GEO-STRUCTURES
Earthquake Engineering Resilience

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Joint Academia-Industry NHERI Workshop
NHERI@UC San Diego

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University of California, San Diego
FACT: Smaller Events ≠ Less $ or Lost
increasing urbanization, climate change

2018 “unremarkable” for natural hazards with many smaller disasters

Immense toll:
13,500 ♥ lost (vs. 11,000 in 2016).
155B $ losses → 76B in pay-outs (Swiss Re), 4th highest ever

Trend: “new norm” of higher-frequency, more localized events, many related to extreme weather, causing ever greater damage.

With climate change, if extreme events affect a new densely populated area, what was once a small localized event will become now a catastrophic event.
Resilience

Foundation of a new Babel Tower?

Google Searches past 15 years
Bruneau & Reinhorn (2019)

<table>
<thead>
<tr>
<th>SEARCH</th>
<th>2016</th>
<th>2000</th>
<th>factor</th>
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</thead>
<tbody>
<tr>
<td>Resilience</td>
<td>47,000,000</td>
<td>7,880,000</td>
<td>6</td>
</tr>
<tr>
<td>Engineering Resilience</td>
<td>17,300</td>
<td>6,200</td>
<td>3</td>
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<tr>
<td>Quantifying Engineering Resilience</td>
<td>3</td>
<td>1</td>
<td>3</td>
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Bruneau & Reinhorn, 2019

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What do I think?

**Disasters: When/How not If**
- multi-hazard predictions
- climate change
- natural/urbanized environment

**Resilience is a Choice**
- making *informed decisions* based on risk assessments with best knowledge, science, technology, while optimizing funding allocation.
- Simple: *it works* (6-fold return in federal investments)
- Society: building *trust in engineering* through performance

**Do vs. Have Park et al. 2012**
- Emergent property of what an engineering system does, rather than a static property the system has; outcome of a recursive process with sensing, anticipation, learning, and adaptation, making it complementary to risk analysis with important implications for the adaptive management of complex, coupled engineering systems.
Life Safety is NOT Enough

“Life Safety” objective → no loss of life after an extreme event. The structure gives the chance to get out of it alive, while it may be heavily damaged or need to be demolished later.

Life quality, rather than life safety represents societal needs of resilience as not a “bouncing back” but rather “bouncing forward” strategy that relies on Functional Recovery (NIST-FEMA, 2020) goals.
WISDOM OF THE PAST

NBS [NIST] ATC 3-06 (1978): It really is the **probability of failure** with resultant **casualties** that is of concern......The geographical distribution of that probability is **not necessarily same** as the distribution of probability of exceeding some ground motion....
“Although.. Codes of Practice begin with good intentions, they often constrain innovation + ingenuity ... eventually becoming the only basis of acceptable design.”

RESILIENCE-BASED GEOTECHNICAL EQ DESIGN

FS >> 1
FS ~1.0
large deformations

Frequent
Rare
Very rare

Seismic Hazard

Ref: Geostrata ASCE (Nikolaou, 2013)
RESILIENCE-BASED GEOTECHNICAL DESIGN

FUNCTIONAL RECOVERY GOALS
NIST-FEMA (2020)

Remain operational after medium-intensity earthquakes

Preserve structural integrity under extreme loading

Demonstrate redundancies
Resilient Foundation Design
Example - Earth Retaining Systems
RESILIENCE-BASED GEOTECHNICAL DESIGN
Example: Earth Retaining Systems

“equivalent” Walls → Safety Factor (FS) strength-based

Shaking Levels

Low intensity within design levels

Extreme Event well beyond design
**FACTOR OF SAFETY (FS)**

*Equivalent Wall (FS) Systems*

A: Tangent Pile Wall
- Backfill \( \phi = 37^\circ \)
- \( c = 5 \text{kPa} \)
- Depth: 10 m
- Width: 1.2 m

B: MSE Wall
- Depth: 10 m
- Width: 7 m

Static
FS\(_{\text{st}}\) = 1.8

Pseudo-Static
FS\(_{\text{EQ}}\) = 1.2
\( (\alpha = 0.16 \text{ g}) \)
TRANSVERSE BARS

*from actual pull-out tests*

National Technical University of Athens, Soil Dynamics Laboratory
Resilience-Based Geotechnical Application
Numerical Analysis for FS

A: Tangent Pile Wall

- Static: $\text{FS}_{st} = 1.8$
- Pseudo-Static: $\text{FS}_E = 1.2$

B: MSE Wall

- $q = 10 \text{kN/m}$
- $\alpha = 0.16 \text{g}$
- $\text{FS}_{st} = 1.8$
- $\text{FS}_E = 1.2$

