Example of Total Project Planning – Case Study 2: "Geo-Structures"

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December 14, 2015

Example of Total Project Planning – Case Study 2: "Geo-Structures"

- ***Objectives***
  - *This is not a technical research presentation!*
  - *Share my experience with large-scale testing at UC San Diego using the Large Soil Confinement Box (LSCB) to study a dynamic soil-structure interaction problem*

- ***Potential Outcomes***
  - *If you already have a specific test in mind, you might now know something more about the specific steps involved in designing, constructing and testing your idea, and the various decisions you have to make*
  - *If you don't have a specific test in mind, perhaps you will become more aware about the facility's capabilities to envision new tests*

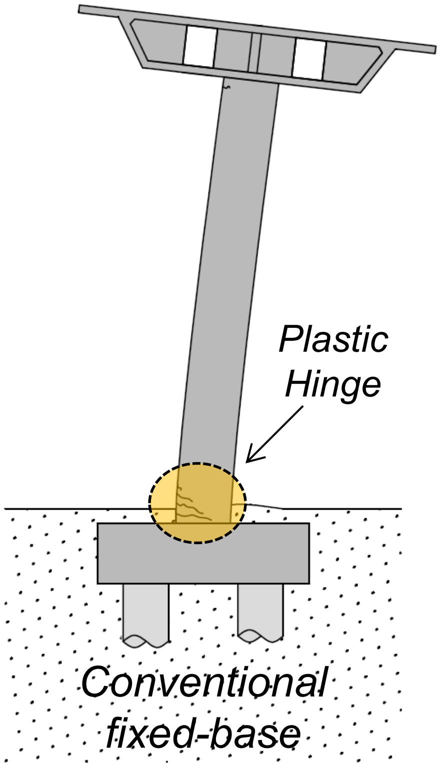
Outline

- *Project Description*
- *Test Design*
- *Experiment Assembly and Construction*
- *Material Testing*
- *Instrumentation*
- *Seismic Testing Protocol*
- *Test Response*
- *Concluding Remarks*

Project Description

Project Description

➢ ***Rocking Foundations as an Earthquake Damage Resistant Mechanism***



Project Description

- ***Why Large-scale 1g Testing of Rocking Foundations at UCSD?***
  - *Both large-scale 1g and centrifuge testing do not come without shortcomings*
  - *Confirm findings from previous centrifuge tests. Will they be different at large-scale?*
  - *Examine response at large rotations / drift ratios*
- ***We also wanted to study***
  - *Effect of ground water table proximity to the rocking footing*
  - *Non-planar rocking response*
  - *(Rocking piled foundations)*

	1g			Centrifuge
Test Type	Full-scale	Large-scale	Small-scale	Reduced-scale
Testing frequency of geo-structural systems				
General scaling laws	🙂 🙂	😐	🙁	🙂
Relative scaling of soil particles	🙂 🙂	🙂	😐	😐
Realistic soil construction	🙂 🙂	😐	😐	😐
Realistic superstructural material	🙂 🙂	🙂	🙁	🙁
Cost	🙁 🙁	🙁	🙂	😐
Previous tests on rocking foundations	🙁 🙁	🙁	🙂	🙂

Project Description

- ***"Analytical and Experimental Development of Bridges with Foundations Allowed to Uplift During Earthquakes"***
  - *Award Amount: $741,479 (50% spent for the experiment)*
  - *Funding: California Department of Transportation (Caltrans)*
  - *Period of Contract: February 2013 – July 2015*

- ***Project Components***
  - ***Experimental response*** *of single bridge columns*
  - ***Numerical modeling validation*** *for single bridge columns*
  - ***Parametric study*** *of single bridge columns*
  - ***System-level analysis*** *of two realistic, archetype bridges*
  - *Displacement-based* ***design method and guidelines*** *for single bridge columns and bridge systems*

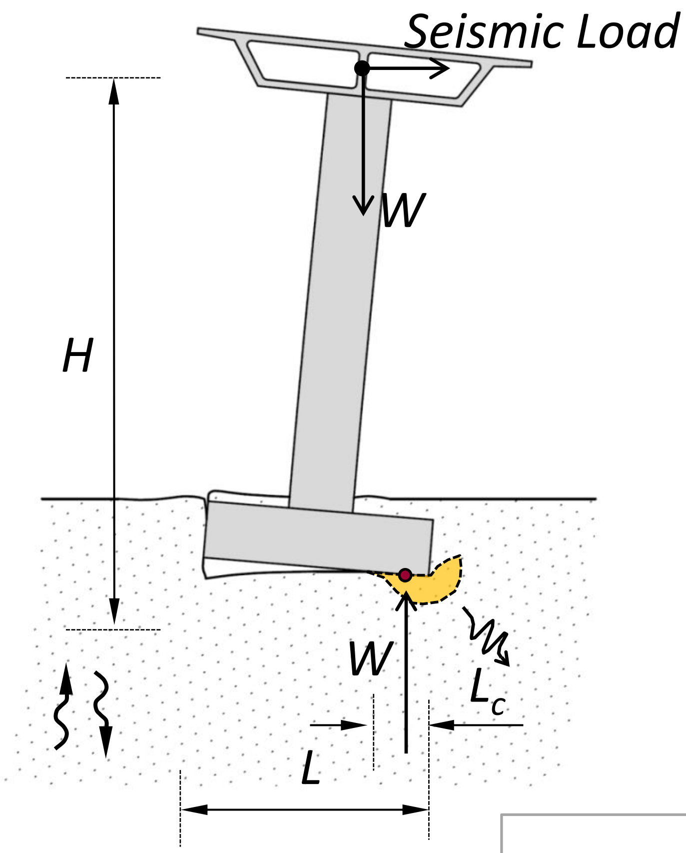
Project Description

- ***Project Team***
  - *Principal Investigators*
    - ✓ *Marios A. Panagiotou (formerly UC Berkeley)*
    - ✓ *Bruce L. Kutter (UC Davis)*
    - ✓ *Jose I. Restrepo (UC San Diego)*
    - ✓ *Patrick J. Fox (formely UC San Diego)*
    - ✓ *Stephen Mahin (UC Berkeley)*
  - *Graduate Student Researchers*
    - ✓ *Grigorios Antonellis (formerly UC Berkeley)*
    - ✓ *Andreas-Gerasimos Gavras (UC Davis)*
    - ✓ *Gabriele Guerrini (formerly UC San Diego)*
    - ✓ *Andrew C. Sander (UC San Diego)*

Test Design

Test Design

➢ *Rocking Foundations' Response Controlling Parameters*



Controlling Parameters

- ***Normalized-moment-to-shear ratio, H / L***
  - ✓ *Rocking vs. sliding and moment-to-shear coupling*
  - ✓ *H / L > 1.5 indicates rocking-dominated response*
- ***Critical contact area ratio, A / A_c***
  - ✓ *Recentering vs. energy dissipation, residual rotations and settlements*
  - ✓ *A / A_c > 8 to minimize settlement*
- ***Rocking base strength ratio, C_r***
  - ✓ *Peak rotations and overturning stability*
- ***Absolute size, H***
  - ✓ *Peak rotations and overturning stability for given H / L*

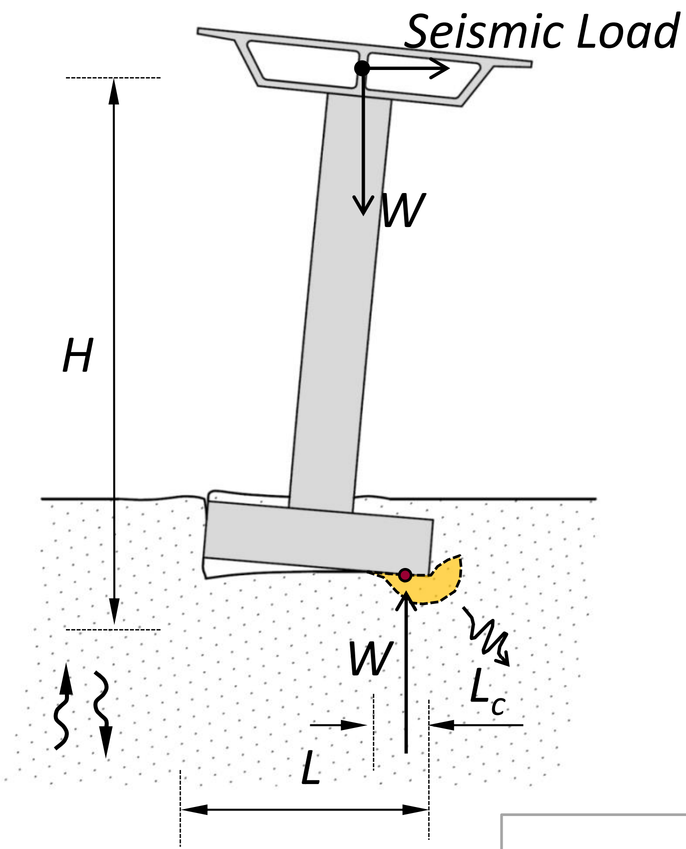
$$\frac{A}{A_c} = \frac{q_c}{q}$$

$$M_{foot} \approx \frac{W \cdot L}{2} \cdot \left(1 - \frac{A_c}{A}\right) + P_p \cdot \frac{D}{3} + k \cdot P_p \cdot \frac{L}{2}$$

$$C_r = \frac{M_{foot}}{H \cdot W}$$

Test Design

- ***Rocking Foundations' Response Controlling Parameters***



Prototype vs. Model

For $S_a = 1$, $L_p = S_L \times L_m$ and $W_p = (S_L)^2 \times W_m$

- $\boldsymbol{L_p >> L_m}$
- $\boldsymbol{(H / L)_p = (H / L)_m}$ *(correct scaling)*
- $q_p = q_m$
- $(q_c)_p >> (q_c)_m$ *(due to strong dependency of sand bearing capacity to actual footing size)*
- $\boldsymbol{(A/A_c)_p >> (A/A_c)_m}$ *(prototype has significantly better re-centering)*
- $\boldsymbol{(C_r)_p \sim (C_r)_m}$ *(prototype is slightly stronger statically)*

$$\frac{A}{A_c} = \frac{q_c}{q} \qquad M_{foot} \approx \frac{W \cdot L}{2} \cdot \left(1 - \frac{A_c}{A}\right) + P_p \cdot \frac{D}{3} + k \cdot P_p \cdot \frac{L}{2} \qquad C_r = \frac{M_{foot}}{H \cdot W}$$

Test Design

➢ *Design Approach*

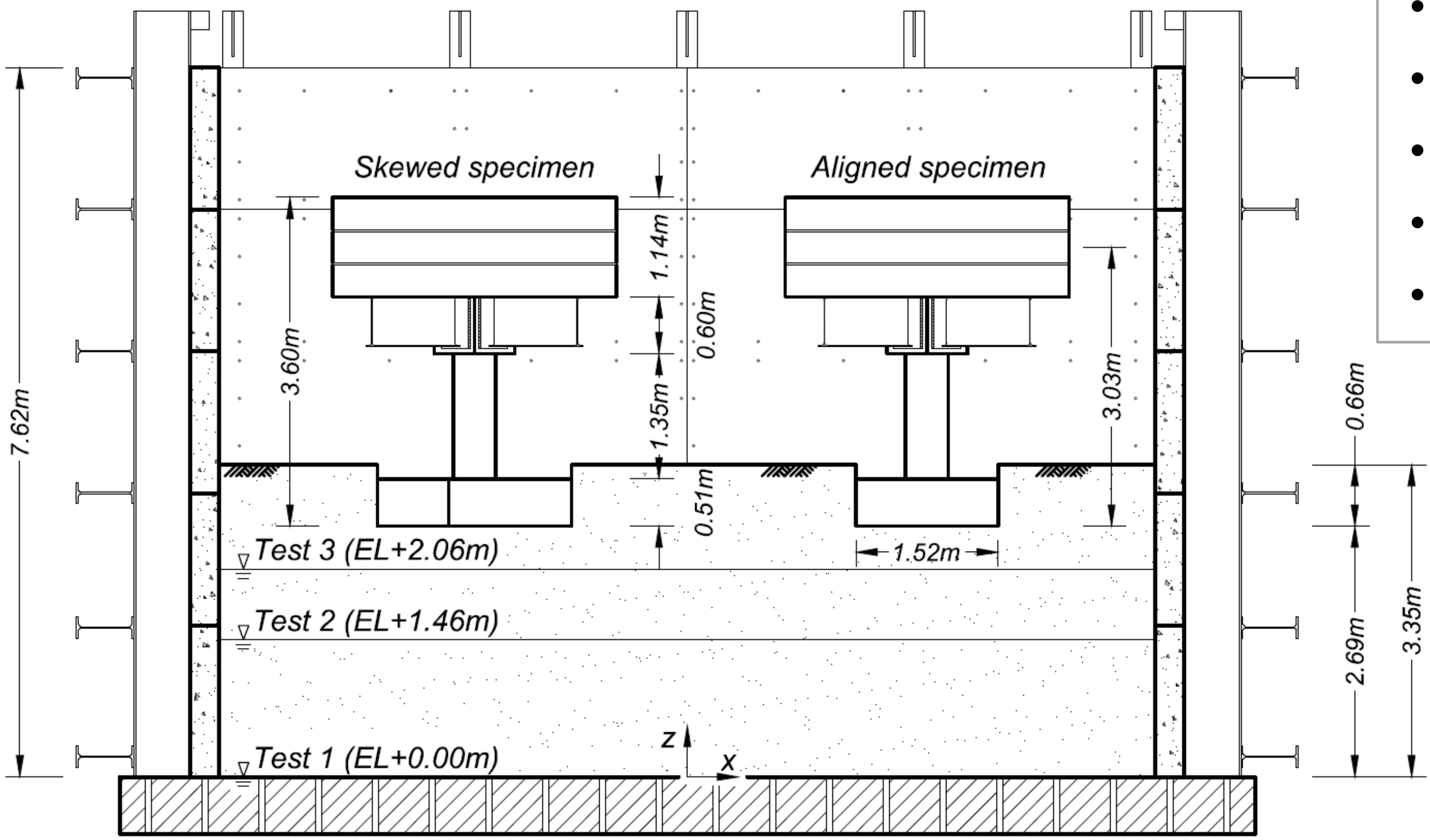
- *Superstructure*
  - ✓ *Structural 1g scaling laws used as a guidance to design superstructure based on the Restrepo et al. (2010) full-scale bridge column test and the available PEER mass blocks*
  - ✓ *Length scale factor,* $S_L = sqrt(W_{ss\_m} / W_{ss\_p}) = 1/3$
  - ✓ *Time scale factor,* $S_t = sqrt(S_L / S_a) = sqrt(1/3 / 1) = 0.577$

