# *Foundation Rocking as a Bridge Design Strategy*

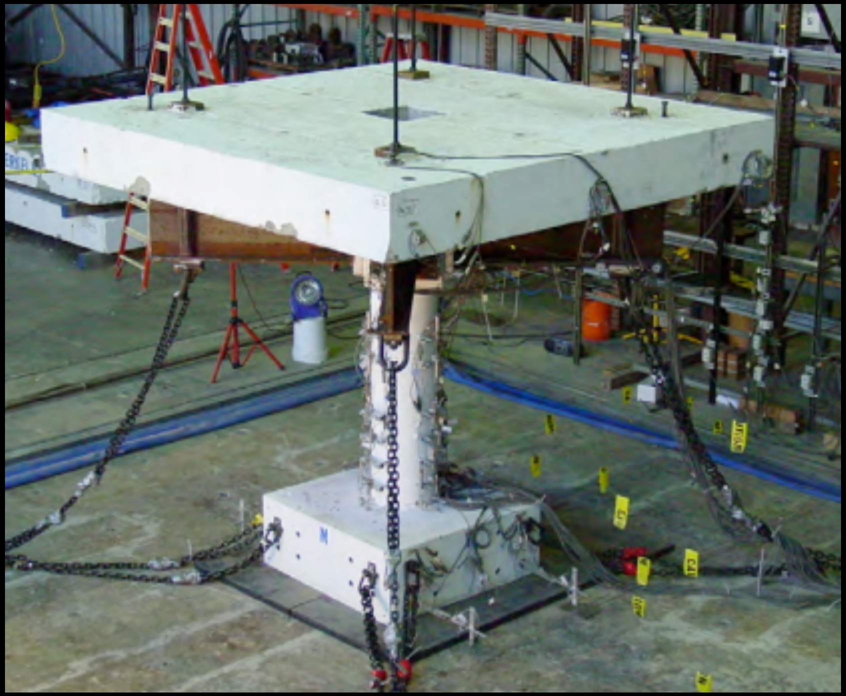
*Marios Panagiotou*
*Assistant Professor*

*University of California, Berkeley*

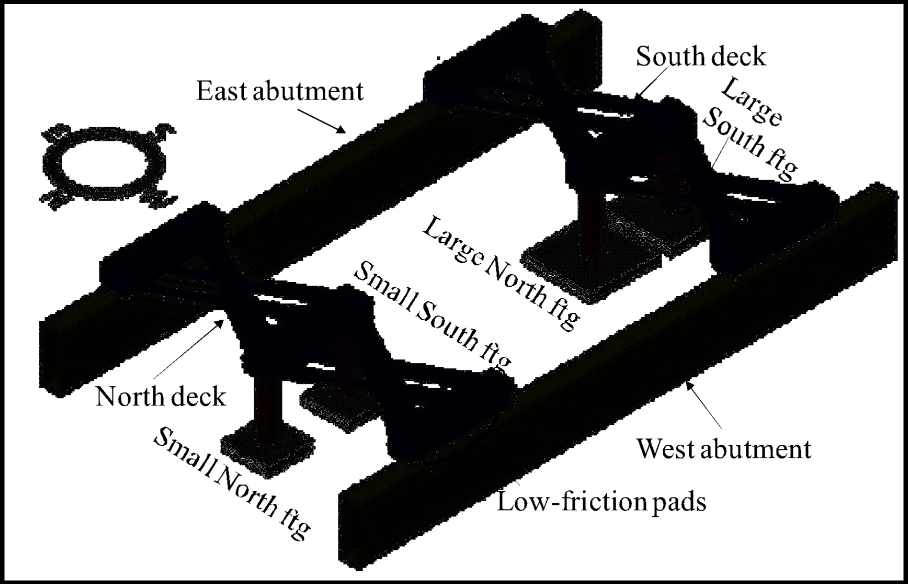
# Past Research on Rocking Foundations

***Numerical*** studies of single piers (Muto, Chopra and Yim), rigid blocks (Housner, Zhang and Makris) and bridge systems (Mergos and Kawashima)

***Experimental*** studies include Caltrans-funded studies :



Shake table tests of bridge piers on rocking shallow foundations
*Espinoza and Mahin (2008)*




Centrifuge tests of Systems
*Deng, Kunnath and Kutter*

# *Question*

Can we design economical bridges at near-fault sites
using rocking foundations to
minimize earthquake induced damage and
ensure post-earthquake functionality ?

# PART I

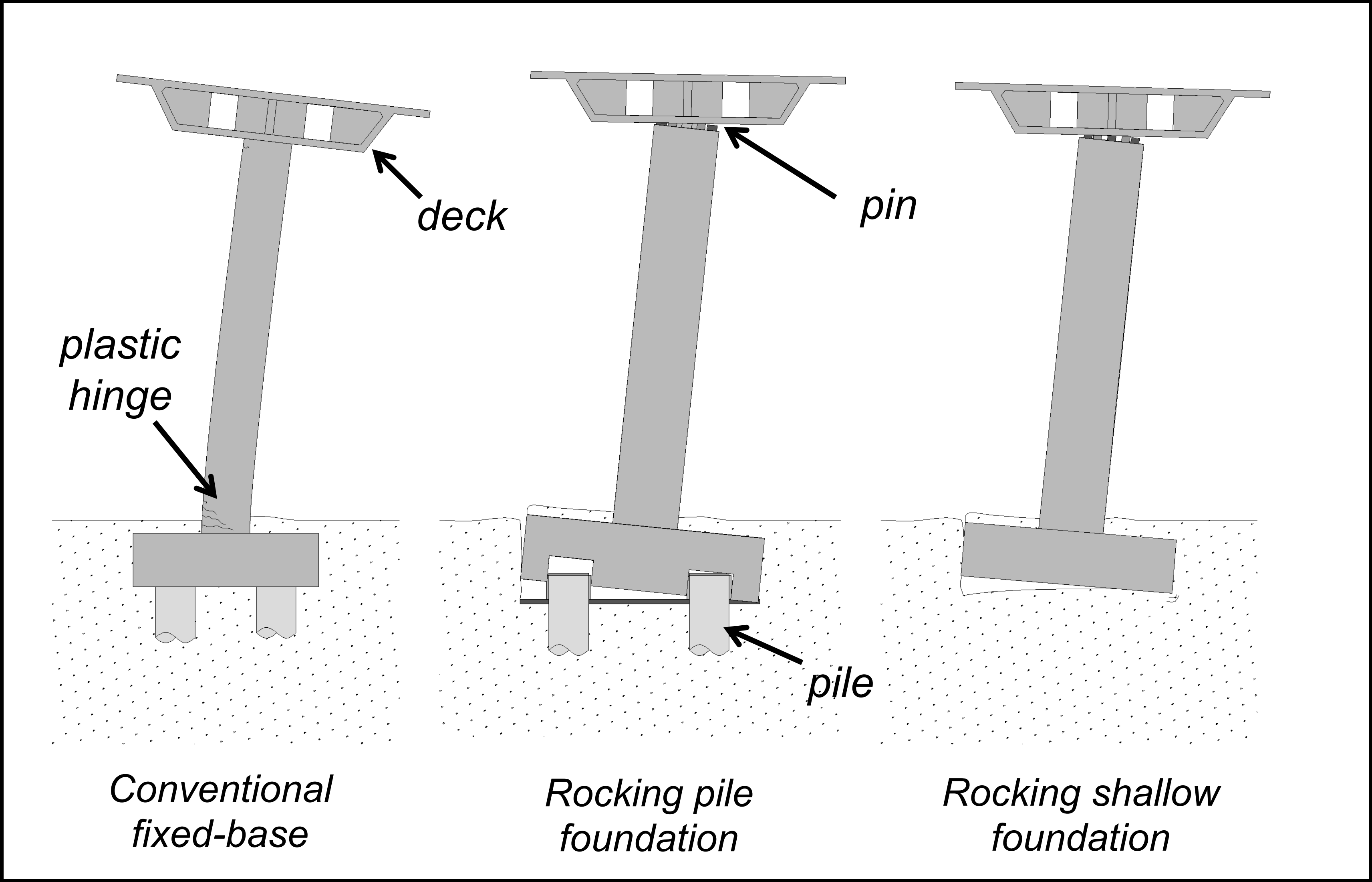
# Seismic Design and Analysis of Bridges with Rocking Foundations at a Near-fault Site

