National Science Foundation

University of California at San Diego
NHERI
Natural Hazards Engineering Research Infrastructure

UC San Diego
JACOBS SCHOOL OF ENGINEERING
Structural Engineering

NHERI@UC San Diego: Description and Capabilities

Joel Conte, Professor

University of California, San Diego

Lehigh Joint Researcher Workshop
UC San Diego & SimCenter

September 23-24, 2019
Lehigh University, Bethlehem, PA

LEHIGH NHERI
Real-Time Multi-Directional Testing Facility

University of California at San Diego
NHERI
Natural Hazards Engineering Research Infrastructure

SIMCENTER
COMPUTATIONAL MODELING AND SIMULATION CENTER

Outline

- Overview of NHERI@UC San Diego Shake Table Experimental Facility
  - Description of Facility
  - Performance Characteristics
  - Capabilities and Limitations

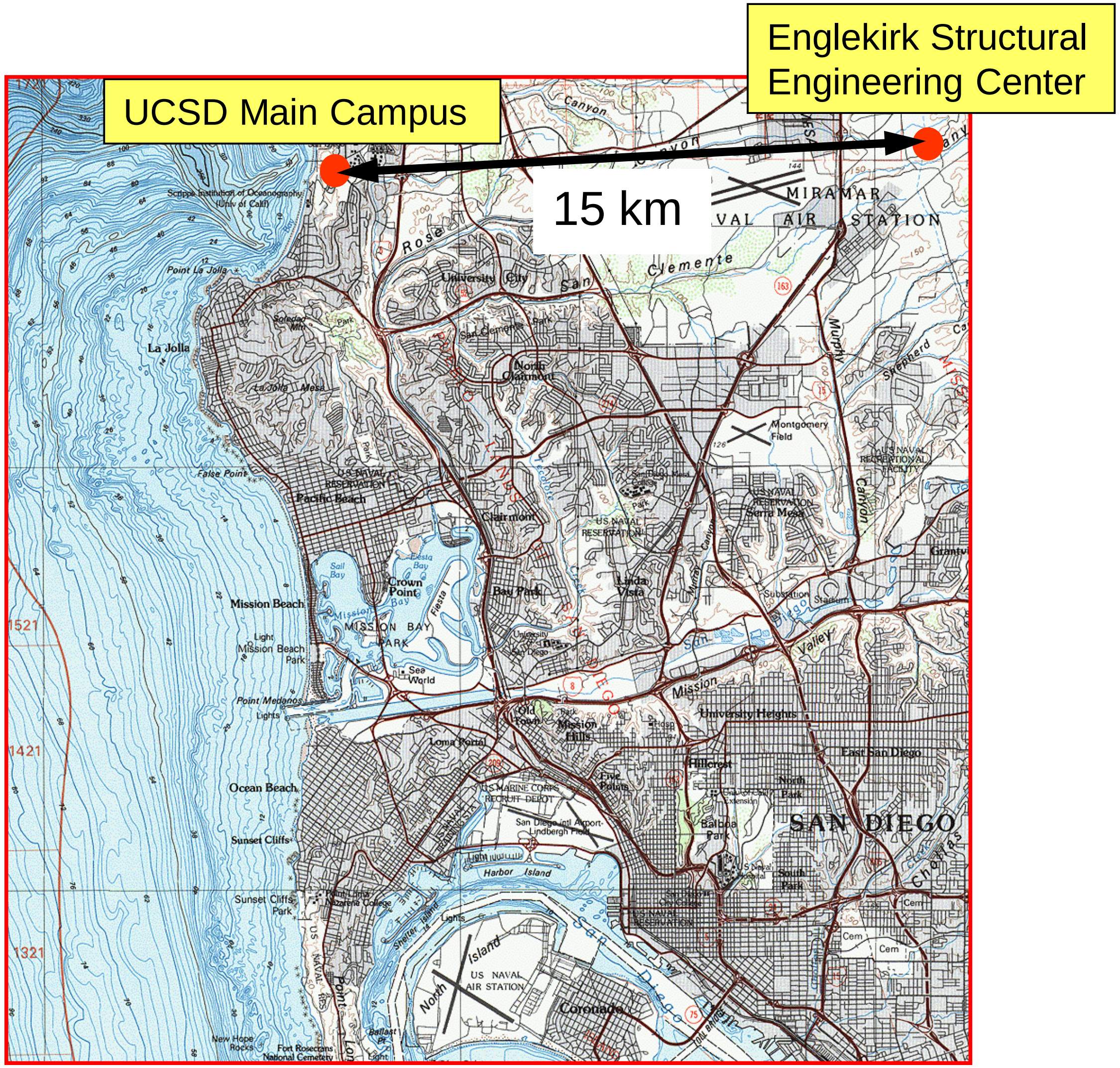
- Select Set of Large-Scale Shake Table Tests Performed on the NHERI@UC San Diego Shake Table