- *Rocking foundation*
  - ✓ *Designed directly in model-scale to* $C_r = 0.26$, $A / A_c = 8\text{-}15$ *and* $H / L > 1.5$
  - ✓ *Obtained response is representative of the tested model and not of a prototype*

- *Soil deposit*
  - ✓ *Sand with target relative density of 80%+ to represent competent soil conditions*
  - ✓ *Sufficiently deep soil profile to minimize boundary effects from the shake table platen*

Test Design

➢ ***Structure and Test Geometry***

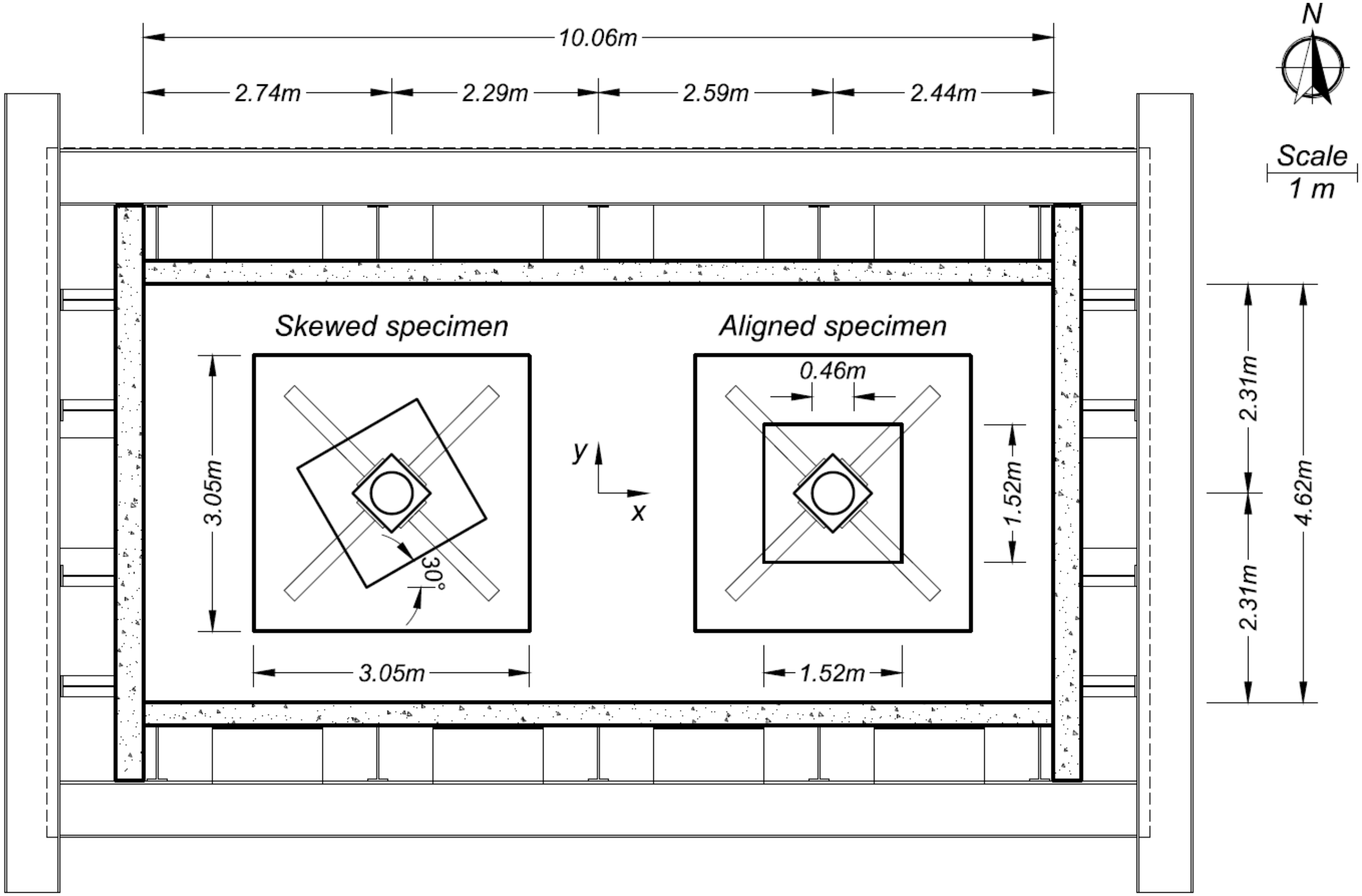


Key parameters

- W = 290 kN
- H / L = 2.0
- A / A_c = 13
- FS_v = 24
- C_r = 0.26
- C_y = 0.47

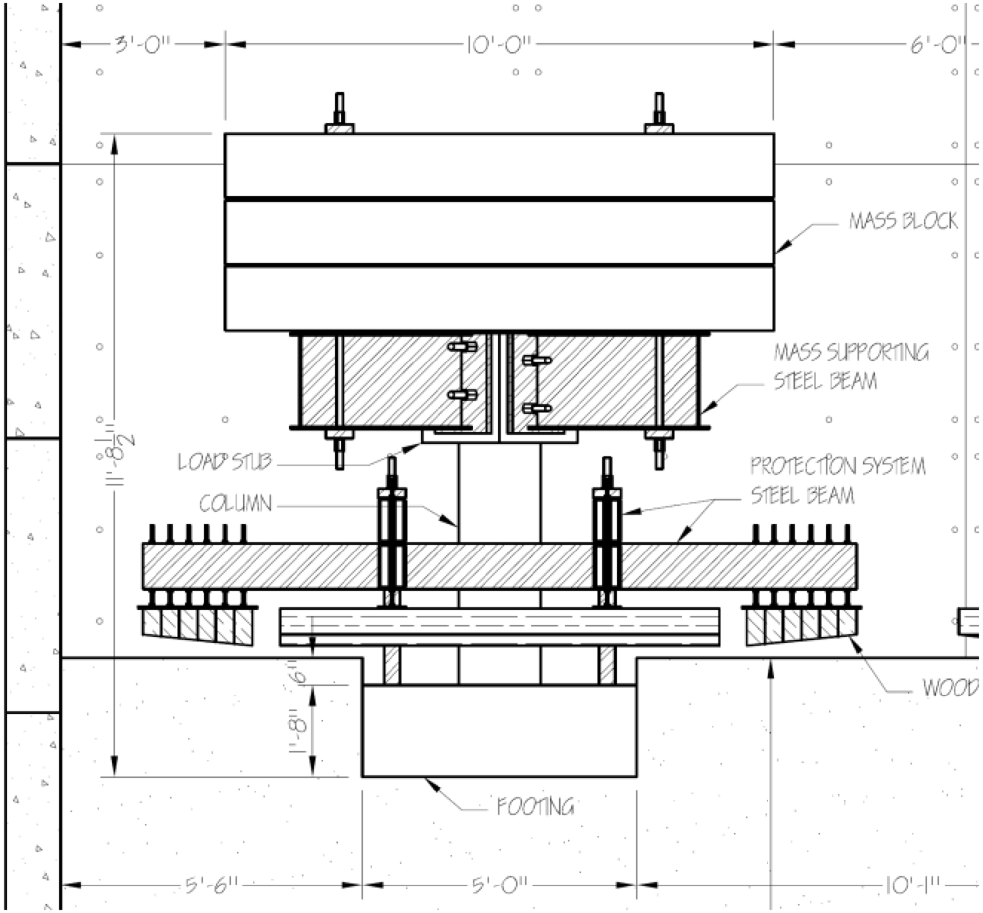
Test Design

- ***Structure and Test Geometry***
  - *2 structures tested concurrently with different footing orientation*



Test Design

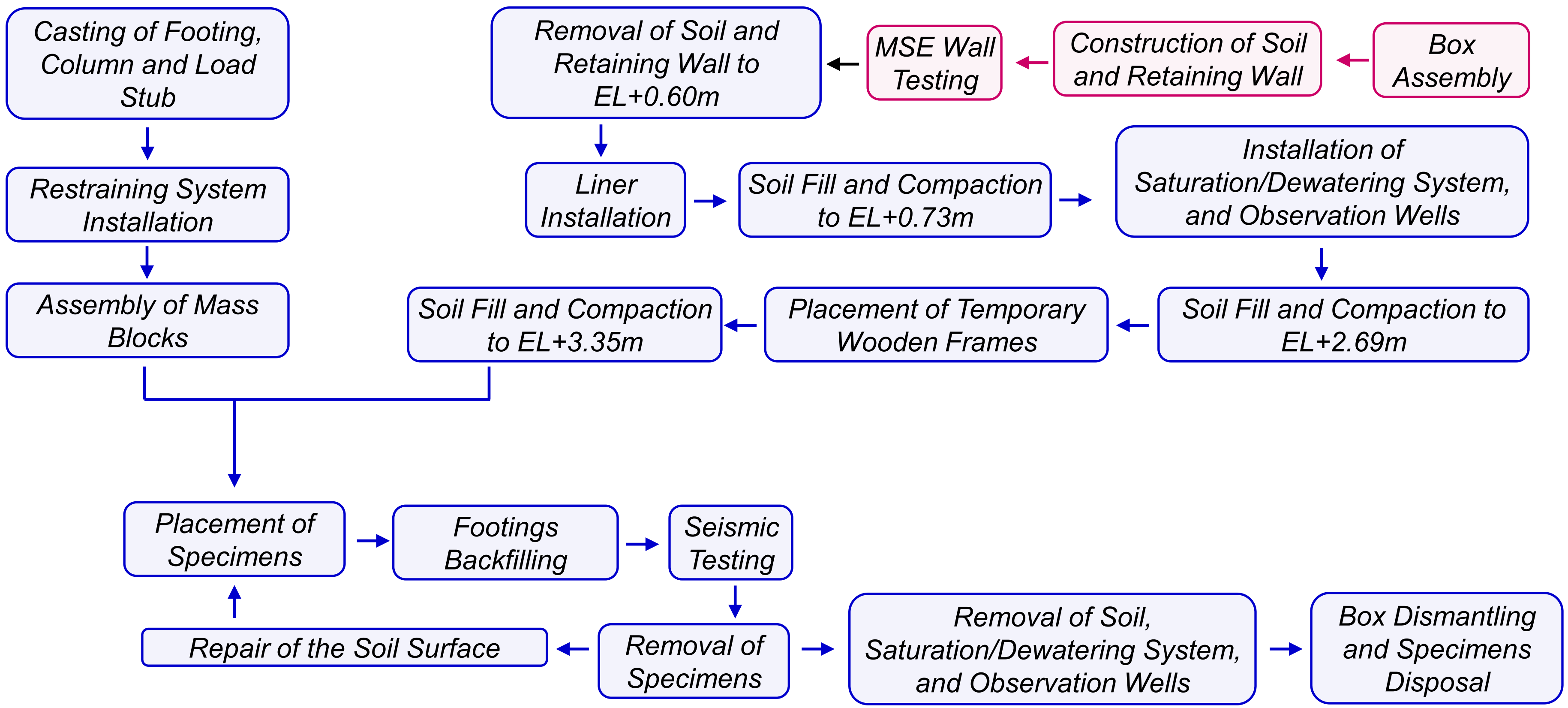
- ***Restraining System***
  - *To prevent overturning and collision of the mass blocks with the box*



Experiment Assembly and Construction

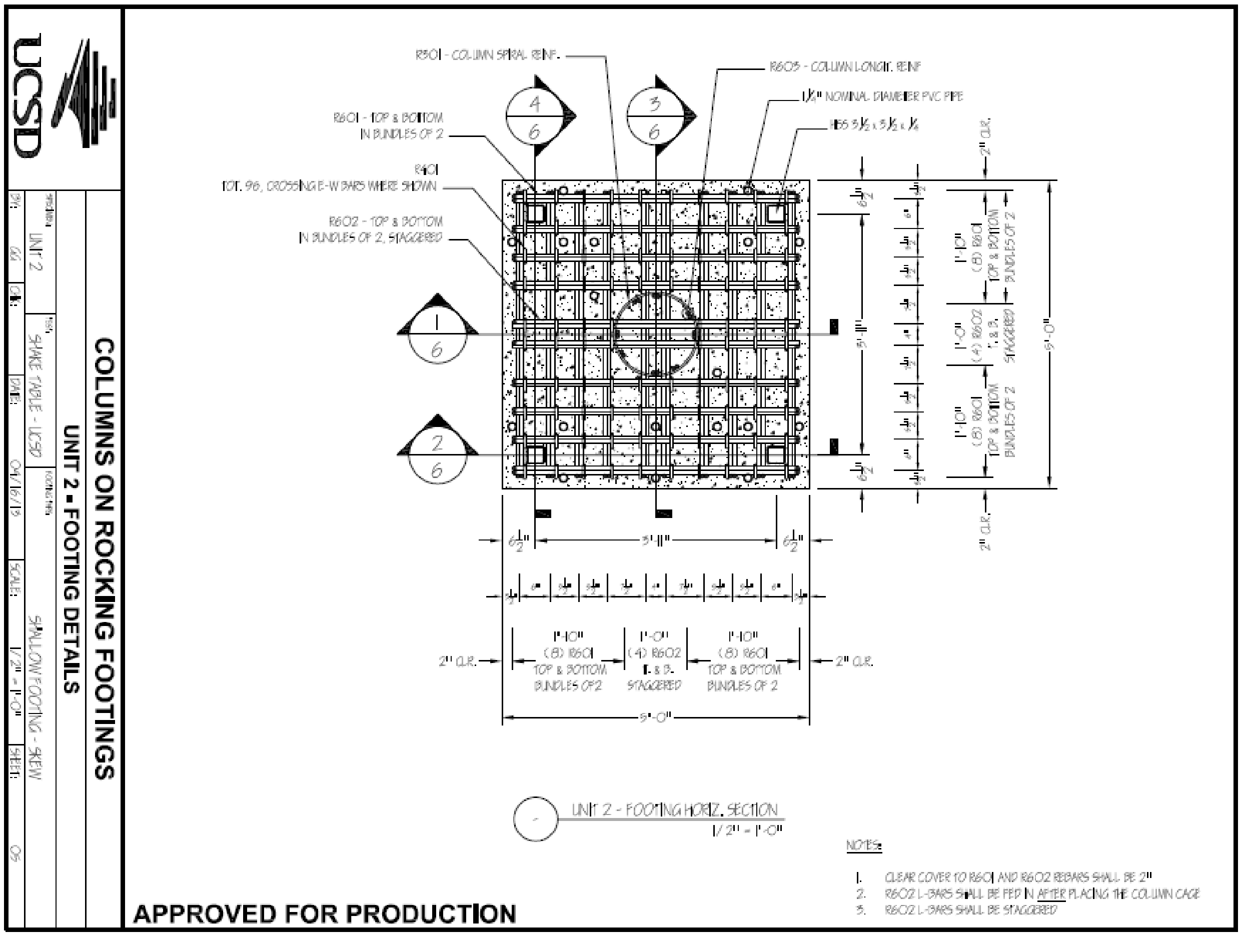
Experiment Assembly and Construction

➢ ***Simplified Construction Flowchart***



Experiment Assembly and Construction

- ***Casting of footings, columns and load stubs***
  - *Detailed Construction Drawings*