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INPUT GROUND MOTIONS

Spectral Acceleration SA : g

Period T : s
DYNAMIC RESPONSE
Top of Wall Displacement

PGA ≈ 0.4g
Gilroy, Loma Prieta (1989)

PGA ≈ 0.8g
Rinaldi, Northridge (1994)

\[ \delta_{\text{top}}: \text{cm} \]

"Dynamic Response" [Diagram]
DYNAMIC RESPONSE
Top of Wall Displacement

**Gilroy, Loma Prieta (1989)**

PGA ≈ 0.4g

<table>
<thead>
<tr>
<th>t (s)</th>
<th>δ_{top} (cm)</th>
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<td>3</td>
<td>5 cm</td>
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<tr>
<td>8</td>
<td>14 cm</td>
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**Rinaldi, Northridge (1994)**

PGA ≈ 0.8g

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<th>t (s)</th>
<th>δ_{top} (cm)</th>
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<td>30 cm</td>
</tr>
<tr>
<td>8</td>
<td>50 cm</td>
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*MSE wall behaves significantly better*

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PERFORMANCE QUANTIFIERS

Extreme Excitation (Rinaldi)

Quantification of Performance
Pile Wall: Moment-Curvature at fixity (left)

PILE WALL
MOMENT-CURVATURE AT FIXITY

M: kN m
0 500 1000 1500 2000
0 0.005 0.01 0.015 0.02
1/r

capacity curve
end of shaking

M: kN m

PGA ≈ 0.8g
x: m
7
3.5
0
Row 7
Row 17 (bottom)

MSE WALL

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PERFORMANCE QUANTIFIERS

Extreme Excitation (Rinaldi)

Quantification of Performance
MSE Wall: Axial stresses along rib length
@ middle, bottom heights

Axial Stress

PGA ≈ 0.8g

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PERFORMANCE QUANTIFIERS

Extreme Excitation (Rinaldi)

Quantification of Performance
Pile Wall: Moment-Curvature at fixity

PILE WALL
MOMENT-CURVATURE AT FIXITY

M: kN m

0 500 1000 1500 2000

1/r

0 0.005 0.01 0.015 0.02

σxx: MPa

0 50 100 150 200 250 300

PGA ≈ 0.8g
x : m

Row 7
Row 17 (bottom)

σyield

MSE WALL
AXIAL STRESSES ALONG RIB

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REDUNDANCY EVALUATION

MSE Wall

Full Reinforcement

Half Reinforcement

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MSE Wall Redundancy Evaluation

full reinforcement

0.6 m

half reinforcement

1.2 m

Plastic strain contours
Both systems *may avoid collapse* during strong earthquakes, but the *pile wall deformation* would be unacceptable.

The *MSE system* is more *redundant*, making it likely to sustain multiple & smaller events offering both risk optimization and cost-effectiveness.

Reviewing in-depth *numerical results* provide valuable insight in the behavior of the system.

**Actual Observations**

2011 Tohoku, Japan Earthquake

> 98% of ~1,400 Reinforced Soil walls had only *light to non-existent* damage...

Ref: Kuwano et al. (2014)
This could save me money!

This could sponsor my research
DARE

to Think Differently, Beyond Codes

Is Stronger Better?
IS STRONGER BETTER?
Intentionally **UNDER-design** the foundation so plastic "hinging" will develop at soil. Utilize soil **DUCTILITY**, Allow **FS < 1**!!!
LEARNING from EARTHQUAKES
Why Did this Work?
2014 Greece EQs
1995 Havdata RC Structure ~ 2 km north of CHV1

Ground Motion Simulation

Ref: Structure (2015); GEER-034 (2014)
Resilient Behavior Explained

Structural Period (with infill)
$T_1 \sim 0.08 \text{ s}; \ T_2 \sim 0.05 \text{ s}$

without infill
$T_1 \sim 0.31 \text{ s}; \ T_2 \sim 0.26 \text{ s}$

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VISUALIZATION TO COMMUNICATE WITH OTHER DISCIPLINES

DISPLACEMENT RECORD

North - South

East - West

North Displacement (cm)

East Displacement (cm)
RESILIENCE-BASED GEOTECHNICAL DESIGN
Needs for NHERI @UCSD Shake Table

Understand *fundamental behavior* of both systems

Perform *experiments in various scales* and the laboratory to *calibrate and validate* computational models.

Incorporate *reconnaissance lessons* of success

*Innovate* with materials, concepts and construction methods that can provide *redundancy*

Prove concepts with extreme and *multiple & smaller multi-hazard events* offering both *risk optimization* and *cost-effectiveness*.

*Communicate* and *collaborate* with practice
Many thanks for your attention

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**My collaborators**

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Dr. F. Gelagoti, NTUA  
Dr. I. Georgiou, NTUA  
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“Never, ever, think outside the box.”