- Six Degree-of-Freedom (6-DOF) Upgrade of Shake Table

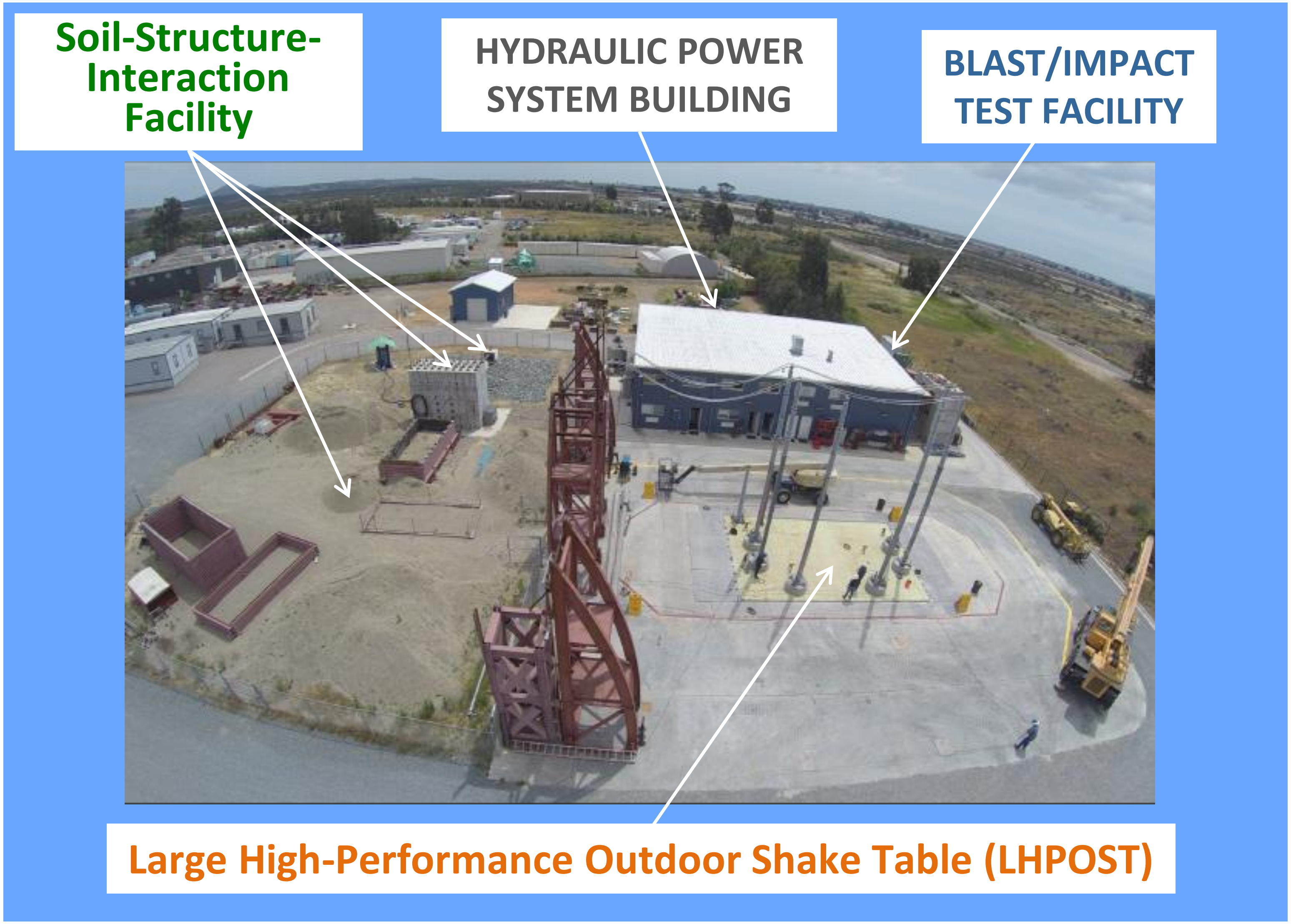
- New Research Opportunities Made Possible by the 6-DOF LHPOST