Experiment Assembly and Construction

➢ ***Casting of footings, columns and load stubs***

Placement of rebars and formwork

Casting of columns and load stubs

Concrete footings, columns and load stubs

Experiment Assembly and Construction

- ***Restraining System Assembly***


Steel rods and grouting of HSS pipes


Placement of outriggers

Placement of tapered wood beams


Completed restraining system

Experiment Assembly and Construction

- ***Specimens and Restraining System Construction***

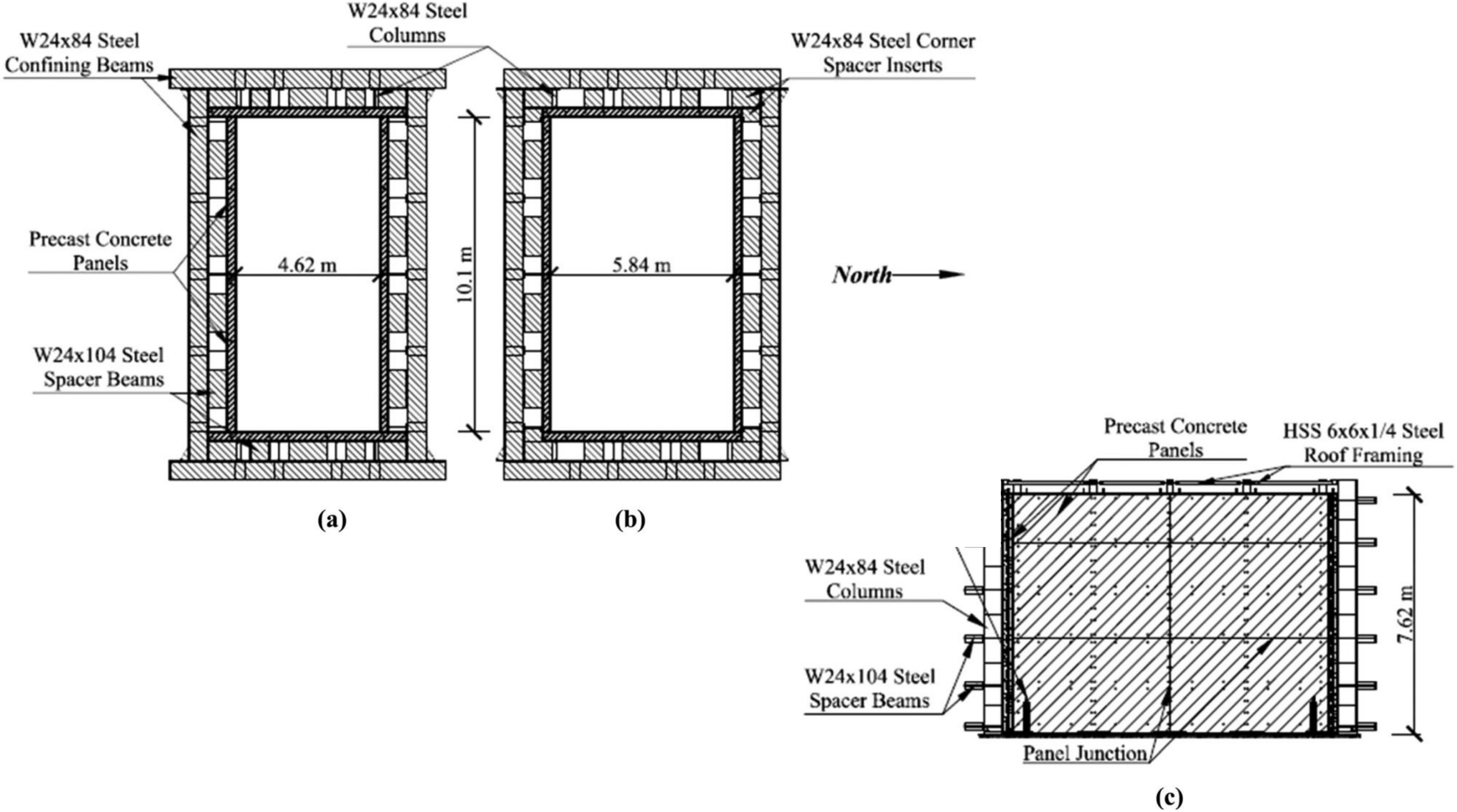
Placement of mass support steel beams

Placement of mass blocks

Completed specimen

Experiment Assembly and Construction

- ***Large Soil Confinement Box***



[Source: Fox et al. (2015), Geotechnical Testing Journal]

Experiment Assembly and Construction

➢ ***Large Soil Confinement Box***
- *Erection of Vertical Elements and Post-Tensioning to the Shake Table Platen*

Experiment Assembly and Construction

- ***Large Soil Confinement Box***
  - *Placement of Concrete Panels*

Experiment Assembly and Construction

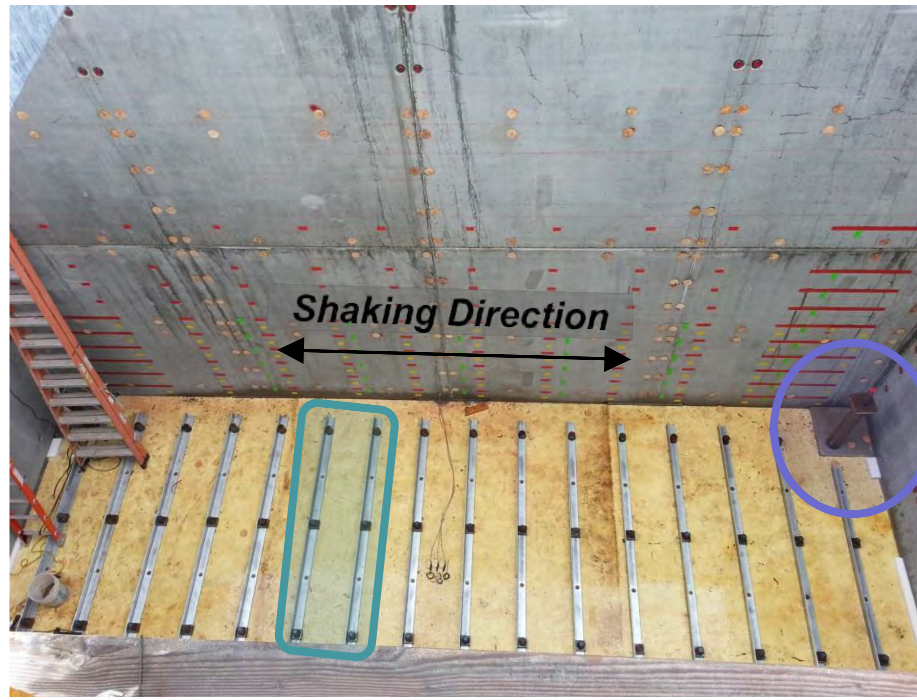
- ***Time Lapse Video of Assembly***

Experiment Assembly and Construction

- ***Large Soil Confinement Box***
  - *Exterior Views of Assembled Box*

Experiment Assembly and Construction

- **_Large Soil Confinement Box_**
  - _Interior Views of Assembled Box_



16 steel angles bolt to the platen to provide no-slip condition at the bottom boundary

4 PT rods running through the parts of corner column base plates sticking into the box

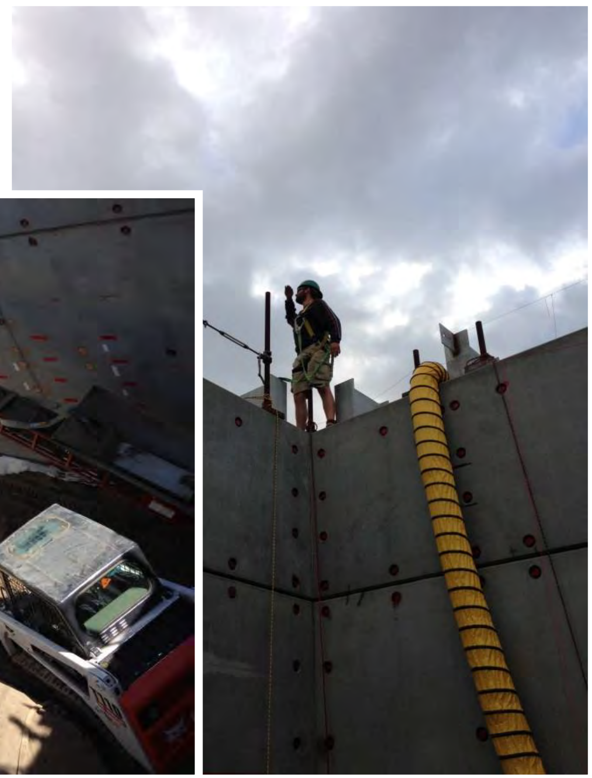
Experiment Assembly and Construction

- ***Soil Filling and Removal***
  - *Series of Conveyor Belts*
    - ✓ *Economic, but slow process*

Experiment Assembly and Construction

➢ ***Soil Filling and Removal***

- *Use of concrete hoppers/buckets and facility's crane*
  - ✓ *Faster process, but less economic due to crane usage*

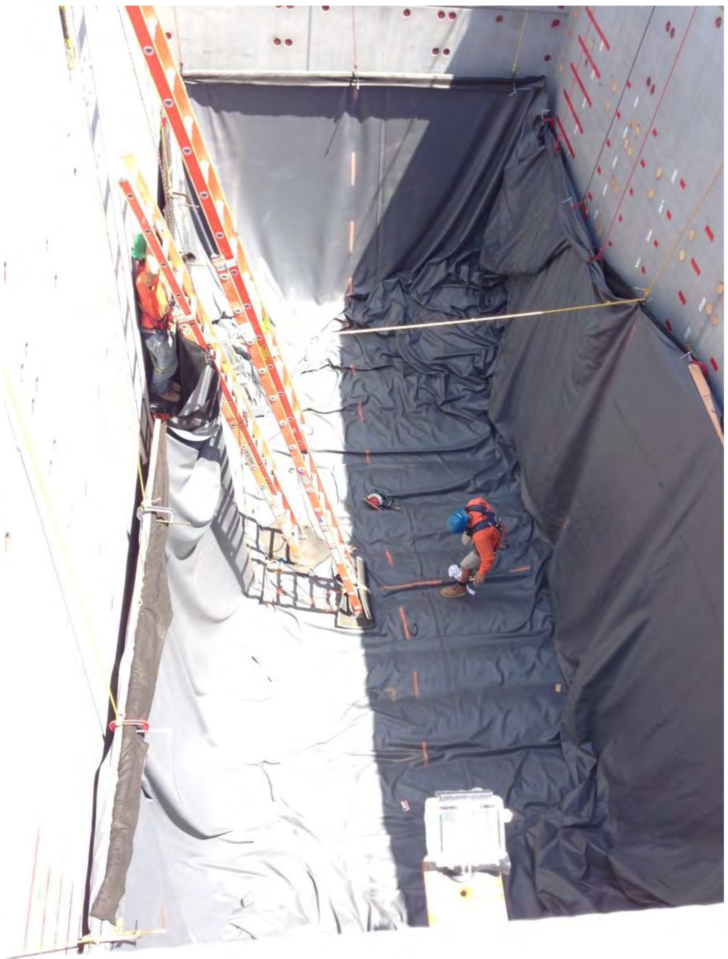


Experiment Assembly and Construction

- ***Liner***
  - *Preparation Before Placement*

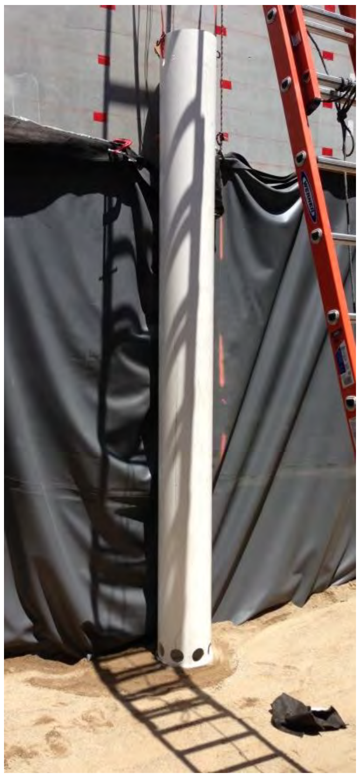
Experiment Assembly and Construction

- **Liner**
  - *Placement and Patching*



Experiment Assembly and Construction

- ***Saturation and Dewatering System***



Experiment Assembly and Construction

➢ ***Soil Compaction***

- *Loose lifts of 200 mm thick compacted at a water content of 6% down to about 150 mm*
- *Walk-behind vibratory plate with 8 passes per lift*
  - ✓ *First 4 lifts after placement of liner and saturation/dewatering system*
  - ✓ *Lifts above the footings' base elevation*
  - ✓ *Near box walls (in general)*
- *Skid-steer loader with an attached vibratory roller (1.22 m wide, 7.95 kN heavy vibrating at 40 Hz) with 6 passes per lift*

