Seismic Behavior of Deep Foundations from Large-Scale Liquefaction Shake Table Experiments

A. Ebeido, A. Prabhakaran, Z. Qiu, L. Luo, A. Alumutairi, and A. Elgamal
University of California, San Diego
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Research Associates

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Motivation

- Case history investigations describe a wide range of damage to structures and their pile foundations.
- Experiments are needed as the observed response is limited.
- Efforts are needed to help reduce conservatism and uncertainty in the State of Practice.
Earlier Research

Topic Subjected to Intense Research Over Last 30 Years

Abdoun, Ashford, Boulanger, Brandenberg, Bray, Cubrinovski, Dobry, Hutchinson, Ishihara, O’Rourke, Kutter, Knappett, Madabhushi, Motamed, Shantz, Suzuki, Tokimatsu, Towhata, Wilson

Abdoun & Dobry 2002
Tokimatsu et al. 2004
Brandenberg et al. 2005
El-Sekelly et al. 2016
Madabhushi et al. 2016

UC Davis, RPI, UCLA, UC Berkeley, Japan, Europe, Asia, …
General Research Objectives

Further assess liquefaction and lateral spreading loads on new and existing bridges

- Explore \( p-y \) curve response via experimentation, and address simplified methods
- Develop tools to more accurately represent global bridge-ground system response (e.g., U. Washington, UC Berkeley, ........)


Spreading-induced damage of short-span bridge (after Cubrinovski et al. 2011)
1g Shake Table Lateral Spreading Experiments
1.8 m high, UC San Diego Shake table tests (Prof. Dobry, RPI Setup)

Laminar container provided by Prof. Scott Ashford, UCSD
UC San Diego Shake table test
UCSD Inclined Laminar Container on Shake Table

4° Ramp

3.90 m

2.90 m

1.80 m
UCSD Large Inclined Laminar Container on outdoor shake table

- 4.90 m
- 6.75 m
- 4° Ramp
Experimental Program
Experimental Program

1.84 ton Head Mass

Dry Crust

Loose Sand

Dense Sand

4° INCLINED LAMINAR CONTAINER BASE

0.70 m

0.70 m

2.90 m

1.50 m

Pressure Transducer
Strain Gauge × Pore Pressure Transducer ⬤ Accelerometer □ LVDT ➔
Experimental Program

\[ D_r = 100\% \]
\[ D_r = 80\% \]
\[ D_r = 60\% \]
Results

Single loose sand stratum

[Diagram of a steel pile with sensor placements and graphs showing displacement, bending moment, and excess pore pressure ratio over time.]
Two layer layout: 2° and 4° Inclined models

Pipe Steel Pile
Outer Diameter 25 cm
Thickness 3 mm

UPSLOPE ARRAY

DOWNSLOPE ARRAY

INCLINED LAMINAR CONTAINER BASE

Strain Gauge × Pore Pressure Transducer ● Accelerometer □ LVDT

1.95 m 3.90 m 1.95 m

1.10 m 0.70 m 1.80 m
Results

- Increase in ground inclination caused an additional 60% - 75% in bending moment and pile head displacements
Higher locked-in driving shear stress in the 4 degree scenario triggered the crust to start moving earlier, with lower excess pore pressure ($r_u=0.70$ vs $0.95$).
Further accumulation of soil displacement, caused no appreciable increase in pile bending moment
10 ft (2.9 m) height

(3.9m long x 1.95m wide x 2.9m high)
10” RC Pile (174” Length)
Top Mass (2 tons)
Ottawa Sand
UCSD RC Test 5 (10 ft high) General Response

- **Crust**
- **Isolation**
- **Drift**
- **Dense**

Graphs showing acceleration and excess pore pressure over time for different depths and locations.
Results

Reinforced Concrete 10 foot high (UCSD 2017)

- **Upslope Side**
- **Downslope Side**

**Dry Crust**
- (1) 0.25 m
- (3)
- (5)
- (7)
- **Loose Sand**
- 0.70 m
- (9) 0.70 m
- (11) 12 x 15.5 cm
- (13) Average Crack extends to more than \( \frac{1}{2} \) the Perimeter
- **Dense Sand**
- 0.33 m
- 0.20 m
- **Failure and rebar exposure on tension side & crushing on compression side at base**

**Notes:**
- 6x#3 bars (Longitudinal)
- #3 bars @ 8 in spacing (Spiral)
• Video – 5m Steel Pile (Test 6)
Experimental Program

Shaking Table Tests: US-Japan Research (UCSD, NSF, NIED, PEER, CALTRANS)
5m height: Liquefaction-Induced lateral Spreading Effects on Piles (NIED, Tsukuba)
Kohji Tokimatsu, Masayoshi Sato, Akio Abe, Tom Shantz
Experimental Program

NIED, Japan

4 Large-scale Mildly Inclined Tests
Before

1m of Lateral Spreading ( > 3 pile diameters)

After

Very Large Shear Strains!