Overview of Englekirk Structural Engineering Center (ESEC) and Large High-Performance Outdoor Shake Table (LHPOST)

Englekirk Structural Engineering Center (ESEC)



Location of NHERI@UCSD Site and Relation to the Englekirk Structural Engineering Center



IAS Accreditation of ESEC

INTERNATIONAL ACCREDITATION SERVICE®

CERTIFICATE OF ACCREDITATION

This is to attest that

ENGLEKIRK STRUCTURAL ENGINEERING CENTER
10201 POMERADO ROAD
SAN DIEGO, CA 92131

Testing Laboratory TL-356

has met the requirements of AC89, *IAS Accreditation Criteria for Testing Laboratories,* and has demonstrated compliance with ISO/IEC Standard 17025:2005, *General requirements for the competence of testing and calibration laboratories.* This organization is accredited to provide the services specified in the scope of accreditation maintained on the IAS website (www.iasonline.org).

This certificate is valid up to April 1, 2019.

This accreditation certificate supersedes any IAS accreditation bearing an earlier effective date. The certificate becomes invalid upon suspension, cancellation or revocation of accreditation. See www.iasonline.org for current accreditation information, or contact IAS at 562-364-8201.

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ilac-MRA

Raj Nathan
President

15-12065

Soil-Foundation-Structure Interaction Facility

Bridge Abutment - Soil Interaction
(Caltrans)

Pile – soil interaction
(Port of Los Angeles)

NEES@UCSD SHAKE TABLE
2004-2014

NHERI@UCSD SHAKE TABLE
2016-2020

Investigators & Senior Personnel: J. P. Conte, L. Van Den Einde, G. Mosqueda, T. Hutchinson, B. Shing, J. I. Restrepo, J. E. Luco

Staff:	**O. Ozcelik:**	**Research Scientist & Site Operation Manager**
	D. McKay:	**Research & Development Engineer**
	A. Sherman:	**Senior Development Technician**
	R. Beckley:	**Site IT Manager**
	J. Fitcher:	**Senior Development Technician**

NHERI@UC San Diego Personnel

Joel Conte
PI
Site Admin.

Tara Hutchinson
Co-PI
Site User Services

Gilberto Mosqueda
Co-PI
Site Performance

Benson Shing
Co-PI
Site Operations

Lelli Van Den Einde
Co-PI
Education and Community Outreach

José Restrepo
Senior Personnel

Enrique Luco
Senior Personnel

Ozgur Ozcelik
Res. Scientist, Site Operations Manager

Darren McKay
Res. & Dev. Engineer, Shake Table Operator

Robert Beckley
IT Manager

Alex Sherman
Site Foreman
Development Technician

Jeremy Fitcher
Development Technician

Objectives of the NHERI@UCSD Site

- The **vision for the NHERI@UCSD Shake Table experimental facility** is rooted on **three critical needs** for advancing the science, technology, and practice in earthquake disaster mitigation and prevention:

  - Fundamental knowledge for understanding the **system-level behavior** of buildings, critical facilities, bridges, and geo-structures during earthquakes, **from the initiation of damage to the onset of collapse**.