Experiment Assembly and Construction

- **Testing Cycle**

Specimen placement


Backfill compaction


Testing

Specimen removal

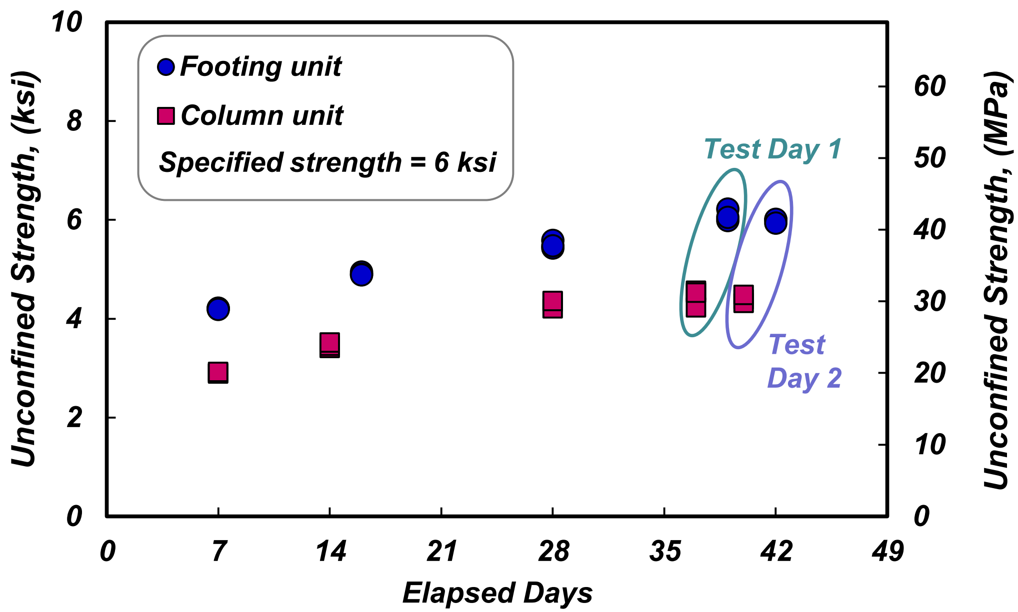

Water addition


Leveling/compaction of soil surface

Material Testing

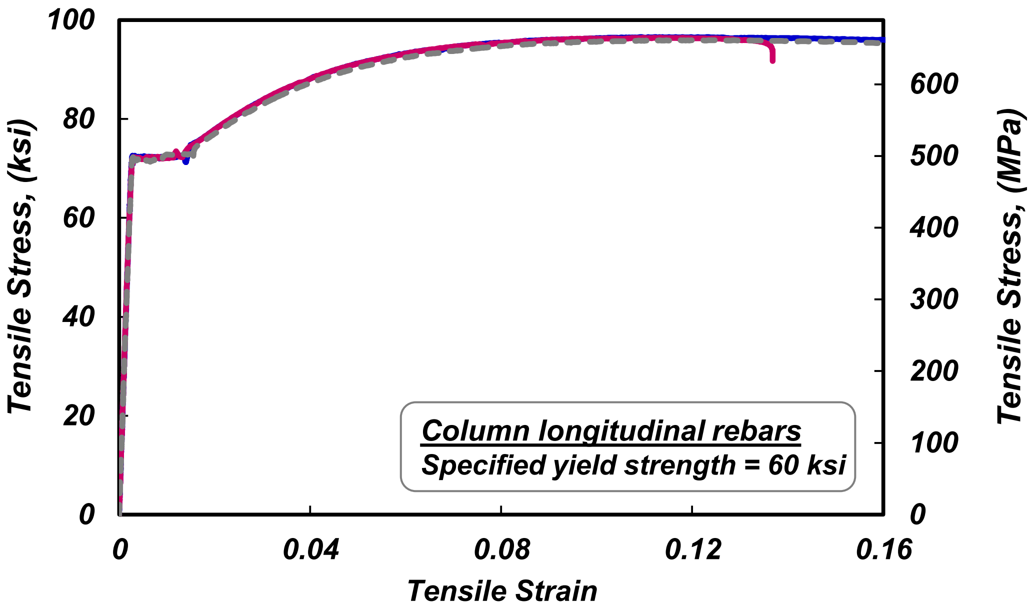
Material Testing

- **Concrete**
  - *Slump tests taken prior to casting*
  - *Cylindrical samples taken for UC tests from the footing and column batches to be tested 1, 2, and 4 weeks after casting and at Test Days 1 and 2*



Material Testing

- **Reinforcing Steel**
  - *3 samples taken for tension tests from each of*
    - ✓ *Footing main rebars*
    - ✓ *Column longitudinal rebars*
    - ✓ *Column spiral*
    - ✓ *Load stub J-bar stirrups*
    - ✓ *Load stub staples*



Material Testing

- ***Soil Properties Overview***
  - *Clean, angular, poorly-graded medium sand (ASTM C33 washed concrete sand))*

Classification		SP
Gravel content	[%]	0
Fines content	[%]	2.8
Specific gravity, G_S		2.63
Grain size, D_{50} (D_{10})	[μm]	737 (186)
Coefficient of uniformity, C_u		5.3
Coefficient of curvature, C_c		0.9
Dry unit weight, $\gamma_{d,min}$ ($\gamma_{d,max}$)	[kN/m^3]	14.41 (17.72)
Void ratio, e_{max} (e_{min})		0.790 (0.456)
Constant-volume friction angle, φ_{cv}	[deg.]	≈ 33

Material Testing

- ***Considered Methods for Measuring In-situ Relative Density (D_R)***
  - *Sand Cone Test*
    - ✓ *Easy and cheap; can be done by the students*
    - ✓ *Also measures water content*
    - ✓ *High user uncertainty for D_R measurements; can yield scattered results*
    - ✓ *Two measurements possible per day; results available after 24h*
  - *Cone Penetration Test*
    - ✓ *Back-calculates D_R and effective friction angle*
    - ✓ *Needs to be conducted by subcontractors; more expensive, logistic / time issues*
  - *Nuclear Density Gage*
    - ✓ *Accurate measurement of D_R*
    - ✓ *Needs to be conducted by subcontractors; more expensive, logistic / time issues*

Material Testing

- ***Selected Method for Measuring In-situ Relative Density (D_R)***
  - *Sand Cone Test*
    - ✓ *Logistics and time constraint issues for planned CPT pushes*
    - ✓ *Consistent compaction protocol with previous project yielding D_R = 88% based on sand cone tests and nuclear density gage measurements*




Material Testing

➢ Sand Cone Test Results

Description	Location			Relative density,	Water content,
	x (m)	y (m)	z (m)	D_R (%)	w (%)
Under skew footing center	-2.29	0.30	0.97	**86.9**	5.1
Under aligned footing center	2.59	0.30	0.97	**72.8**	4.4
Under skew footing center	-2.29	0.30	1.83	**105.7**	5.2
Under aligned footing center	2.59	0.30	1.83	**95.3**	5.7
Under skew footing center	-2.29	0.30	2.49	**91.3**	3.8
Under aligned footing center	2.59	0.30	2.49	**78.4**	4.5
Under skew footing center	-2.29	0.00	2.69	**68.1**	4.9
Under aligned footing center	2.59	0.00	2.69	**83.0**	4.9
Skew footing backfill before test 1, SE side middle	-1.79	-0.86	3.35	**88.6**	4.4
Aligned footing backfill before test 1, SE corner	3.58	-0.99	3.35	**69.5**	3.4
Aligned footing backfill before test 1, S side middle	2.59	-0.99	3.35	**95.7**	3.2
Skew footing center before test 3	-2.29	0.00	2.69	**64.5**	5.5
Aligned footing center before test 3	2.59	0.00	2.69	**86.9**	5.8

***Interpreted** achieved average relative density, $D_R \approx 90\%$*

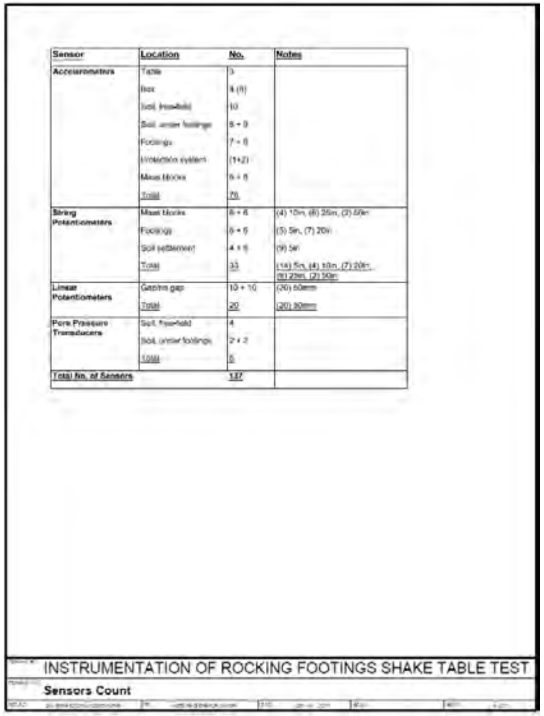
Instrumentation

Instrumentation

- ***General Considerations***
  - *Must consider available facility instrumentation in advance, and the need to purchase/fabricate sensors specific to your test*
    - ✓ *Pore Pressure Transducers (PPT) to monitor pore pressure build-up in saturated soil*
    - ✓ *Custom-made gap sensors to monitor dynamic evolution of the soil surface under the footings*
  - *Clear instrumentation drawings and list of sensors distributed to data acquisition and video personnel before start of construction*
  - *Understand construction and instrumentation placement time constraints – coordinate with data acquisition personnel*
    - ✓ *What instrumentation is essential to my test?*
      - *No strain gage installation for the columns*
    - ✓ *What is reasonable instrumentation redundancy?*
      - *Installed sensors = 137; initially proposed = 221*

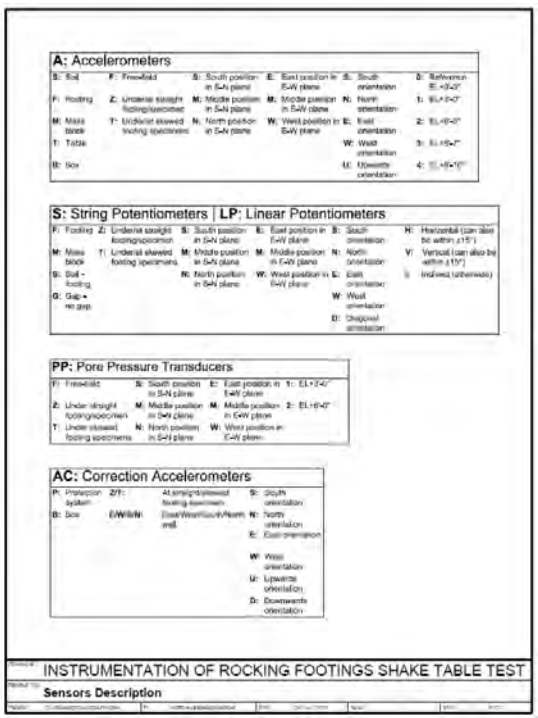
Instrumentation

- ***Sensors Summary***



Sensor	Location	No.	Notes
Accelerometers	Table	3	
	Box	4 (8)	
	Soil, free-field	10	
	Soil, under footings	8 + 9	
	Footings	7 + 8	
	Protection system	(1+2)	
	Mass blocks	8 + 8	
	Total	76	
String Potentiometers	Mass blocks	6 + 6	(4) 10in, (6) 25in, (2) 50in
	Footings	6 + 6	(5) 5in, (7) 20in
	Soil settlement	4 + 5	(9) 5in
	Total	33	(14) 5in, (4) 10in, (7) 20in, (6) 25in, (2) 50in
Linear Potentiometers	Gap/no gap	10 + 10	(20) 50mm
	Total	20	(20) 50mm
Pore Pressure Transducers	Soil, free-field	4	
	Soil, under footings	2 + 2	
	Total	8	
Total No. of Sensors		**137**	

➢ *Sensors Nomenclature*

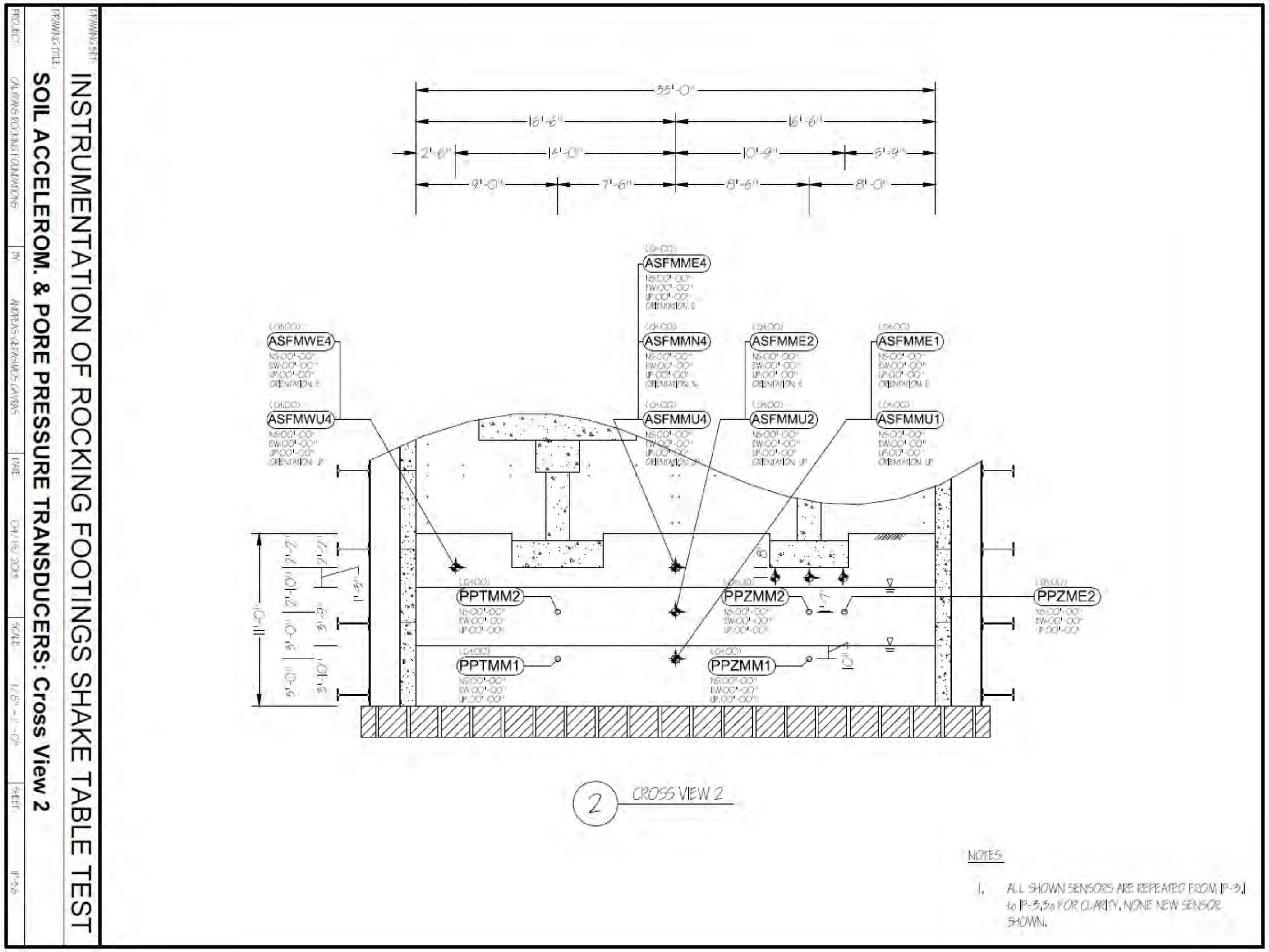

A: Accelerometers
S: String Potentiometers | LP: Linear Potentiometers
PP: Pore Pressure Transducers
AC: Correction Accelerometers
INSTRUMENTATION OF ROCKING FOOTINGS SHAKE TABLE TEST
Sensors Description