Grigorios Antonellis
Graduate Student Researcher

Marios Panagiotou
Assistant Professor

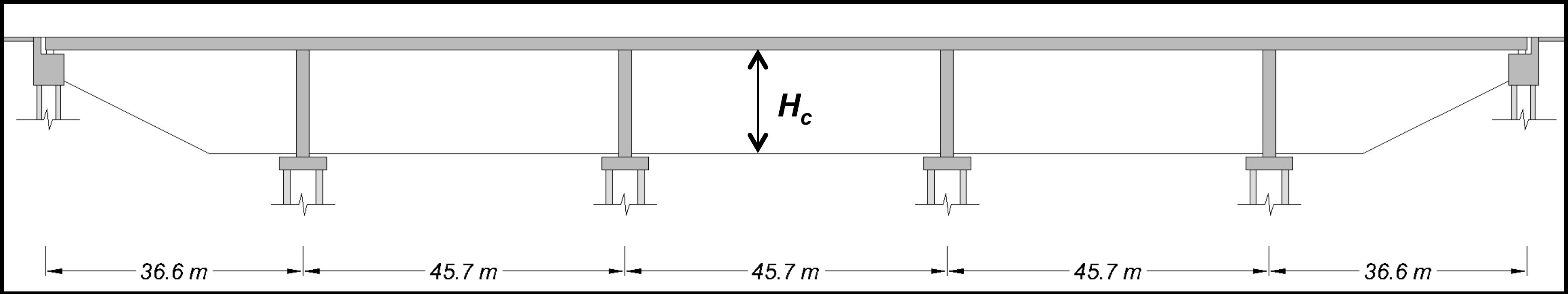
University of California (UC) Berkeley

# Design concepts studied

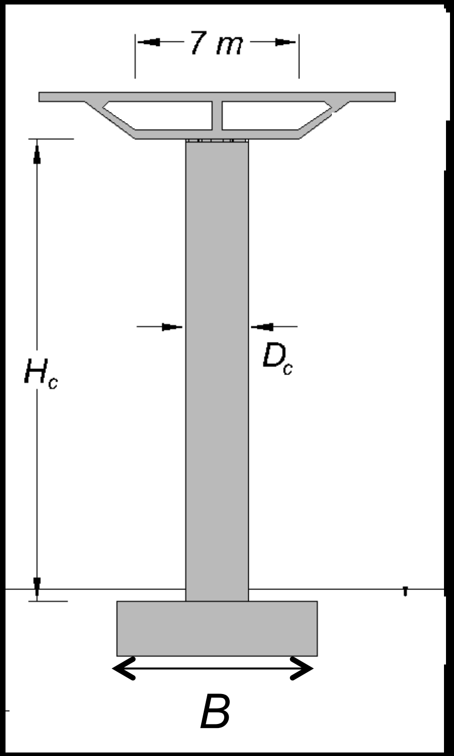



**FB** **RPF** **RSF**

# Geometry of bridges




(a) Side view

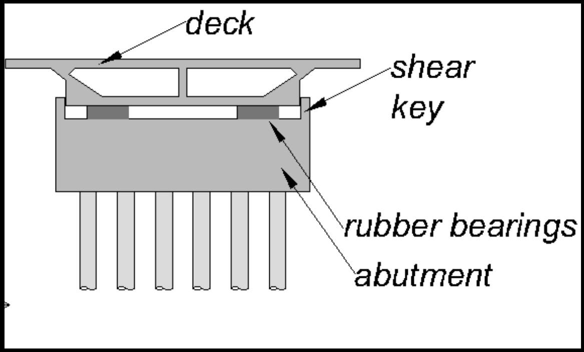



(b) found.-column-deck elevation

Two column heights

$H_c$ = 15.2 m

$H_c$ = 6.7 m

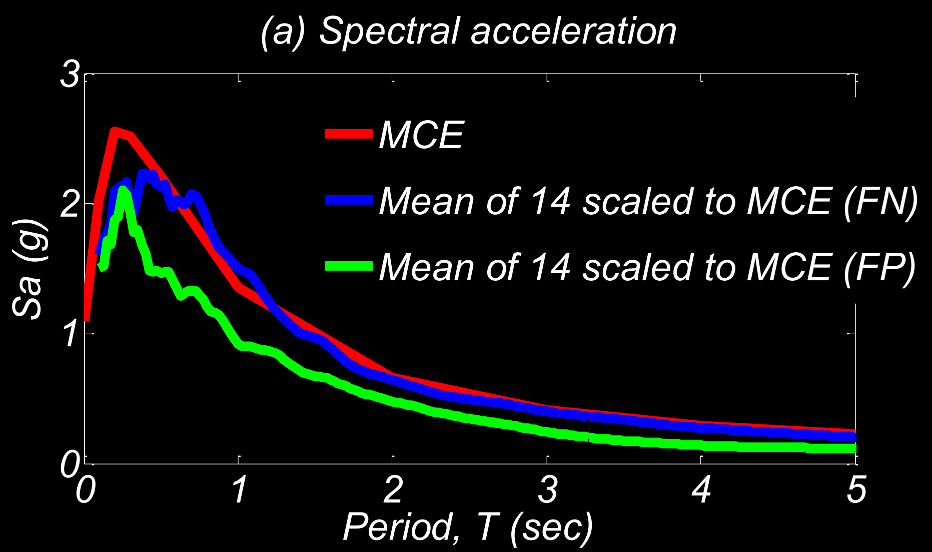


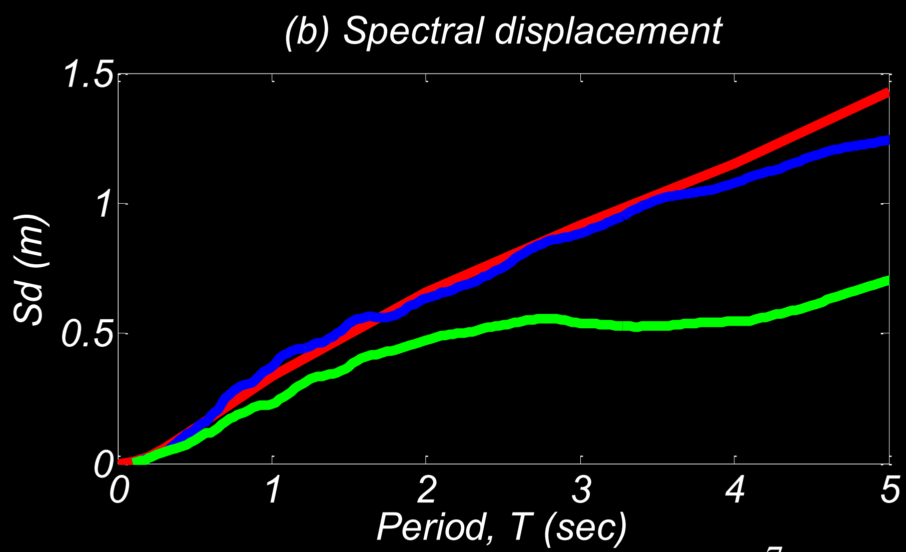

(c) abutment-bearings section view

# Description of site and ground motions

- *Site: Oakland, California, 3 km from Hayward fault, $V_{s,30}$ = 400 m / s (Soil type C)*
- *Bi-axial horizontal excitation*
- *14 ground motions linearly scaled*