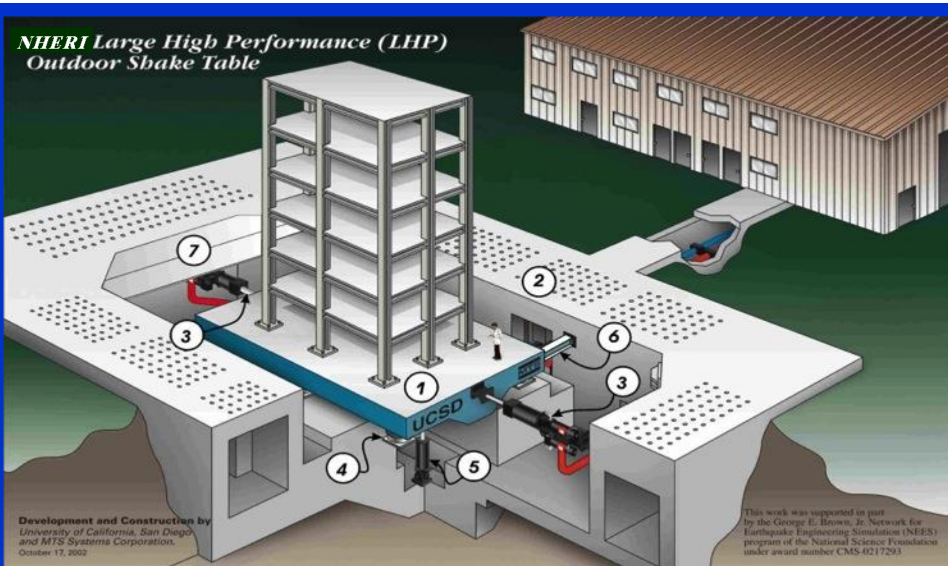
  - Experimental data to support the **development, calibration and validation of high-fidelity physics-based computational models** of structural/geotechnical/soil-foundation-structural systems that will progressively shift the current reliance on physical testing to model-based simulation for the seismic design and performance assessment of civil infrastructure systems.

  - **Proof of concept, benchmark and validation/verification tests** for seismic retrofit methods, protective systems, and the use of new materials, components, systems, and construction methods that can protect civil infrastructure systems against earthquakes.

Large High-Performance Outdoor Shake Table (LHPOST)

- Designed to permit accurate simulation of severe earthquake ground motions and, particularly, strong near-source ground motions.
- Lack of height limitation allows testing of full- or very large-scale structural specimens.
- Table designed in 2001-2002, built in 2002-2004, and commissioned on October 1, 2004, as part of the NSF NEES Network.
- 33 major research and commercial projects were conducted in 15 years of operation:
  - Reinforced concrete buildings and bridge column
  - Precast concrete parking structure
  - Unreinforced and reinforced masonry building structures
  - Metal building structures
  - Woodframe dwellings and buildings
  - Wind turbine
  - Soil retaining walls
  - Underground structures (deep and shallow)

Large High-Performance Outdoor Shake Table (LHPOST)