A: Accelerometers

S: Soil	**F:** Free-field	**S:** South position in S-N plane	**E:** East position in E-W plane	**S:** South orientation	**0:** Reference EL+0'-0"
F: Footing	**Z:** Under/at straight footing/specimen	**M:** Middle position in S-N plane	**M:** Middle position in E-W plane	**N:** North orientation	**1:** EL+3'-0"
M: Mass block	**T:** Under/at skewed footing specimens	**N:** North position in S-N plane	**W:** West position in E-W plane	**E:** East orientation	**2:** EL+6'-0"
T: Table				**W:** West orientation	**3:** EL+8'-7"
B: Box				**U:** Upwards orientation	4: EL+8'-10"

Instrumentation

- ***Soil Instrumentation Drawings***

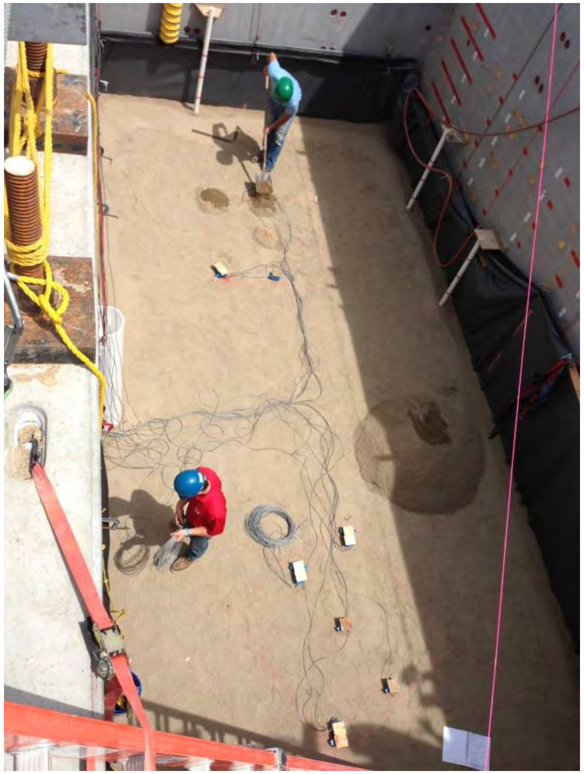


Instrumentation

➢ ***Soil Accelerometers Placement***

Marking of locations before placement

Placement of accelerometers

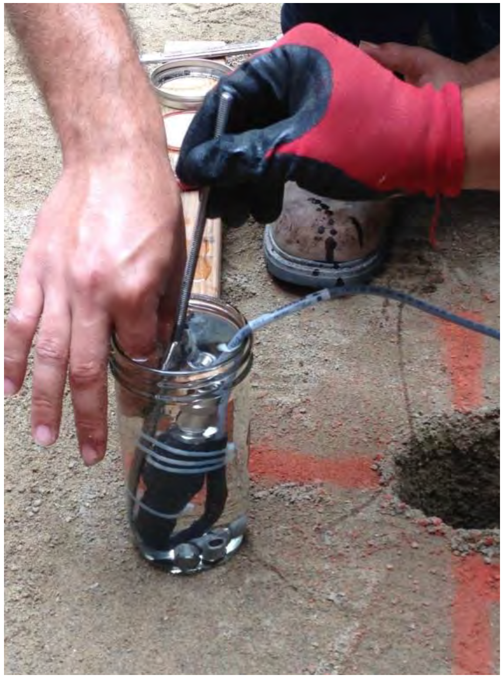


Covering with soil and cables running

Instrumentation

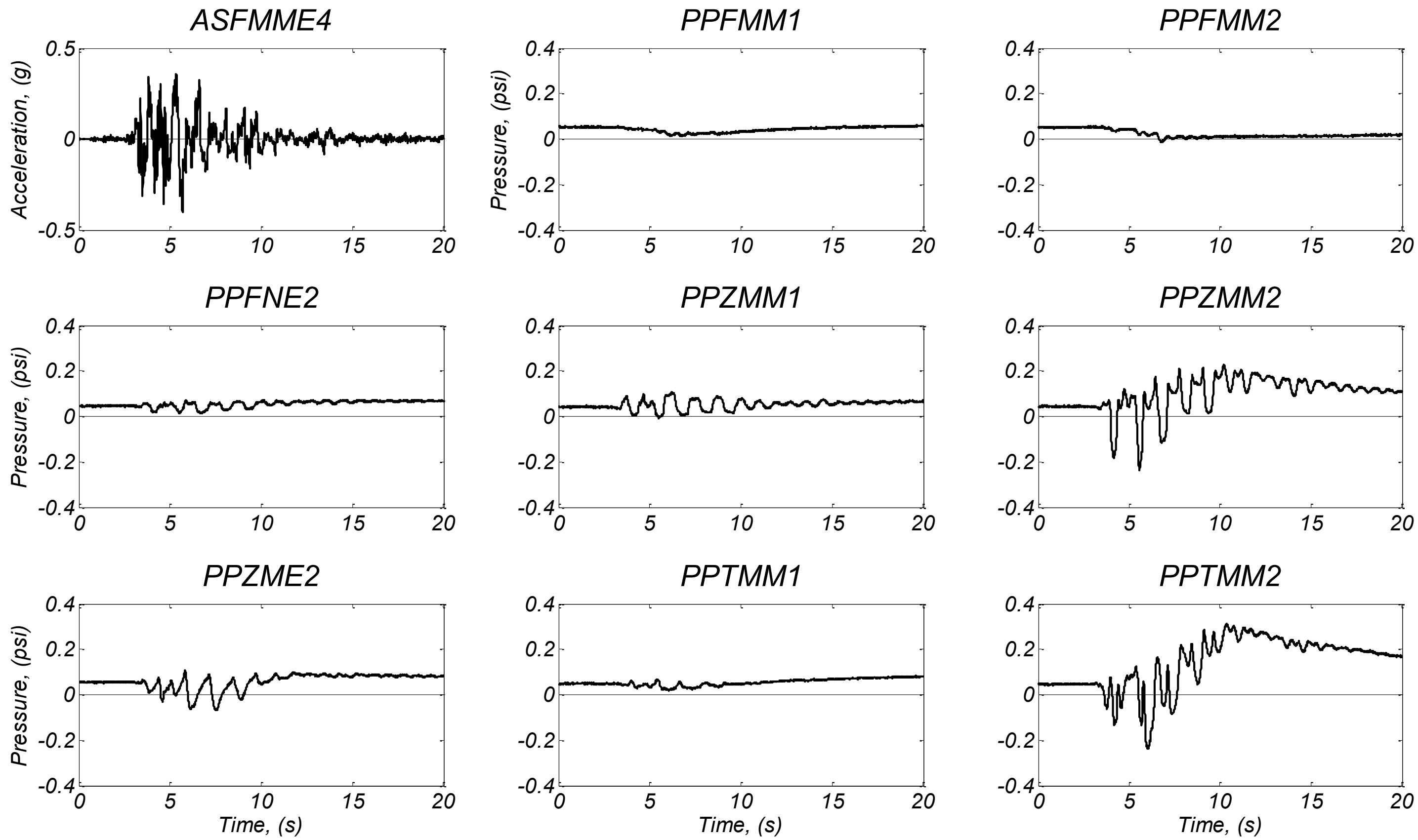
- ***Pore Pressure Transducers (PPT) Placement***
  - *Challenging to prevent desaturation of sensors during the 2-3 weeks period for which they remained above water table*






Instrumentation

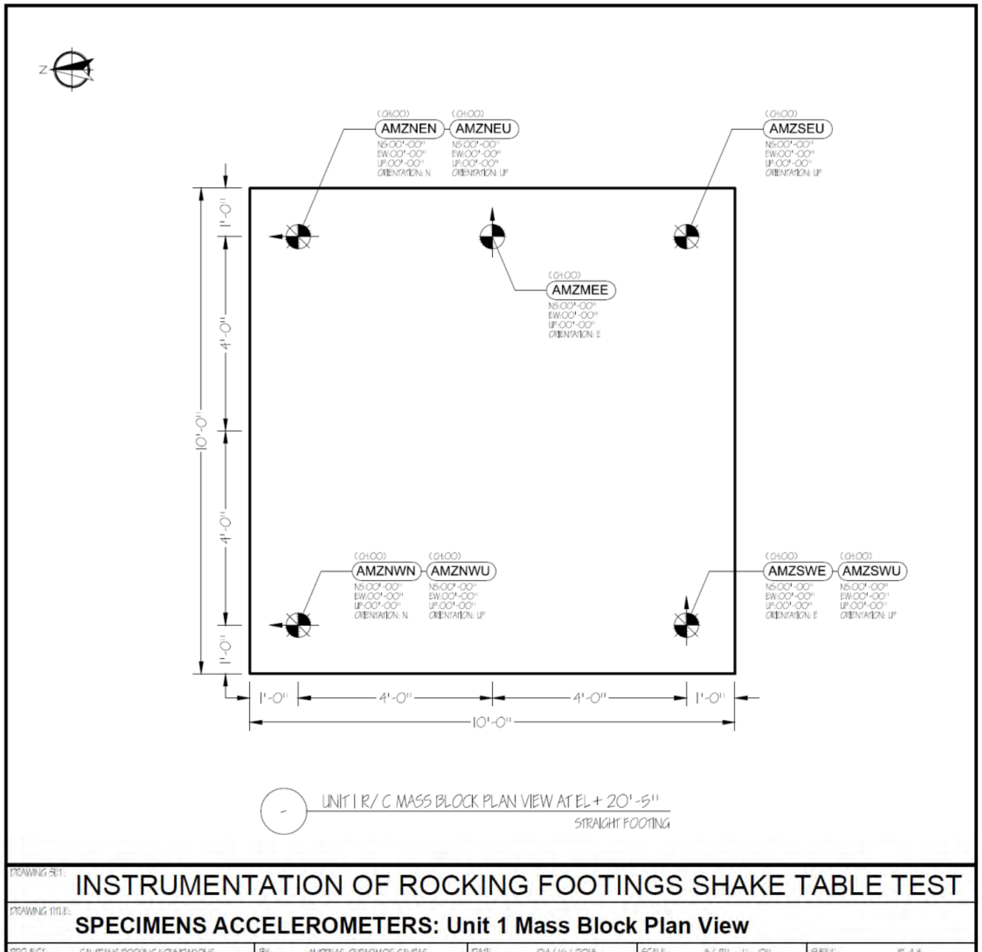
➢ ***Soil Pore Pressure Response***

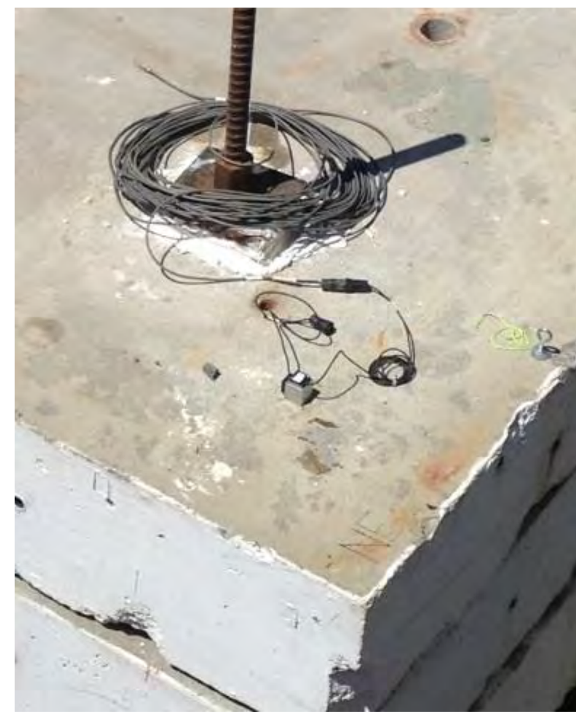


Sensor de-saturation or incomplete soil saturation?

Instrumentation

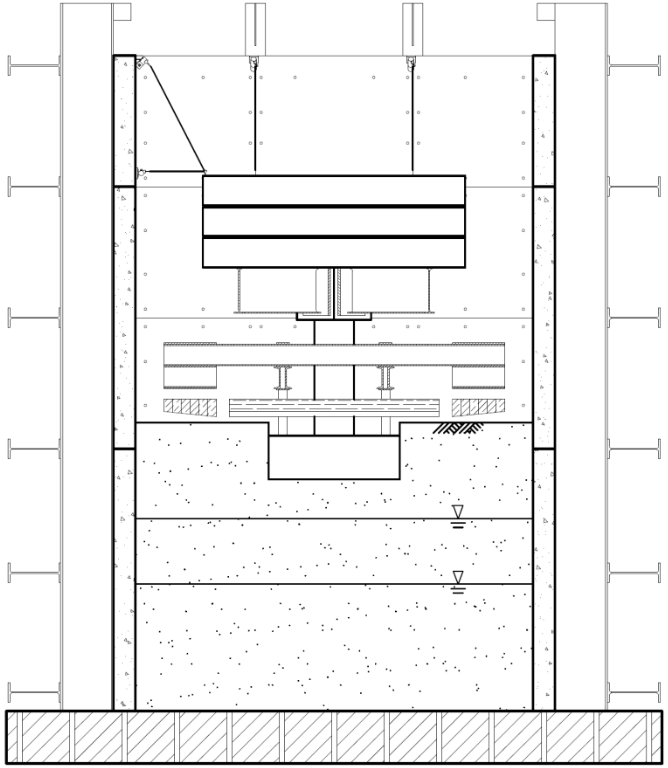
- **_Structures' Instrumentation_**
  - _Mass Blocks' Accelerometers_