*Maximum Considered Earthquake (MCE) : 2% probability of exceedance in 50 years*



# Design of bridges

## Fixed-base bridges

- $D_c$ = 1.8 m, $\rho_l$ = 2%
- *Rubber bearings* $D_b$ = 0.6 m

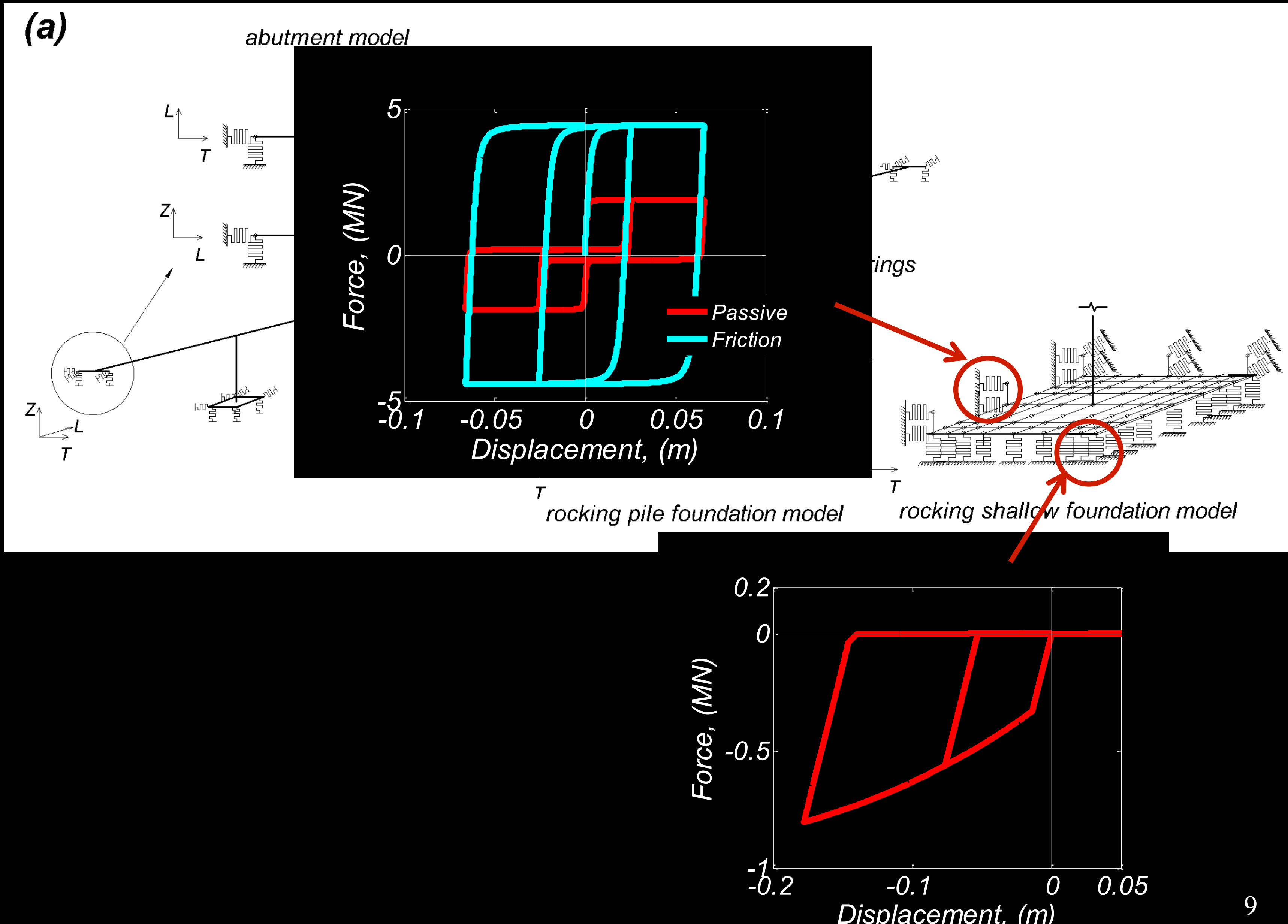
## Rocking foundation bridges

**Design Objectives at MCE**

- Nominally elastic response of columns, deck and piles
- Less than 0.03B soil settlement

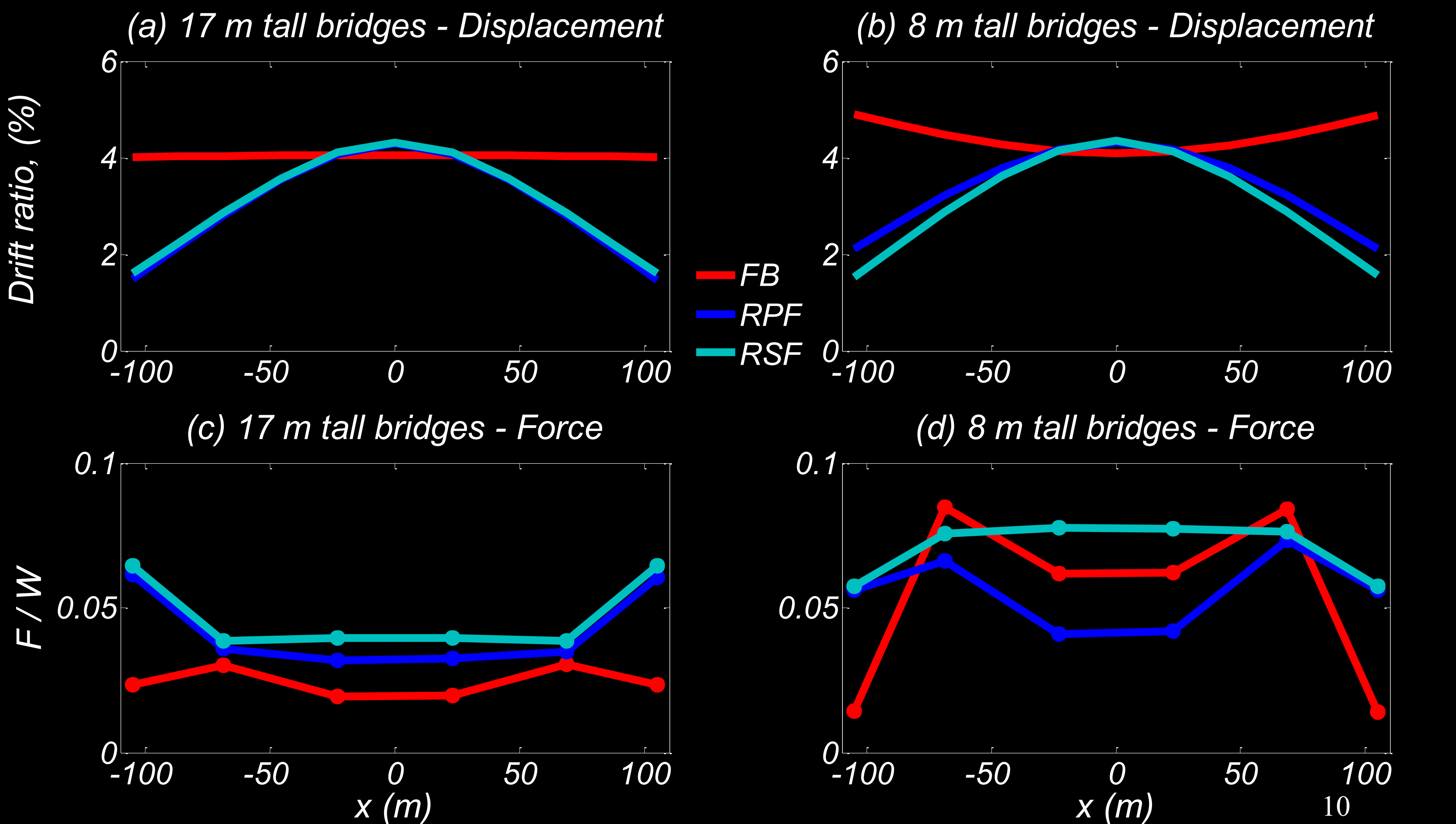
- $Dc$ = 2.5 m, $\rho_l$ = 3%
- *Lead rubber bearings*
  $D_b$ = 1.3 m, $D_{lead}$ = 0.34 m
- *Square B=8 m shallow footings*
- *25 m long piles -1.5 m diameter*

# 3D Numerical Modeling (OpenSees)



# Analyses results

## Lateral displacement and force profiles at 4% column drift ratio



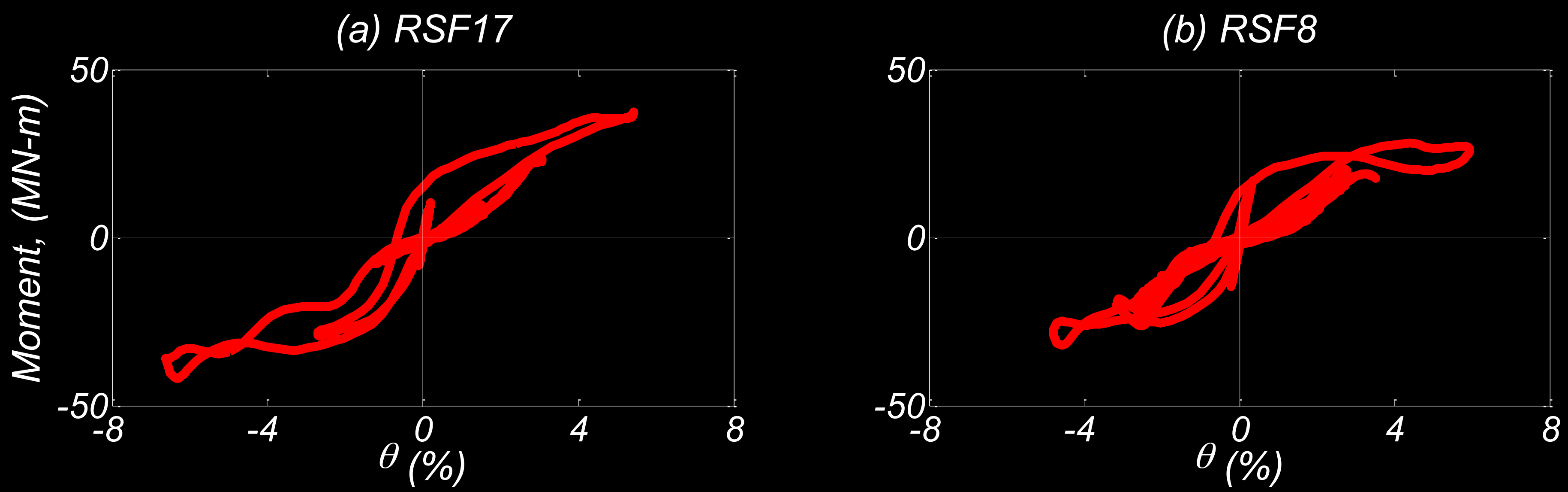
# *Analyses results (mean values)*

| | FB17 | RPF17 | RSF17 | FB8 | RPF8 | RSF8 |
|---|---|---|---|---|---|---|
| Column drift ratio, (%) | 4.9 | 4.1 | 4.0 | 3.6 | 4.6 | 5.0 |
| Residual drift ratio, (%) | 0.15 | 0.01 | 0.17 | 0.07 | 0.07 | 0.16 |
| Tensile strain at column base (%) | 5.3 | 0.2 | 0.1 | 5.6 | 0.3 | 0.1 |
| Column axial compression force increase | 0.2 | 0.7 | 0.4 | 0.5 | 1.3 | 1.0 |