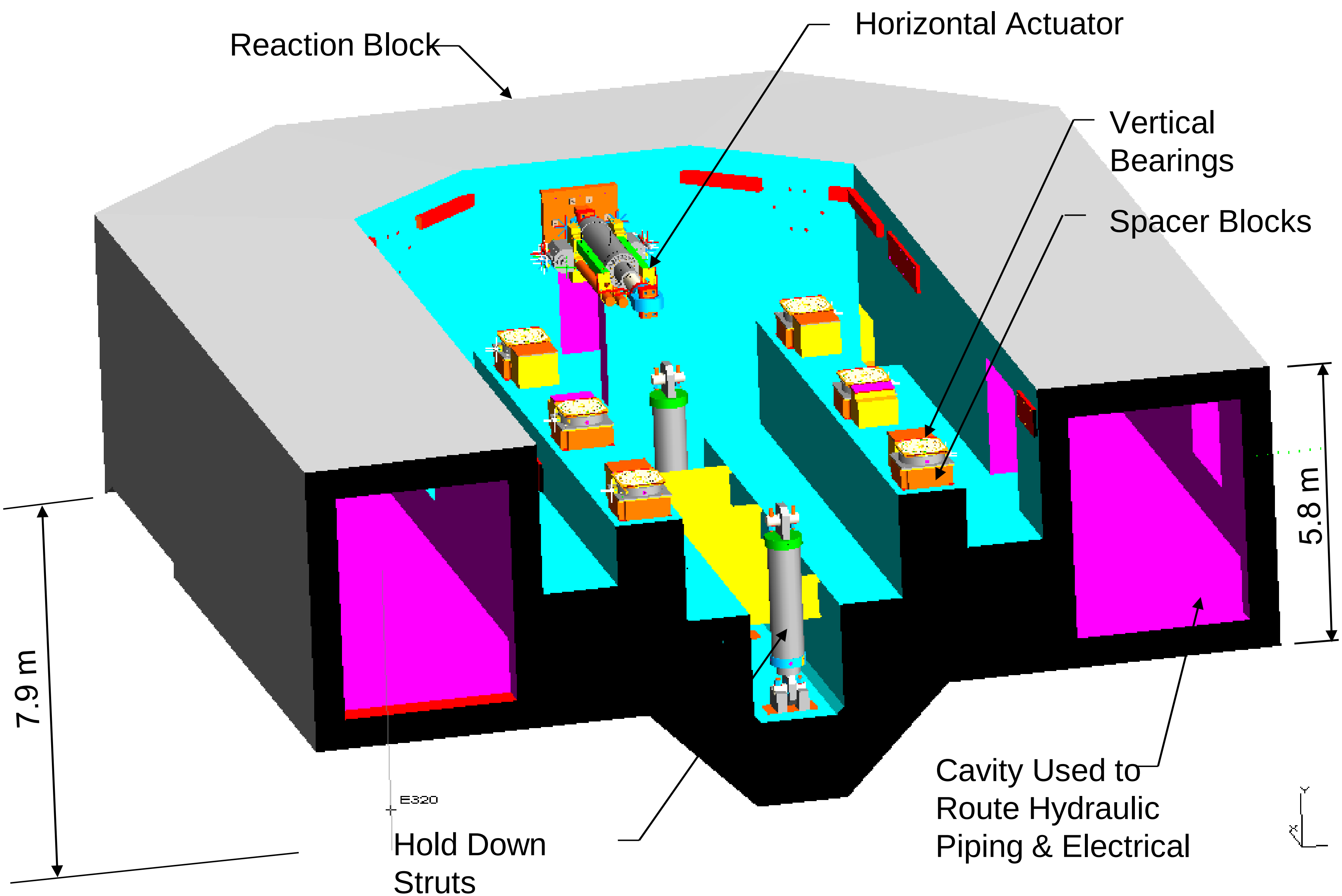


Performance Characteristics in Current 1-DOF Configuration	
Designed as a 6-DOF shake table, but built as a 1-DOF system to accommodate funding available	
Stroke	**± 0.75m**
Platen Size	40 ft × 25 ft (12.2 m × 7.6 m)
Peak Velocity	**1.8 m/sec**
Peak Acceleration	4.7g (bare table condition); 1.2g (4.0MN/400 tons rigid payload)
Frequency Bandwidth	**0-33 Hz**
Horizontal Actuators Force Capacity	**6.8 MN (680 tonf)**
Vertical Payload Capacity	**20 MN (2,000 tonf)**
Overturning Moment Capacity	50 MN-m (5,000 tonf-m)