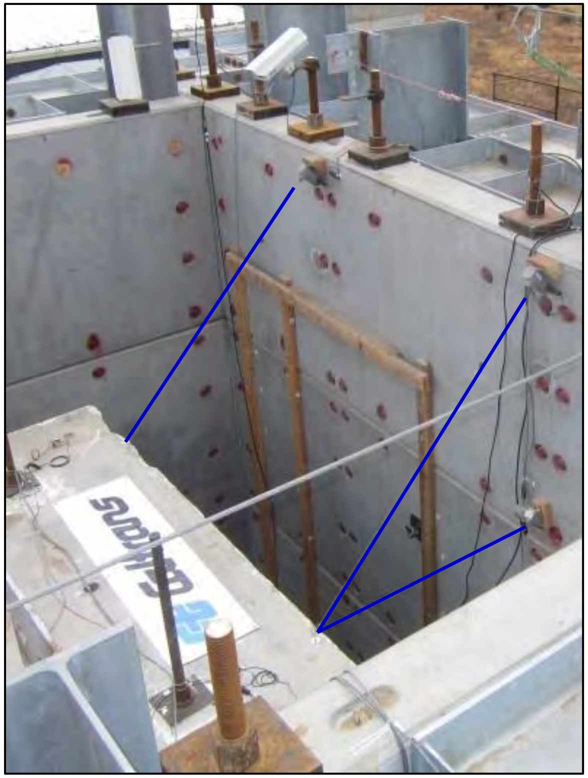




Instrumentation

- **_Structures' Instrumentation_**
  - *Mass Blocks' String Potentiometers*
    - ✓ *6 linearly independent String Pots (3 horizontal + 3 vertical) to determine 6 DoFs*

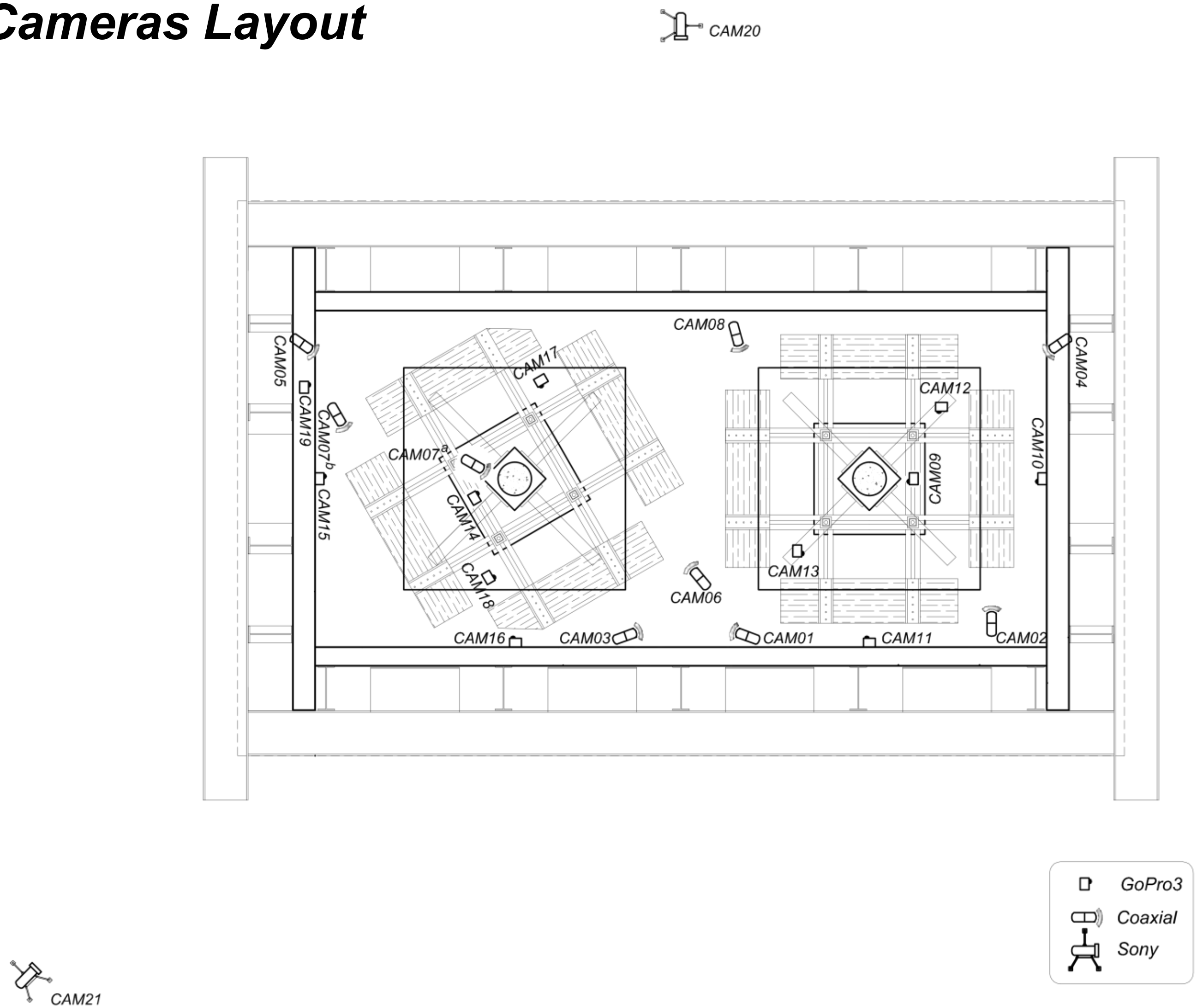




Instrumentation

- ***Video Cameras Used***
  - *Coaxial cameras [8]*
    - ✓ *Wired, power-supported, low resolution (768 × 494 pixels at 30 fps)*
    - ✓ *Live video streaming; can be played back during testing*
    - ✓ *168 out of 168 events successfully recorded*
  - *GoPro2 cameras [11]*
    - ✓ *Wireless, battery-supported, high resolution (1920 × 1080 pixels at 30 fps)*
    - ✓ *Can be accessed and played back after testing*
    - ✓ *126 out of 231 events successfully recorded*
  - *Sony cameras [2]*
    - ✓ *Man-operated, battery-supported, high resolution (1920 × 1080 pixels at 30 fps)*
    - ✓ *Can be accessed and played back after testing*
    - ✓ *29 out of 42 events successfully recorded*

- **Video Cameras Layout**



Instrumentation

➤ ***Coaxial Cameras Views***

Seismic Testing Protocol

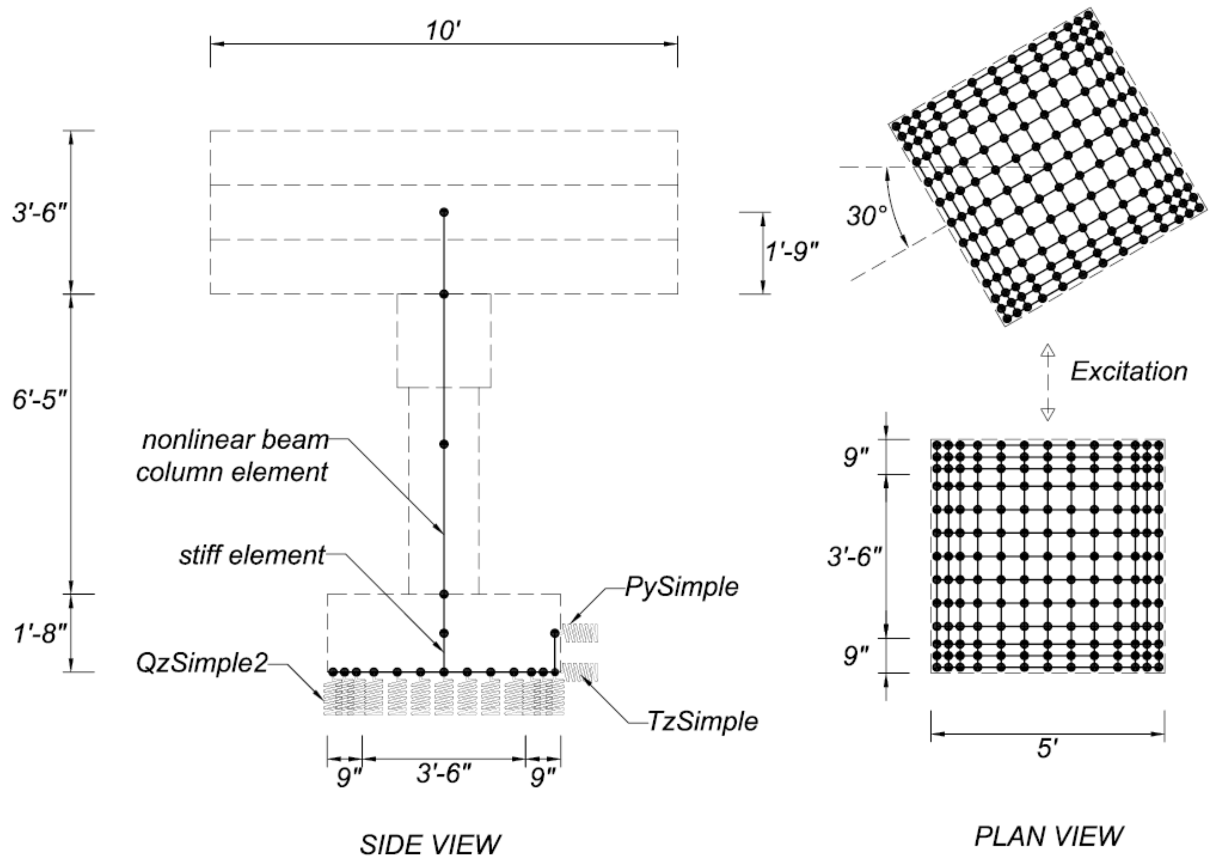
Seismic Testing Protocol

- ***Developing a Motion Protocol***
  - *Selection of number of motions and target drift ratios (Θ) for each motion*
    - ✓ *Test days 1 and 2: 6 motions of increasing intensity (peak Θ < 13% to avoid mobilization of the restraining system and damage to the column)*
    - ✓ *Test day 3: additional 2-3 motions*
  - *Pre-test prediction required to guide selection of motions to match objectives*
  - *Comparison of predicted and achieved response after each motion*

- ***Additional Considerations***
  - *Candidate motions need to be selected and distributed to Operations Manager before filling the box with soil to run OLI tests*
    - ✓ *Candidate motions: 9 unique records; 15 in total*
    - ✓ *Used motions: 6 unique records; 9 in total*
  - *Peak input acceleration < 0.80 g to ensure LSCB integrity due to removal of the roof framing elements*

Seismic Testing Protocol

- ***3D Model in OpenSees for Motion Selection***



Seismic Testing Protocol

➢ ***Motion Protocol***

No.	Earthquake	Ground motion	Scale Factor	Target Drift Ratio, Θ (%)	PGA, (g)
1	1989 Loma Prieta, CA	Gilroy #1	1.0	<0.5	0.47
2	1989 Loma Prieta, CA	Corralitos	0.8	1	0.39
3	Imperial Valley, CA, 1979	El Centro #6	1.1	2	0.49
4	1971 San Fernando, CA	Pacoima Dam	0.8	4	0.52
5	1995 Kobe, Japan	Takatori	0.5	6	0.34
6	1995 Kobe, Japan	Takatori	1.0	>8	0.68
7	1987 Superstition Hills (B)	Parachute Test Site	1.0	>8	0.42
8	1987 Superstition Hills (B)	Parachute Test Site	-1.0	>8	0.42
9	1987 Superstition Hills (B)	Parachute Test Site	1.1	>8	0.46

Notes

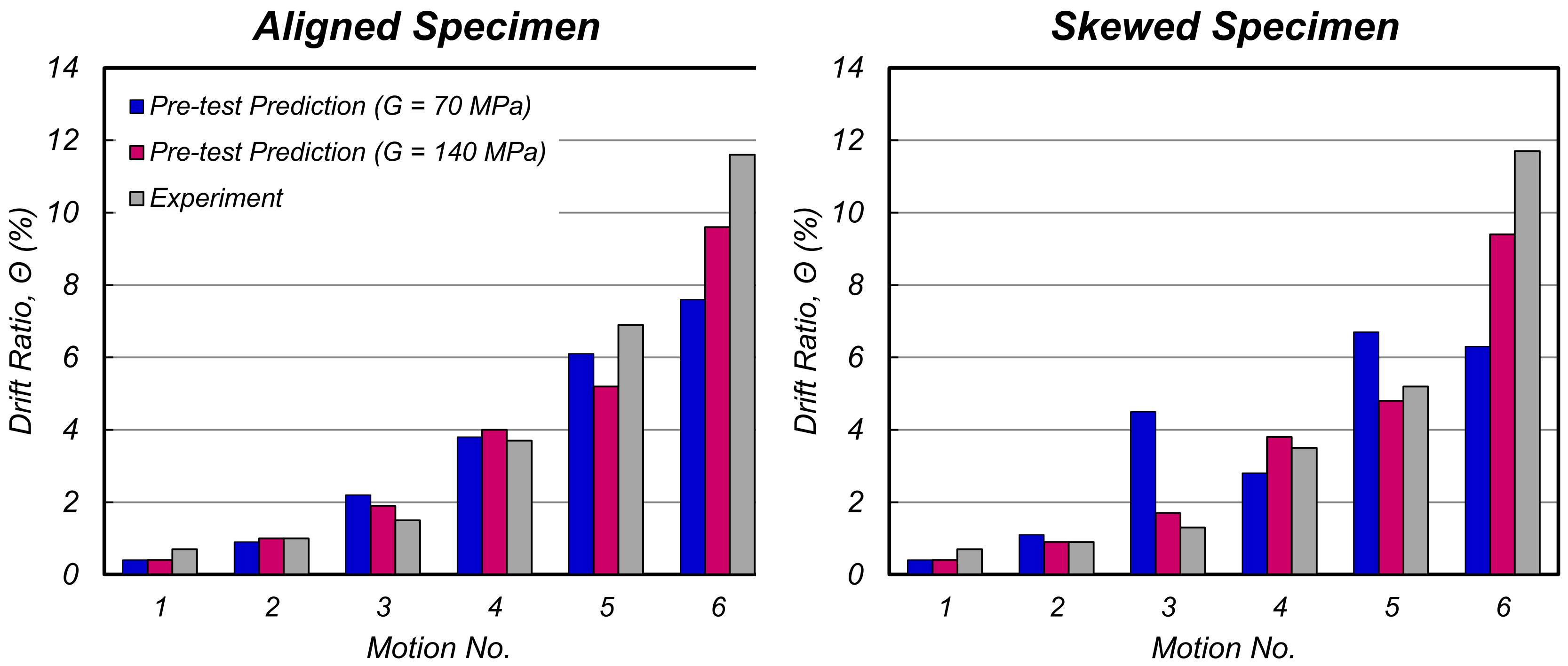
(1) Motions 7 – 9 only for Test 3.

(2) White noise with 0.05g RMS amplitude and 5 mins duration applied before motion 1 and after each motion.

(3) Motions compressed in time by sqrt(1/3) = 0.577.