***Less than 0.8% total tension strain in post-tensioning strands of the deck***

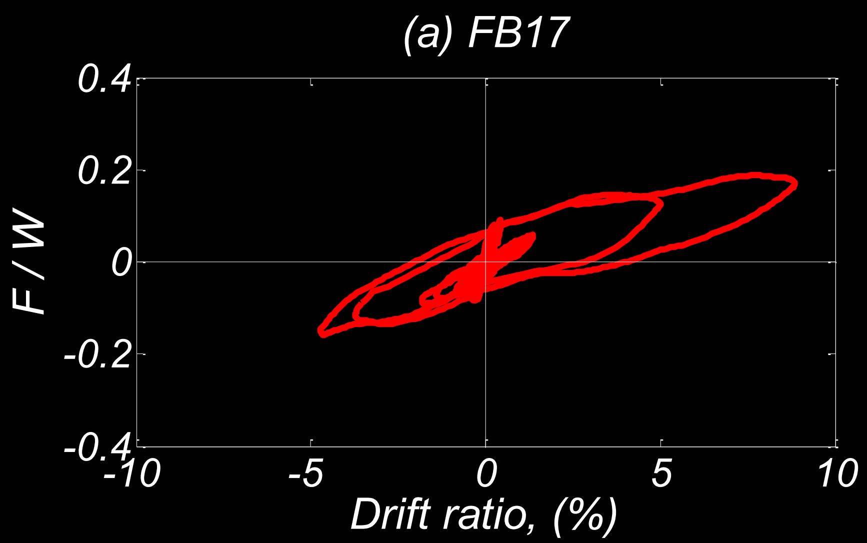
# Analyses results (for individual motion)

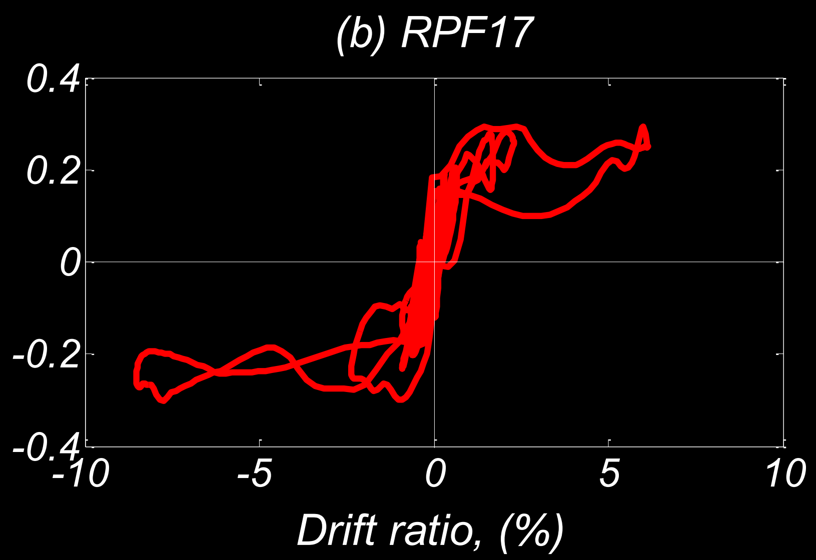
## Shallow foundation moment-rotation response



