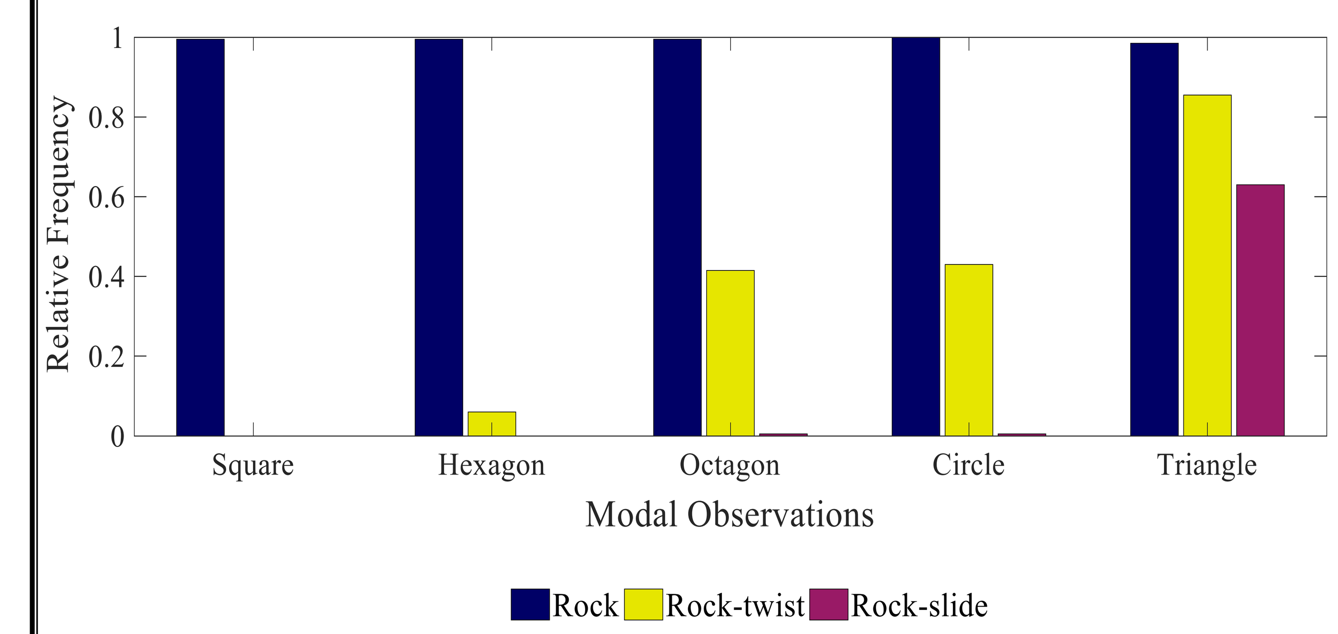

Figure 7: Relative frequency of modal occurrence by footprint geometry

CONCLUSIONS

Despite variations in the 3D footprint, the rate of overturning was largely consistent

- While response varied widely for an individual earthquake motion, rate of overturning was consistent
- Stability compromised when rocking on point instead of edge
- Longer edges perpendicular to acceleration tend to be more stable
- Less stable structures exhibit higher variety of response modes
- Less stable structures significantly more likely to overturn
- Triangular footprint least stable in the test series
  - Approached 100% overturning faster than other geometries
  - Forced to rock on point
  - Narrow angle between edges incites instability

Implications

- 2D projections can be used to model overturning for unidirectional base excitations unless forced to rock on a point
- Future work should attempt to utilize 3-dimensional motions

REFERENCES

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ACKNOWLEDGMENTS

- This research utilized the Nano-Engineering Research Core Facility (NERCF) at the University of Nebraska–Lincoln, which receives funding from the Nebraska Research Initiative.
- UNL McNair Scholars Program, for funding the first author.
- Gabriela Yáñez González, for her assistance with testing.

MCNAIR SCHOLARS PROGRAM