Seismic Testing Protocol

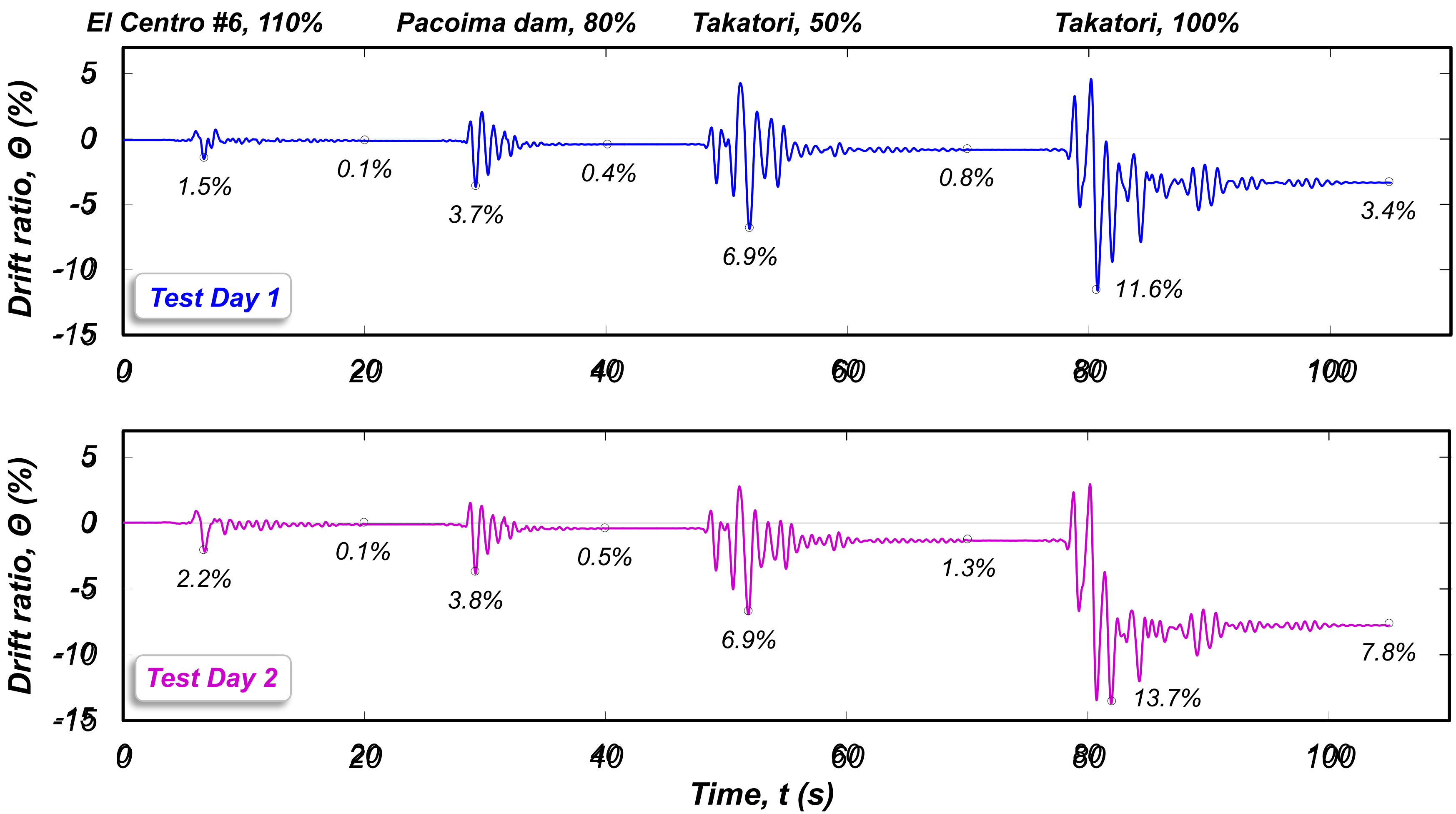
➢ ***Comparison of Pre-test Prediction with Test Day 1 Results***



Test Response

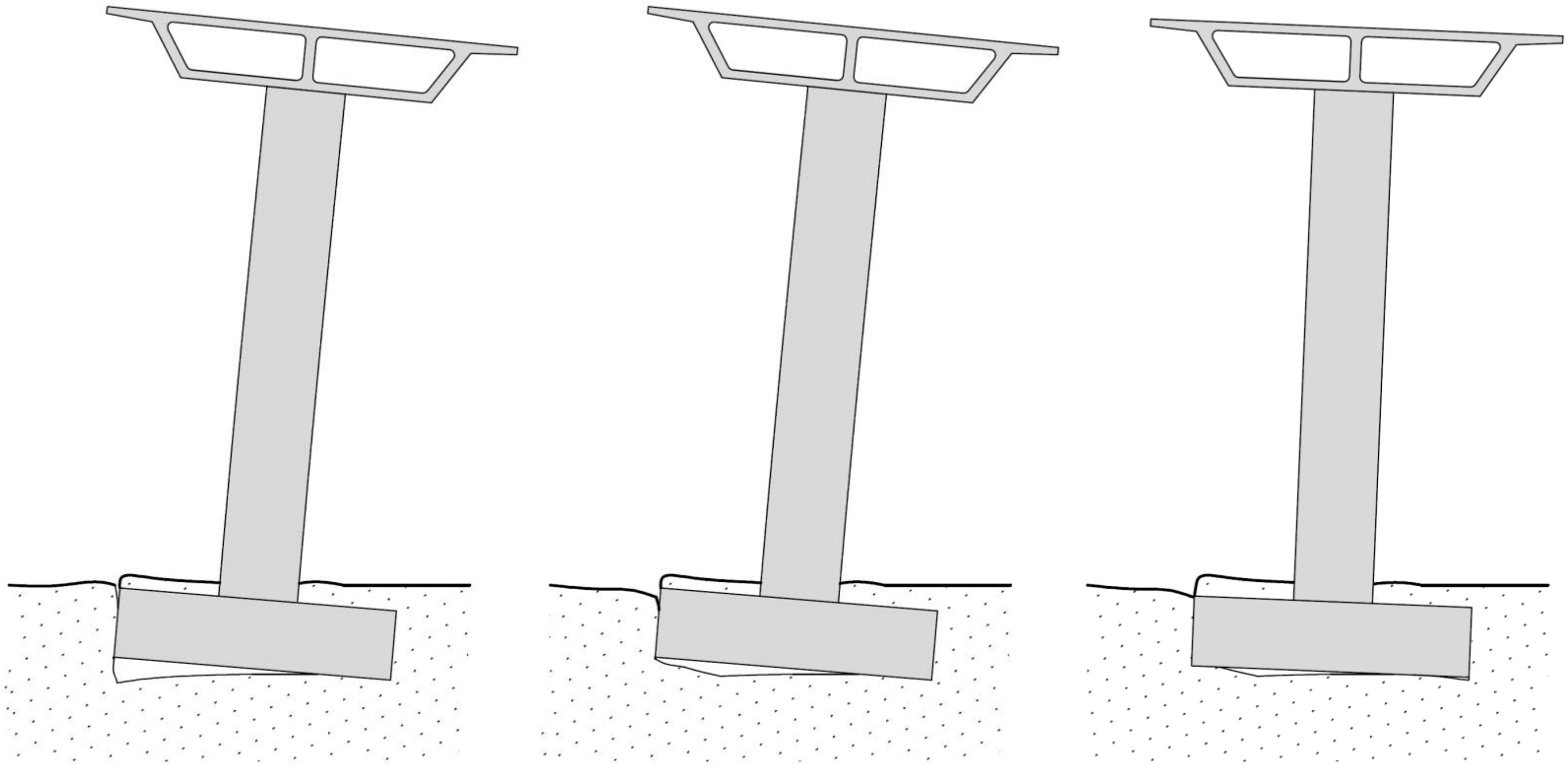
Test Response

- **Column Drift Ratio Time Histories for Test Days 1 and 2**



Test Response

- ***Mechanism for Flow of Sand under the Footing***

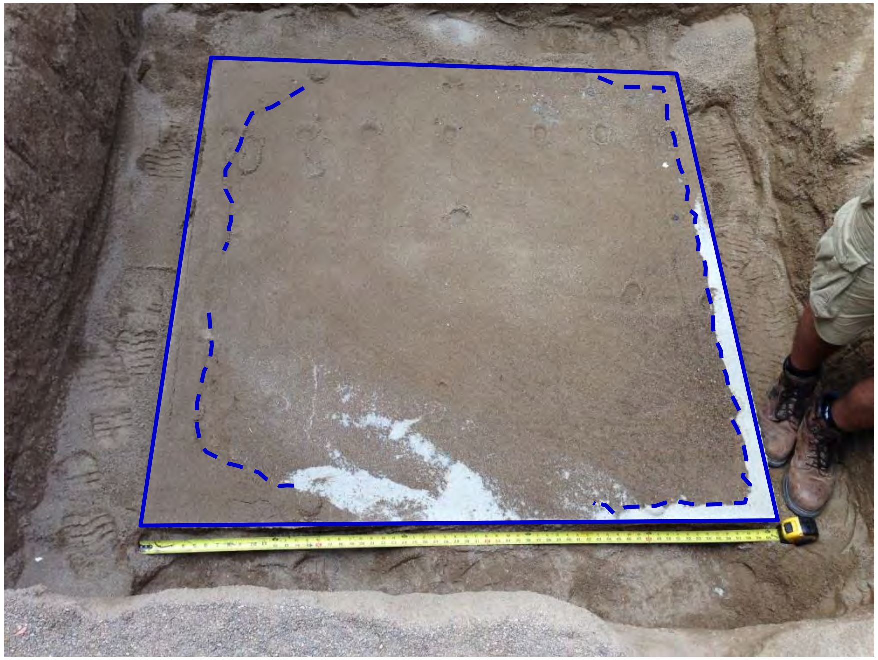


Gap formation *Sand flowing into the gap* *Residual rotation*

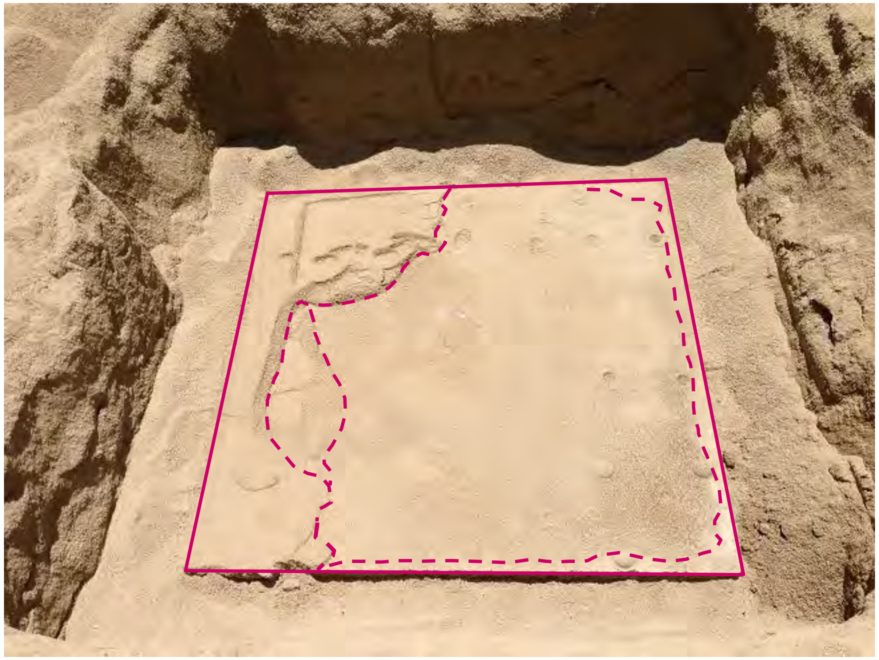
Test Response

➤ ***Post-test Soil Surface under Footings***

Test Day 1

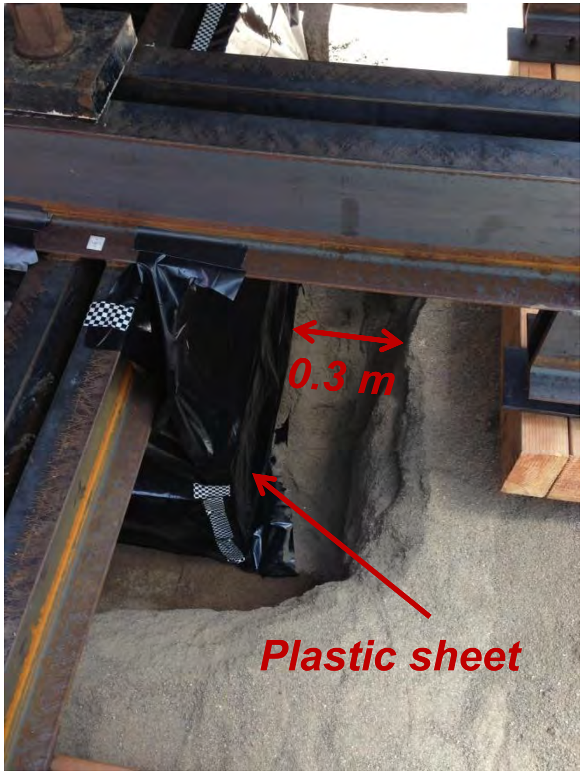


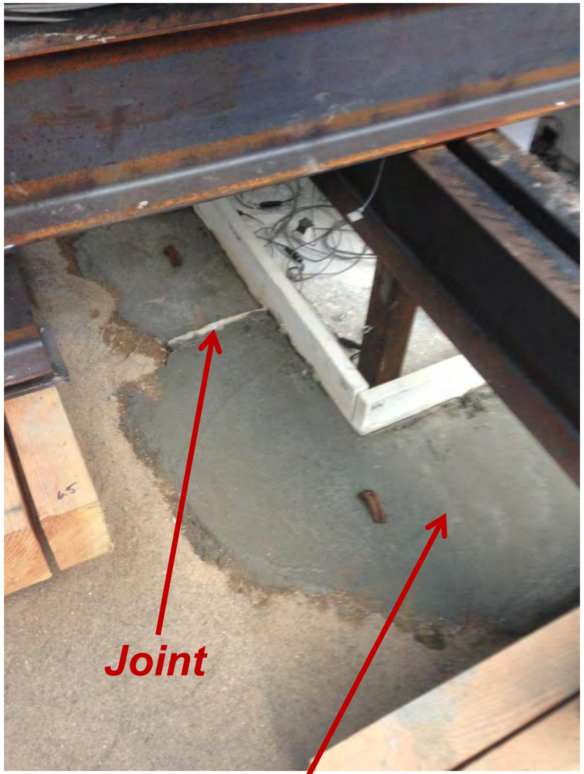
Test Day 2



Test Response

- ***Remediation Method for Test Day 3***
  - *Weak Concrete Cast around the Footings*