NIED, Tsukuba, Japan (K. Tokimatsu, M. Sato, and A. Abe)
NIED Japan Experiment 4  Pile Lateral Response

Stiff (S) Pile
NIED Japan Experiment 3  Pile Lateral Response

Stiff (S) Pile
Pile Lateral Response

Motamed & Towhata (2009)

Abdoun et al. (2003)
Pile Lateral Response

UCSD 2017 Experiment 1
Pile Lateral Response

UCSD 2017
Experiment 4

UC San Diego
Structural Engineering
Developed $p$-$y$ Curve

\begin{align*}
\text{Normalized force } [p/(S_r D)]
\end{align*}

\begin{align*}
\text{Dimensionless displacement } [y/D]
\end{align*}

- **Proposed spring**
- **Goh and O’Rourke 2008**
UCSD $p$-$y$ curve verification

NIED Japan Experiment 4
Lateral Response Conclusions

- Soil softening behavior for lateral response is needed for a more accurate estimation of loads.
- One vital part of the softening response is the reduction in lateral force demands on piles. By the time the bottom springs peak, the upper ones are at the residual stages.
- The developed $p$-$y$ curve is recommended for modelling liquefaction induced lateral spreading mechanism.
- The behavior is different from the existing recommended Soft Clay Matlock model for the liquefied sand.
NIED Japan Experiment 3  Crust $p$-$y$ Relationship

Brandenberg et al. (2007)
Crust $p$-$y$ Relationship

NIED Japan Experiment 3

- West Array
- Center Array
- East Array

Brandenberg et al. (2007)

Liquefied soil $p$-$y$ curves

LVDT  □ Accelerometer  ▪ Pore Pressure Center  × Strain Gauge

Lateral Spreading Effects on Pile Foundations
Crust $p$-$y$ Relationship

Lateral Spreading Effects on Pile Foundations
A computational user interface (MSBridge) is developed to combine nonlinear (THA) with an implementation of the PEER PBEE methodology.

OpenSees is employed to conduct the Nonlinear THA.

Displays seismic response ensembles and PBEE outcomes (pre- and post-processor)

http://soilquake.net/msbridge
Rollins
UCSD
Matlock
Reese
Liquefied
Liquefied
Sand
Clay
Simplified Analysis

(Brandenberg et al., Ledezma and Bray)
I. Abutment Pile

II. Full Bridge

Global Modeling vs Abutment Pile

- Abutment Response
- Pile Response
- Pile Response (Full Bridge)

Resistive Force (kips)

Displacement (in)

22 inches

28 inches
**The Bridge: 197m long and 9.9m wide, 18-span**
Figure 1 Bridge configuration: (a) Plan view; (b) Elevation view and cross sections.
Liquefaction-Induced Seismic Response

At Maximum Deck Displacement
Ground configuration

- Liquefiable soil
- Spreading-induced deformation mechanism of short-span bridge (Cubrinovski et al. 2014)
- Self-weight of deck \( q = 11 \text{kN/m} \)
- Length: 200 m
- Height: 43 m
- Elevation: unit (m)
- Lateral spreading
- Slumping
- Heave
- Back-tilting of abutments
- Pile damage at connection to cap

California Bridge II
At end of shaking: with bridge

0.13 ft
1.2 ft
Mitigation of Liquefaction Effects by Polymer Injection

A. PRABHAKARAN, Dr. K. KIM, M. J. ORANG, Z. QIU, DR. A. EBEIDO, M. ZAYED, Prof. R. MOTAMED, Prof. A. ELGAMAL and C. FRAZAO

UC SAN DIEGO, UNR AND EAGLELIFT

Presented by Ahmed Elgamal
Email: elgamal@ucsd.edu

CalGeo Regional Dinner Meeting: Orange County : June 2019
University of Nevada, Reno
Prof. Ramin Motamed (PI)
University of Nevada, Reno
Prof. Ramin Motamed (PI)

Pre Shake (Benchmark Test)

After Shake02 (Benchmark Test)
INJECTION
Shake01
FE MODEL #2 WITH POLYMER
FE Model #1  Without Polymer

FE Model #2  With Polymer
Geotechnical/SSI Simulation Tools

http://soilquake.net

- Single pile
- m x n pile group
- Piled Raft
- Embedded Structure
- Shallow Foundation
- Stone Columns
- Ground Modification By Cellular Walls
Experimental Program
MSBridge: Capabilities

Curved bridge with foundation and soil springs

Bridge with different number of nonlinear fiber element columns for each bent

*p-y* springs: a) Soft clay (Matlock); b) Stiff clay without free water (Reese); c) Sand (Reese); and d) Liquefied sand (Rollins)

Foundation matrix (Lam and Martin 1986)