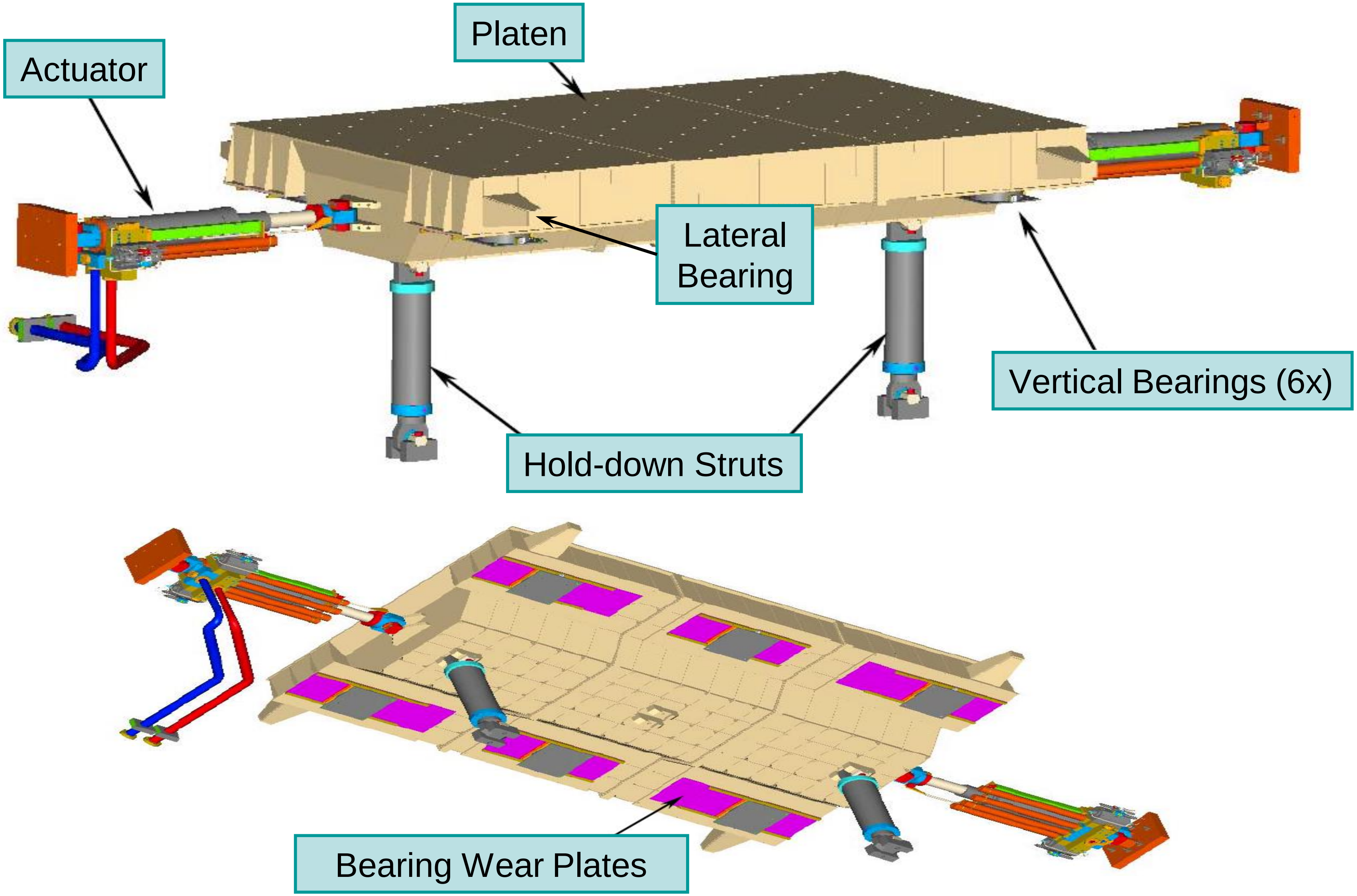
Capabilities/Provisions of NHERI@UCSD Site