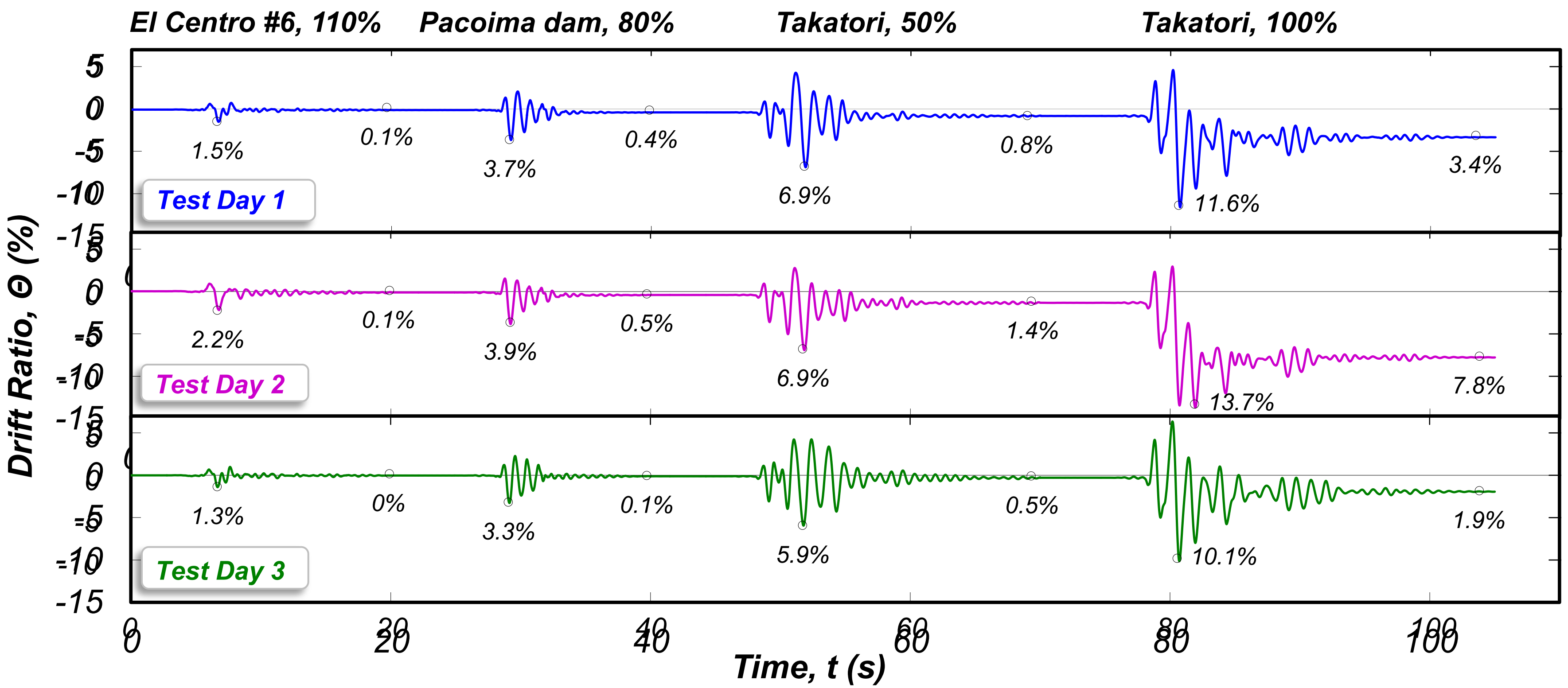




Concrete, $f_c' \approx 3.5$ MPa [0.5 ksi]
(cast one day before the test)

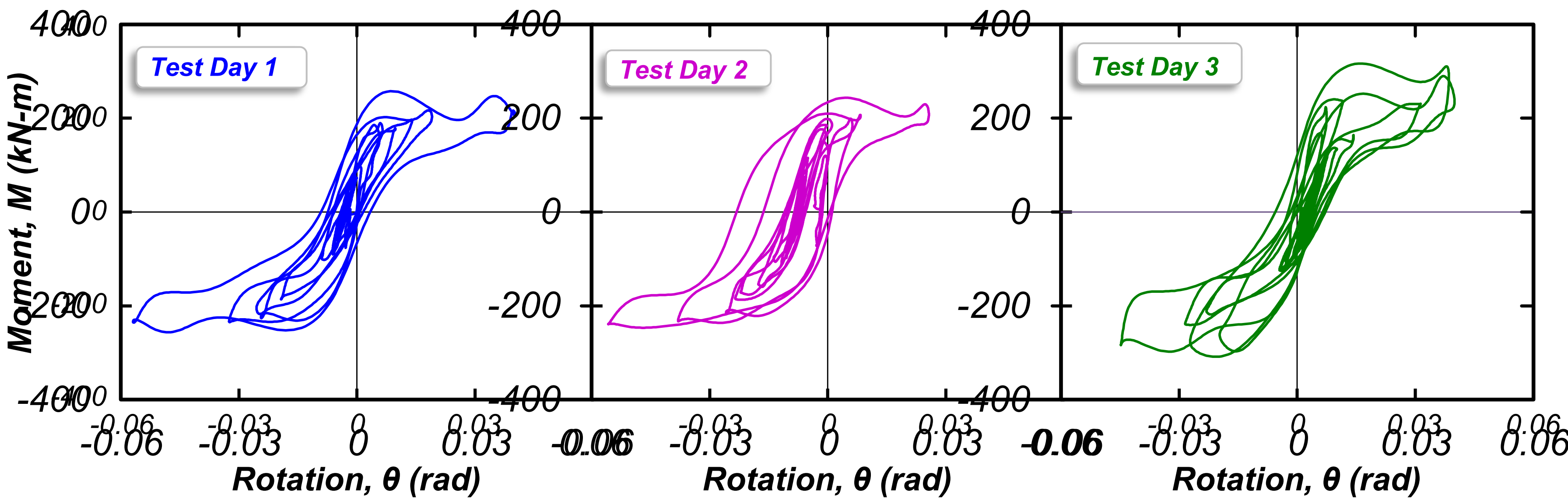
Test Response

➢ ***Column Drift Ratio Time Histories (revisited)***



Test Response

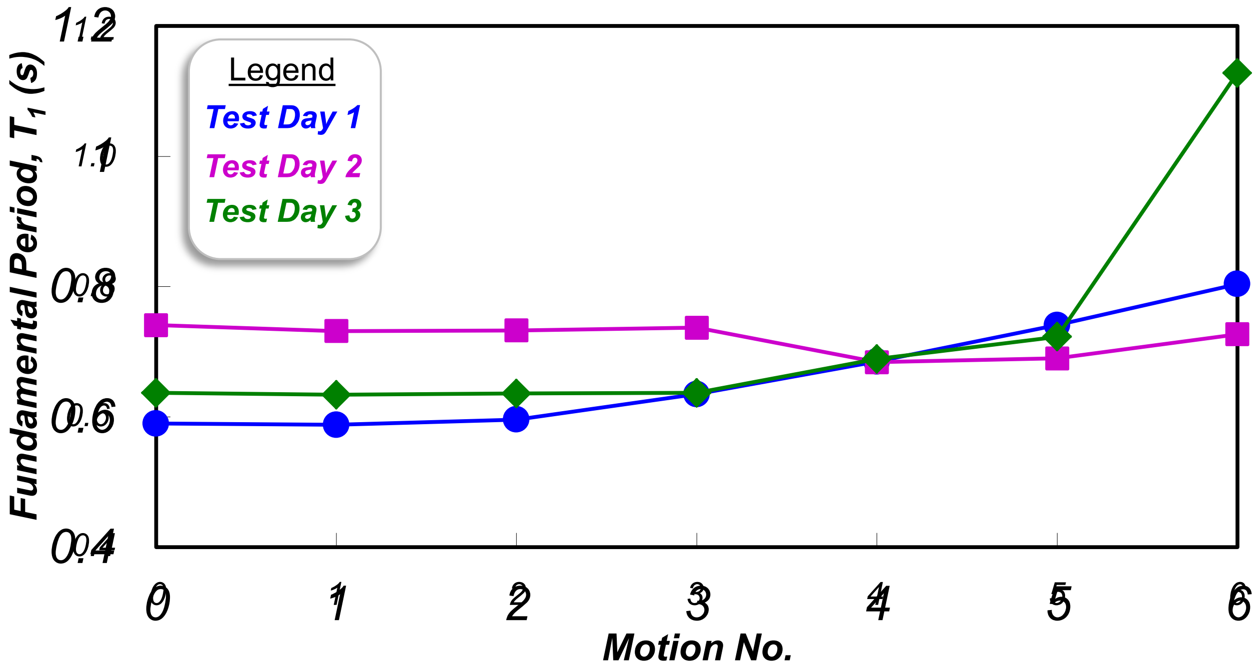
➢ ***Foundation Hysteretic Response – Takatori, 50%***



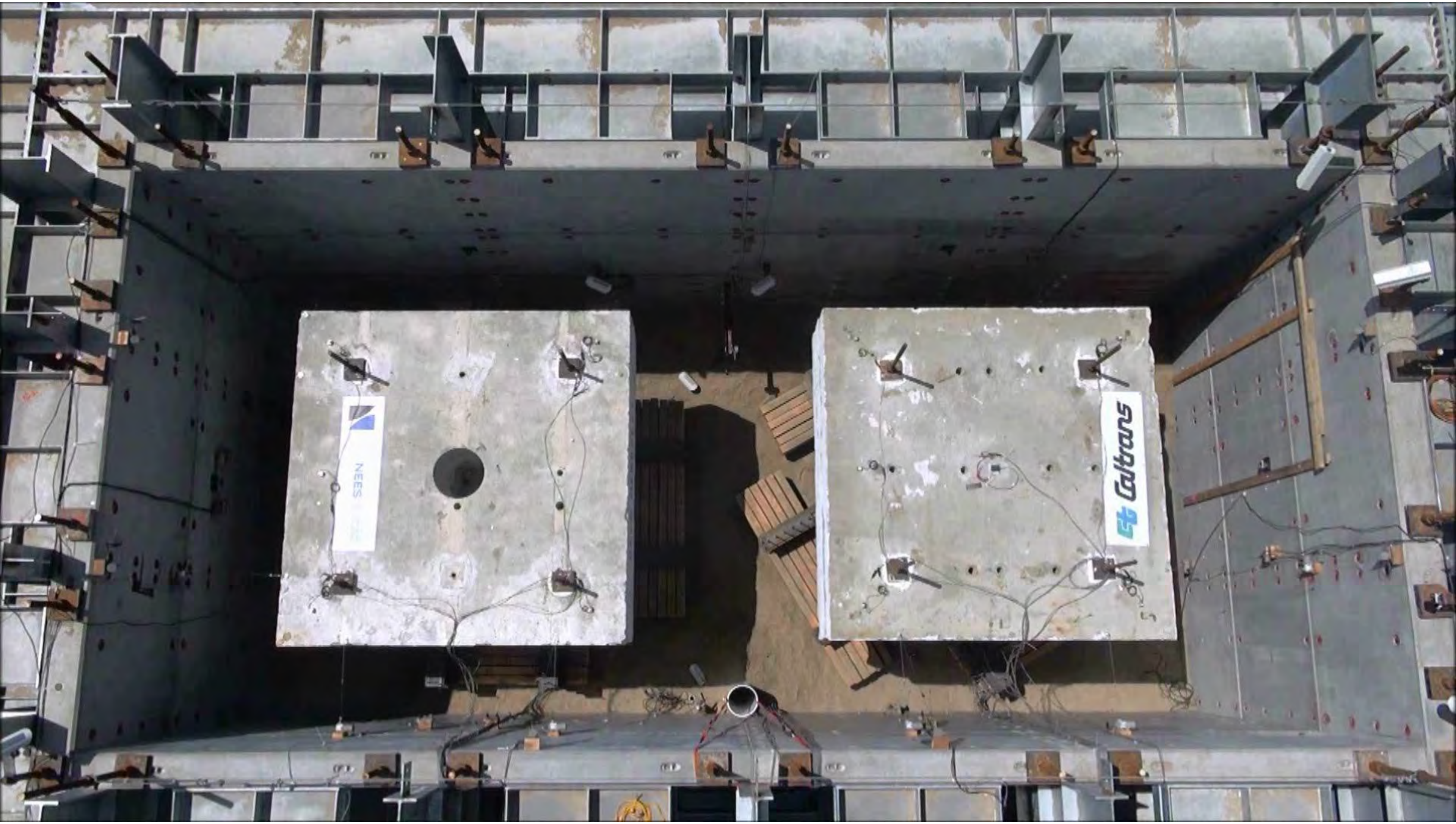
Test Response

➢ ***System Softening and Period Elongation***

- *Determined from white-noise vibrations based on the ARS amplification ratio*



Test Response



Cost Disaggregation

Item	Cost	Percentage (%)
Liner, Saturation and Dewatering System	$2,619	0.7
Pore Pressure Transducers	$1,719	0.5
Analysis of Soil Box	$5,737	1.6
Specimens Construction	$10,502	2.9
Restraining System	$18,000	4.9
Mass Blocks Shipment	$7,800	2.1
Box Demolition	$51,000	13.9
Facility Use	$101,000	27.5
Facility Labor	$98,858	26.9
Equipment Renting	$41,539	11.3
Other Materials	$28,285	7.7
Total Experimental Cost	$367,059	100.0

Concluding Remarks

- *This presentation focused on some of the design, construction and testing aspects of a large-scale 1g testing of a geo-structural system at UCSD*
- *Detailed documentation of protocols and detailed preparation of designs increases quality of communication and coordination amongst the various processes*
- *Testing decisions should reflect the target of measuring and gaining insights into specified targeted responses and mechanisms*
- *The efficacy of a physical modeling test of this scale reflects the details of the preparation and execution phases*

Concluding Remarks

- *The test progress is not a straight line. Adjustments should be expected subject to:*
  - *Preliminary results during the design phase*
  - *Gained insights during testing*
  - *Time- and cost-limitations*

Thank you!
Questions?

Acknowledgements

- *Project funded by California Department of Transportation*

- *Principal investigators*
  - *Marios Panagiotou (formerly UCB)*
  - *Bruce Kutter (UCD)*
  - *Patrick J. Fox (formerly UCSD)*
  - *Jose I. Restrepo (UCSD)*

- *Student researchers*
  - *Grigorios Antonellis (formerly UCB)*
  - *Gabriele Guerrini (formerly UCSD)*
  - *Andrew Sander (UCSD)*

- *Technical staff at NEES @ UC San Diego*
  - *Dan Radulescu*
  - *Paul Greco*
  - *Alex Sherman*
  - *Hector Vicencio*
  - *Raymond Hughey*
  - *Robert Beckley*
  - *Lawton Rodriguez*

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