# Analyses results (for individual motion)

## System lateral resisted force versus lateral drift



# *PART II*

## *Large-scale shake table test of columns supported on rocking shallow foundations*

# Ongoing research project funded by California Department of Transportation (Caltrans)

**Principal Investigators**

Marios Panagiotou, UC Berkeley

Bruce Kutter, UC Davis

Jose Restrepo, UC San Diego

Patrick Fox, UC San Diego

Stephen Mahin, UC Berkeley

**Graduate Student Researchers**

Grigorios Antonellis, UC Berkeley

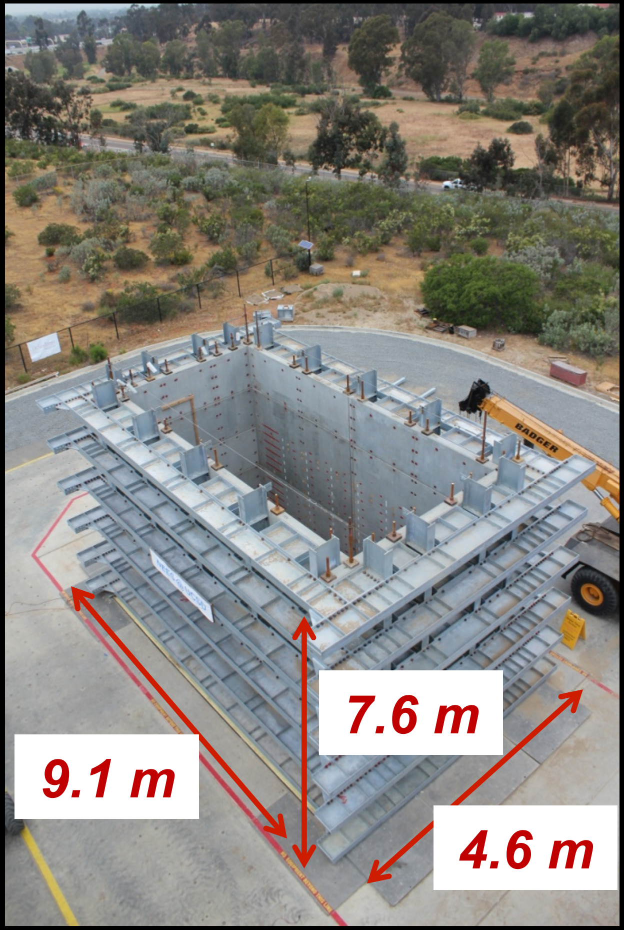
Andreas Gavras, UC Davis

Gabriele Guerrini, UC San Diego

Andrew Sander, UC San Diego

Caltrans

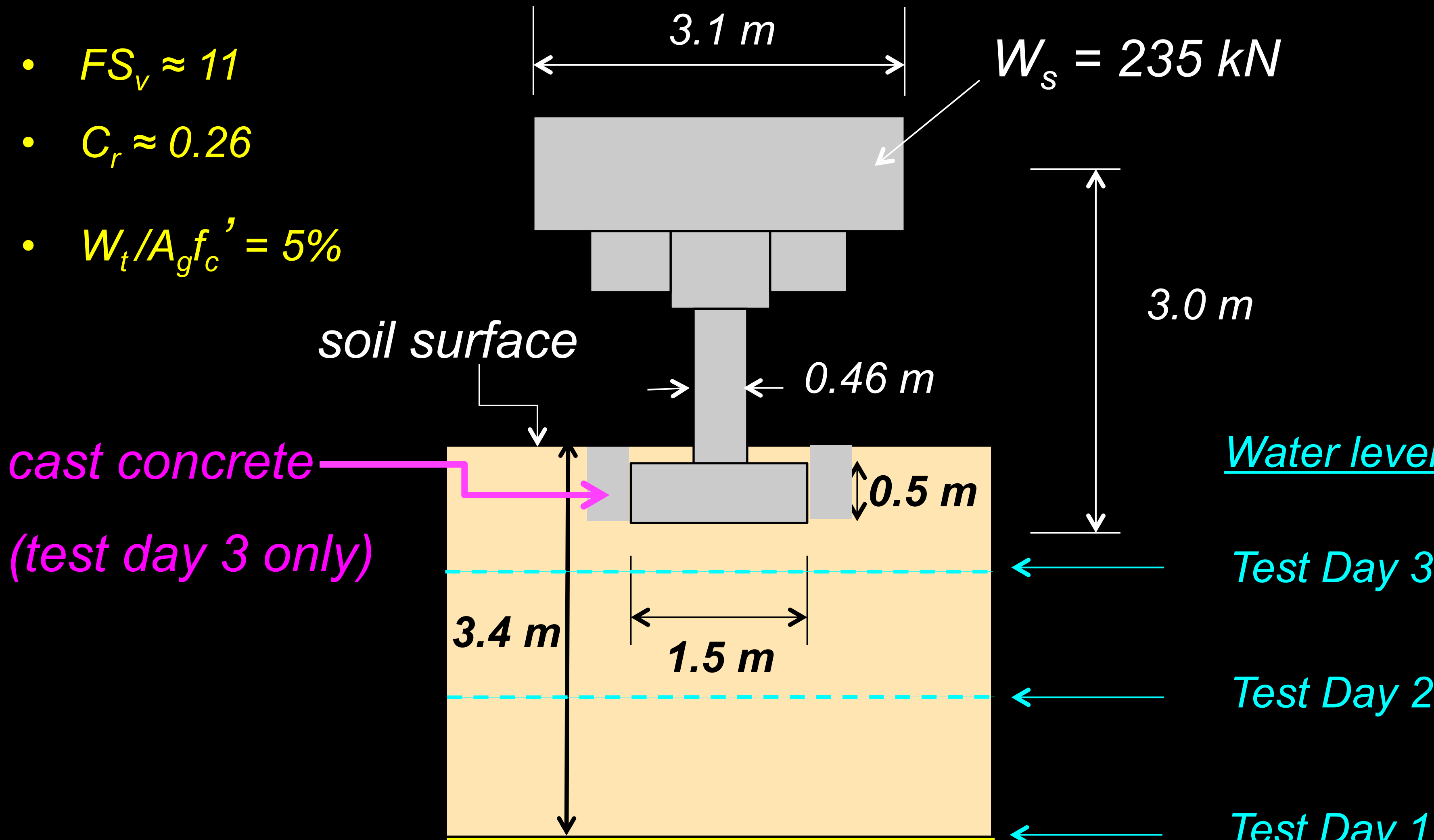
# NEES@UCSD large confinement soil box




# Geometry of the specimens and test setup

- *Clean sand ~ 80% relative density*

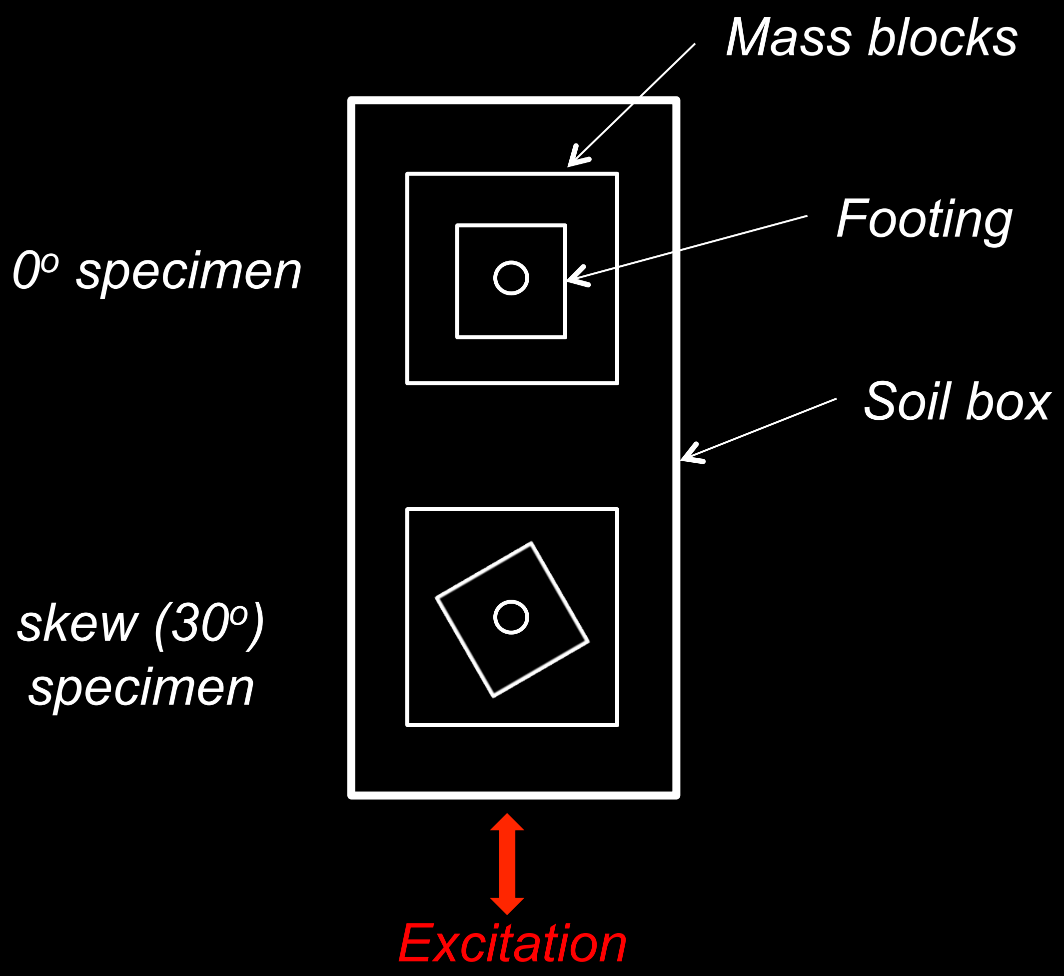
- $FS_v \approx 11$
- $C_r \approx 0.26$
- $W_t/A_g f_c' = 5\%$



# Geometry of specimens and test setup

# Geometry of the specimens and test setup

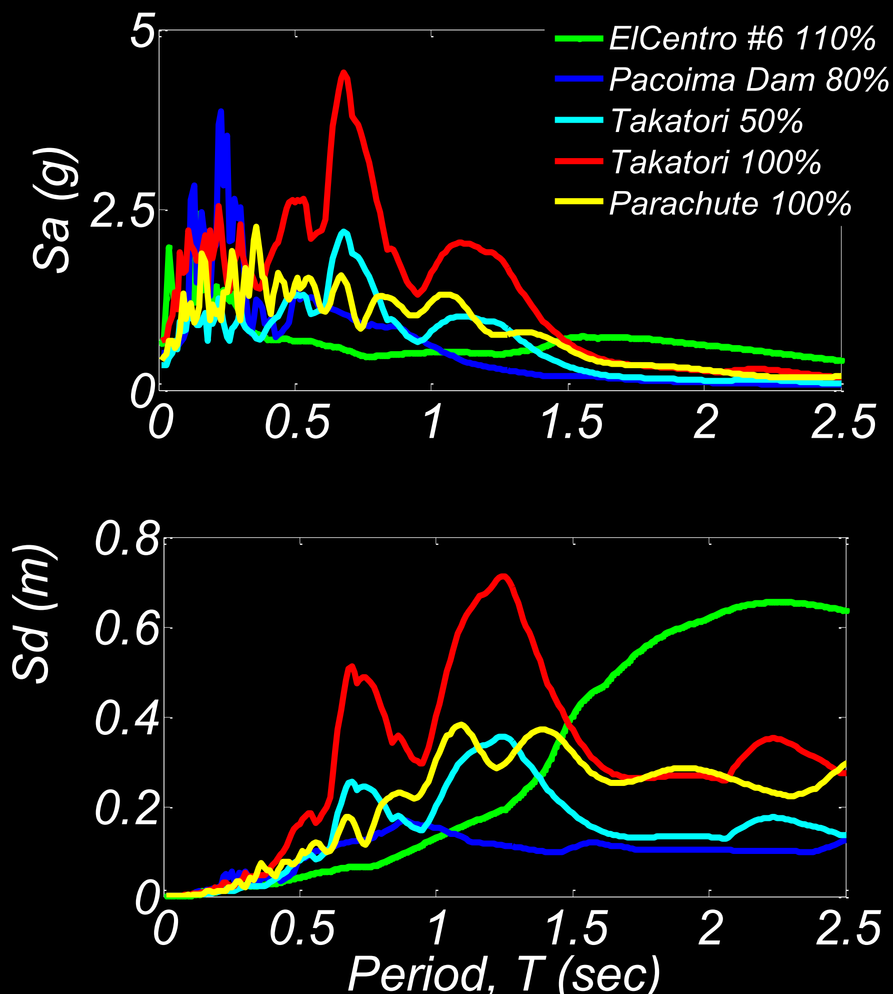
## Plan view




# Test protocol and linear spectra (1% damping)

| | Motion | Scale factor |
|---|---|---|
| 1 | Gilroy Array 1 | 1.0 |
| 2 | Corralitos | 0.8 |
| 3 | El Centro Array 6 | 1.1 |
| 4 | Pacoima Dam | 0.8 |
| 5 | Takatori | 0.5 |
| 6 | Takatori | 1.0 |
| 7* | Parachute Site | 1.0 |
| 8* | Parachute Site | -1.0 |
| 9* | Parachute Site | 1.1 |

**Only for test day 3*




*For all motions the time was compressed by 1.73*

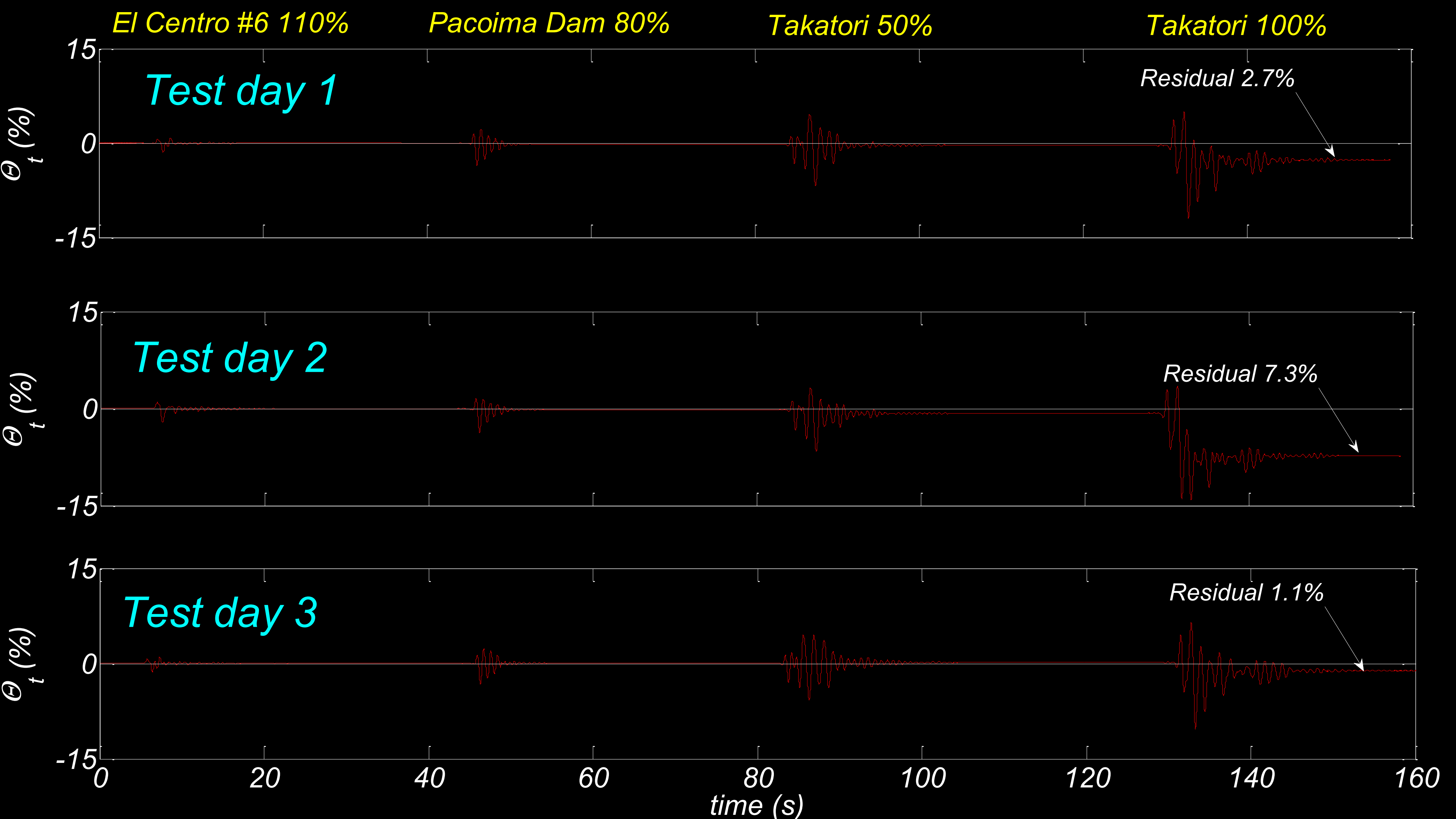
# *Test results – $0^o$ specimen*

## Peak (and residual) responses

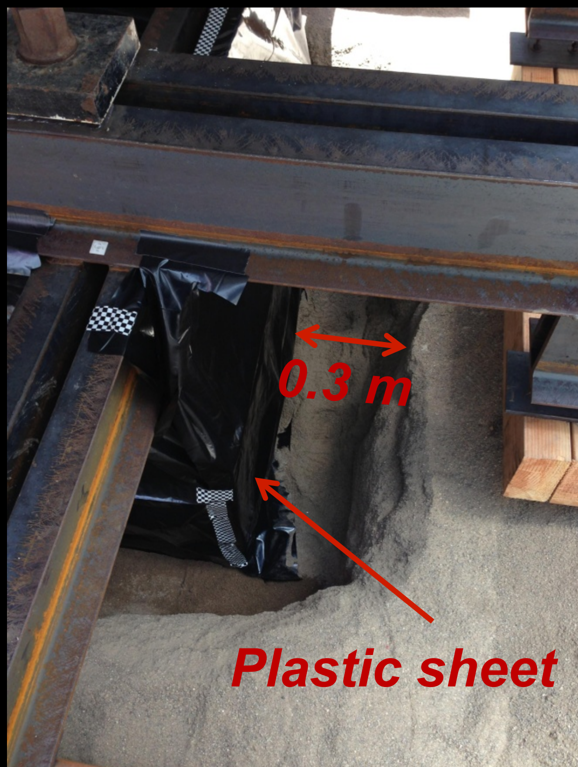
| | **Roof drift ratio, $\Theta_t$ (%)** | | | **Edge settlement (mm)** | | |
|---|---|---|---|---|---|---|
| | Test day 1 | Test day 2 | Test day 3 | Test day 1 | Test day 2 | Test day 3 |
| **Pacoima Dam 80%** | 3.6 (0.2) | 3.7 (0.2) | 3.2 (0.0) | 15 (7) | 18 (7) | 12 (6) |
| **Takatori 50%** | 6.8 (0.4) | 6.7 (0.7) | 5.7 (0.2) | 26 (11) | 26 (12) | 22 (12) |
| **Takatori 100%** | 12.0 (2.7) | 14.2 (7.3) | 10.3 (1.1) | 48 (30) | 54 (44) | 46 (27) |

# *Main results – 0º specimen*

## Drift ratio, $\Theta_t$, response histories



# Test day 3 – detailing around the footings

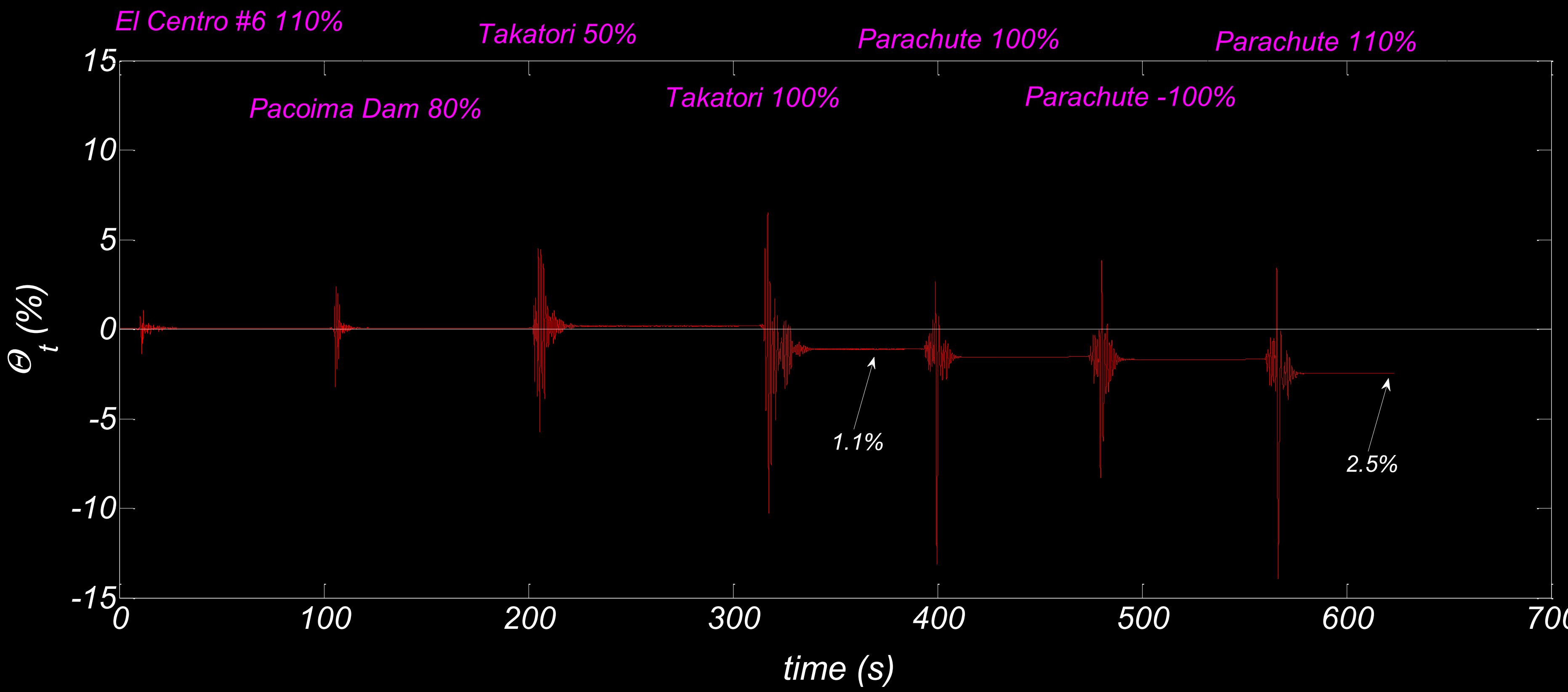




Concrete, $f_c' \approx 3.5$ MPa
(cast one day before the test)

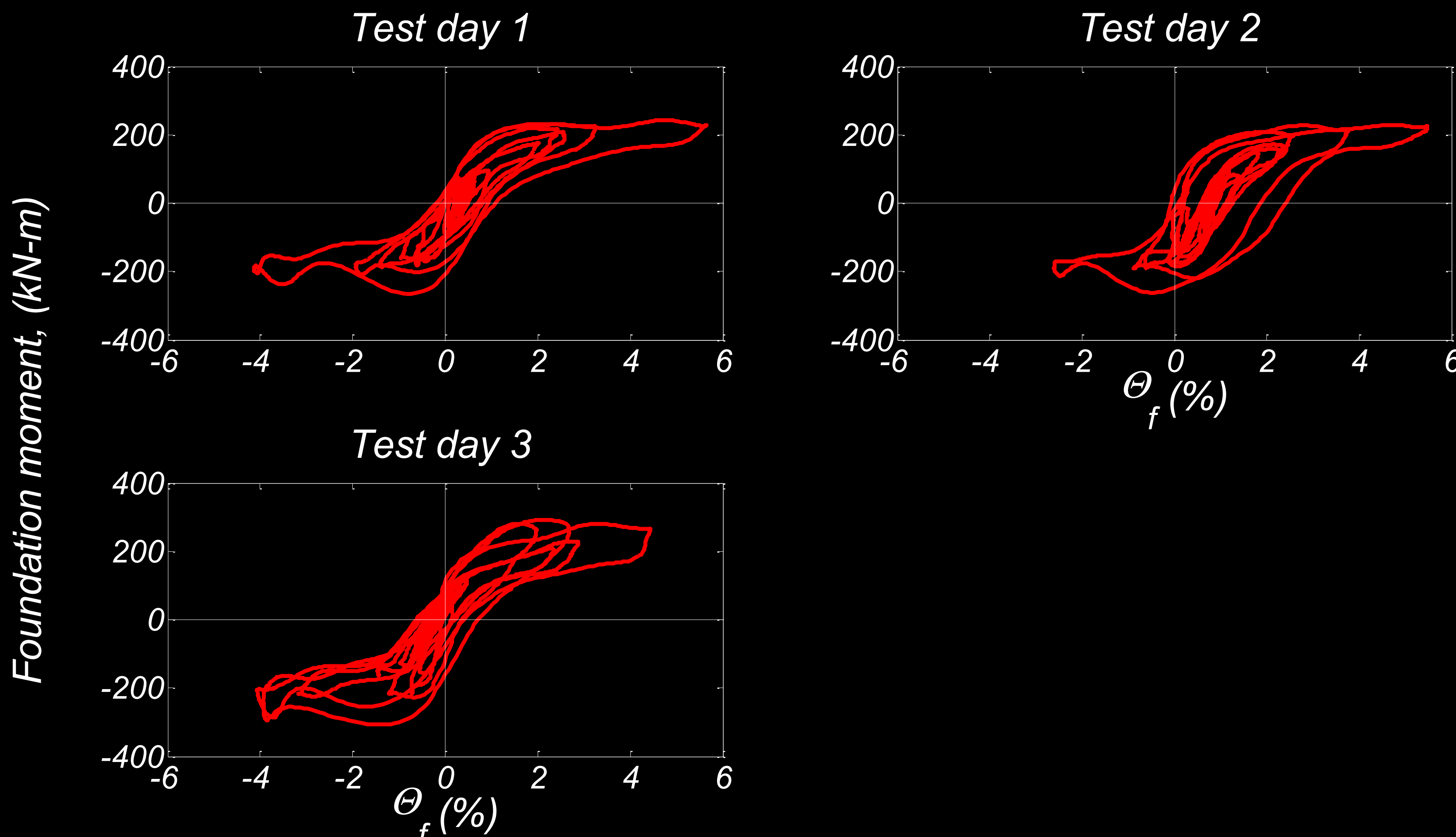
# ***Test day 3 results – 0º specimen***

## Drift ratio, $\Theta_t$, time history



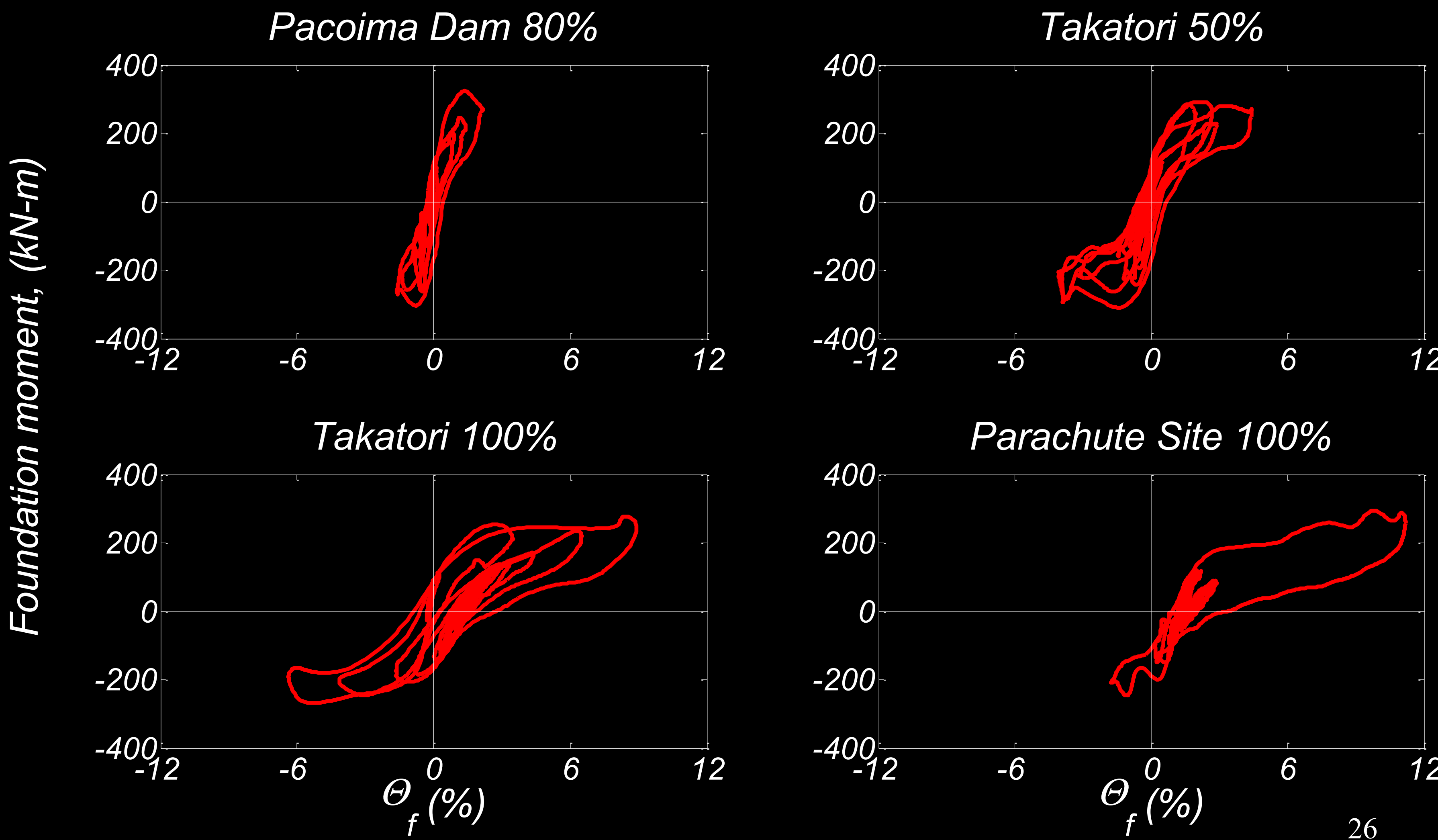
# Test results – 0º specimen

Foundation moment versus foundation rotation (Takatori 50%)



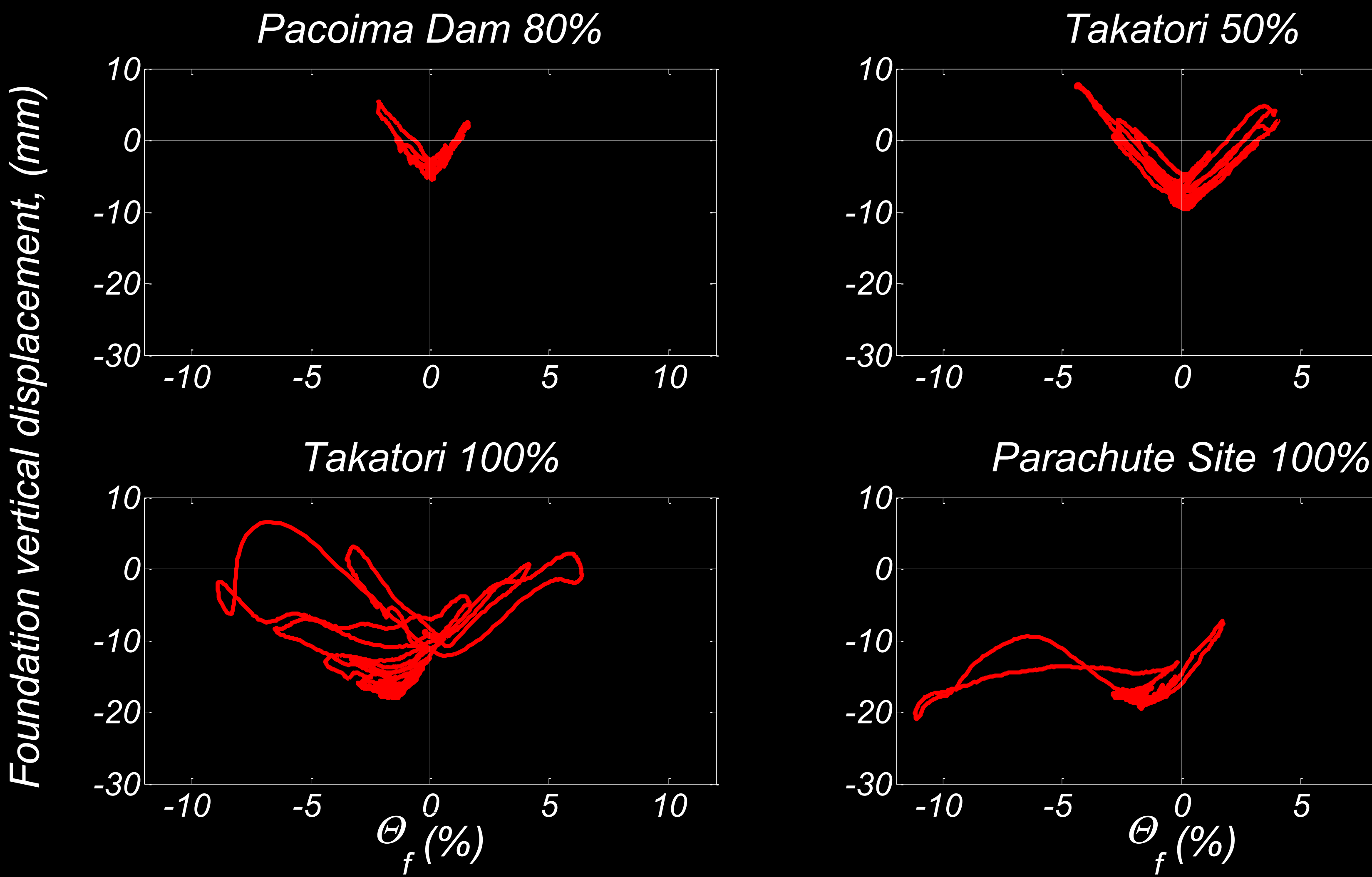
# Test results – 0° specimen

## Foundation moment versus foundation rotation (test day 3)



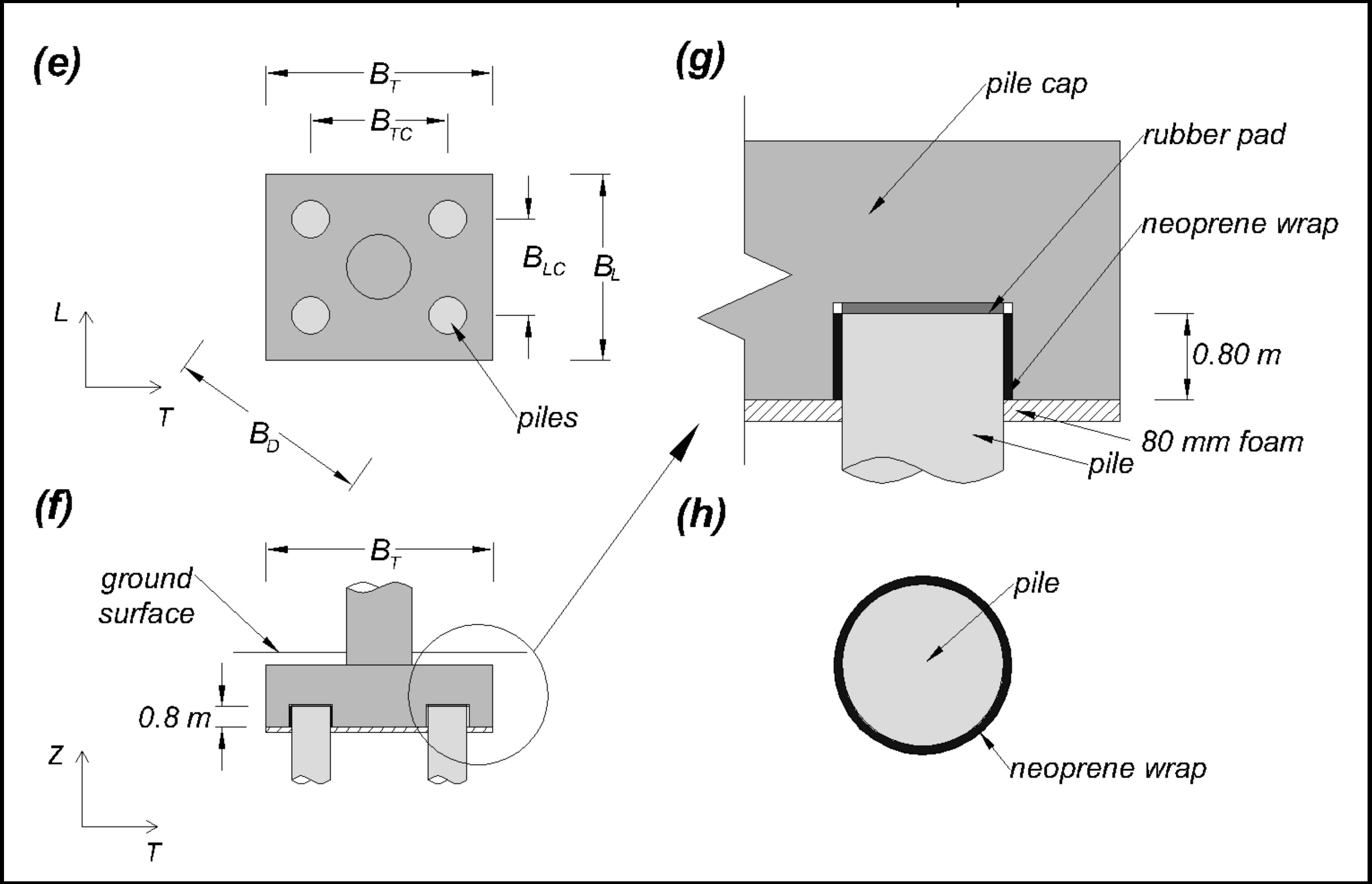
# Test day 3 results

## Foundation rotation versus vertical displacement (test day 3)

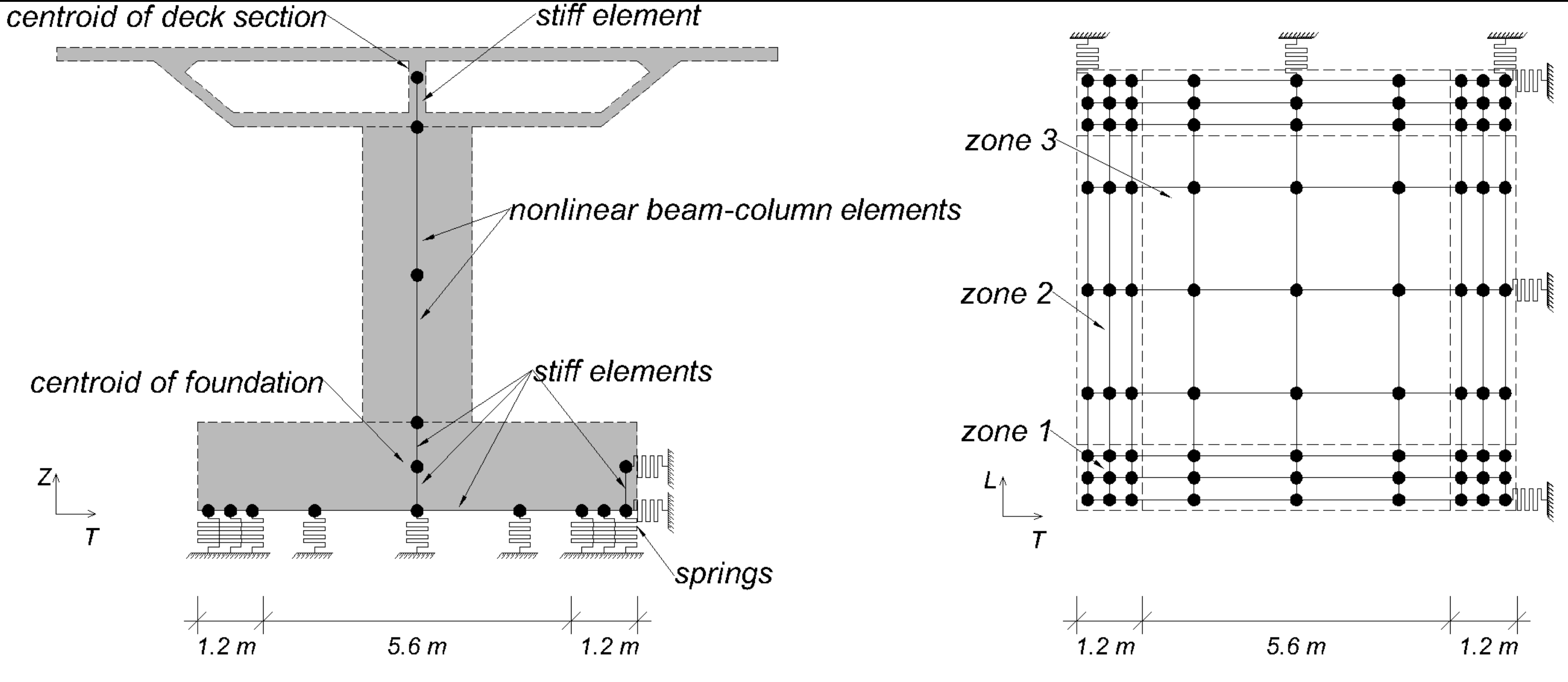


# *Thank you*

# Detailing of rocking pile cap



# 3D Numerical Modeling (OpenSees)



# *Instrumentation*

- ***76 Accelerometers***
- ***33 String potentiometers***
- ***20 Linear potentiometers***
- ***8 Pore pressure transducers***
- ***21 Cameras***