- **Simulation of near-source earthquake ground motions** which involve large acceleration, velocity and displacement pulses.
- Seismic testing of **extensively instrumented large/full-scale structural specimens** under extreme earthquake loads at near real-world conditions.
- Seismic testing of **extensively instrumented large-scale geotechnical and soil-foundation-structural systems** by using the shake table in combination with large soil boxes.
- Basic capabilities for **hybrid shake-table testing**.
- **Education** of graduate, undergraduate, and K-12 students, as well as news media, policy makers, infrastructure owners, insurance and the general public, **about natural disasters** and the national need to develop effective technologies and policies to prevent these natural hazard events from becoming societal disasters.

Connection of Platen to Reaction Block

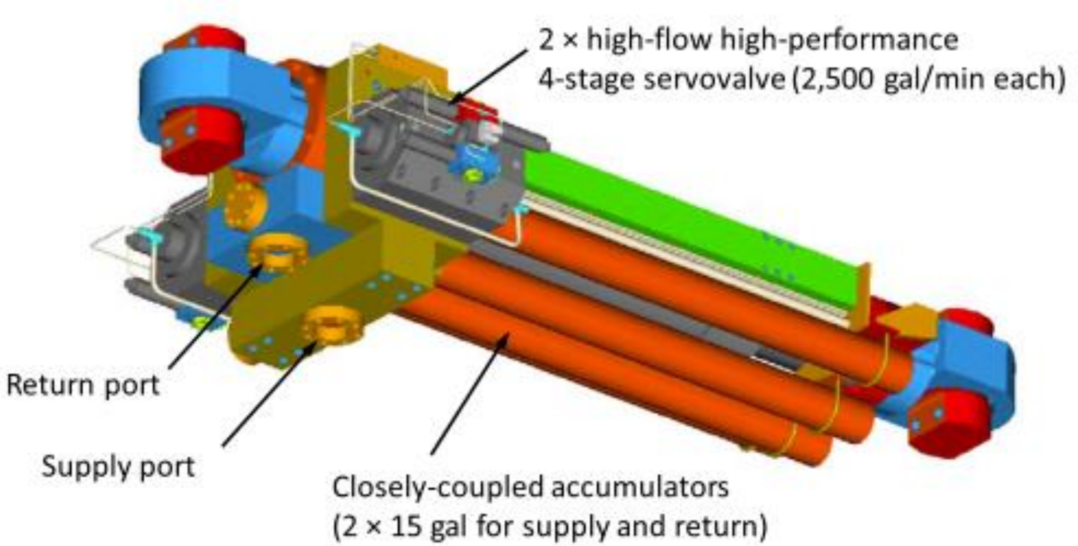


Mechanical and Servo-Hydraulic Components



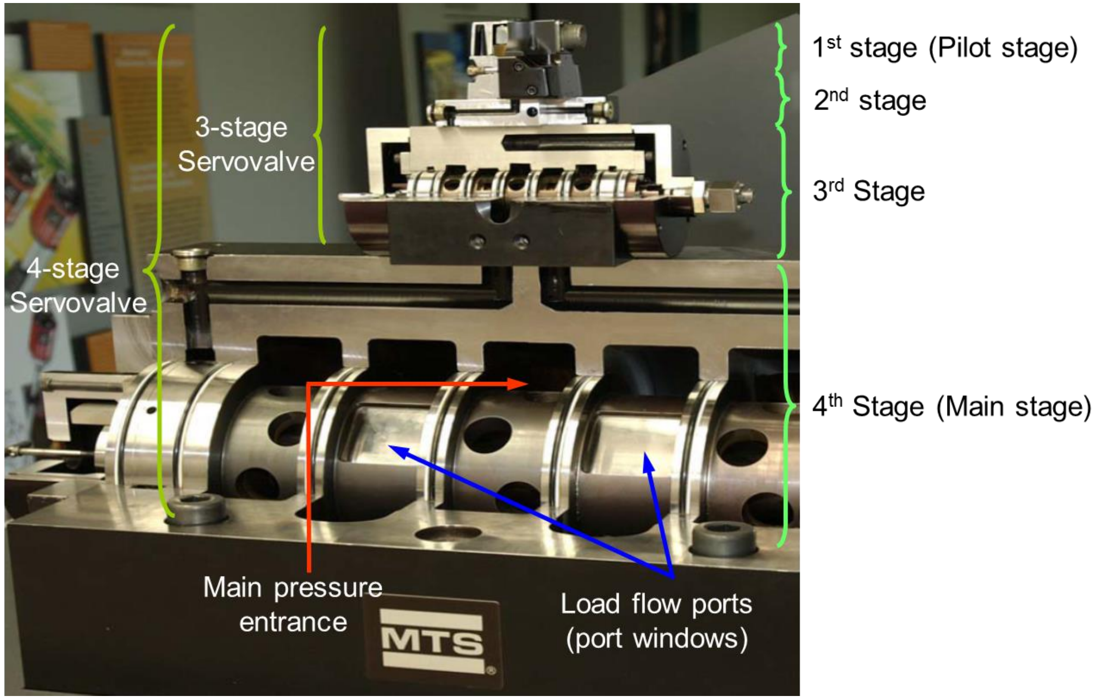
Horizontal Actuators

Horizontal Actuators Specification	
Dynamic stroke	+/- 0.75 m
Force Capacity (Tension/Compression)	2.7 MN / 4.2 MN
Rod diameter	0.3048 m
Piston Diameter	0.5080 m
Tension Area	0.1297 m^2
Compression Area	0.2027 m^2
Peak Extend Flow Rate	21,890 lt/m
Peak Retract Flow Rate	14,010 lt/m



High-Flow High-Performance Servovalves

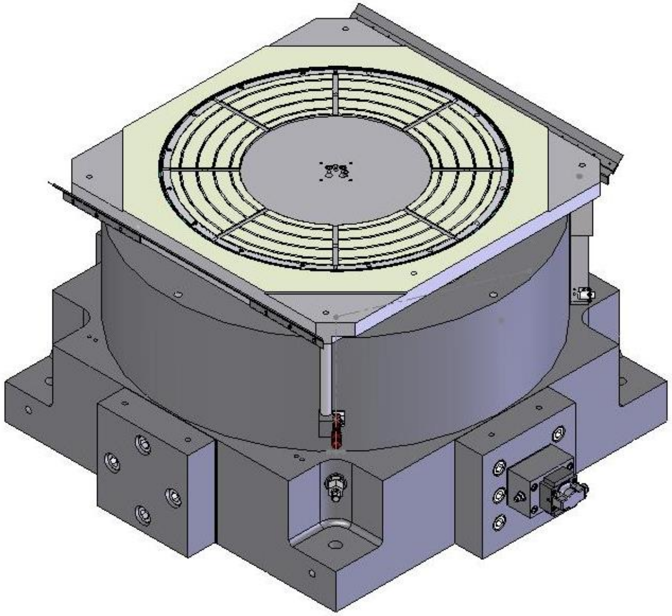
Servovalves (Qty. 2E + 2W)	
Pilot 2nd Stage Rating (Manufacturer Moog)	**19 lt/min**
Pilot 3rd Stage Rating	**630 lt/min**
4th Stage Flow Rating	**10,000 lt/min (2,5000 gpm)**
Port Area Ratios	1:0.8:0.64:0.5
Valve Sleeve Windows Area Ratio	1:0.64

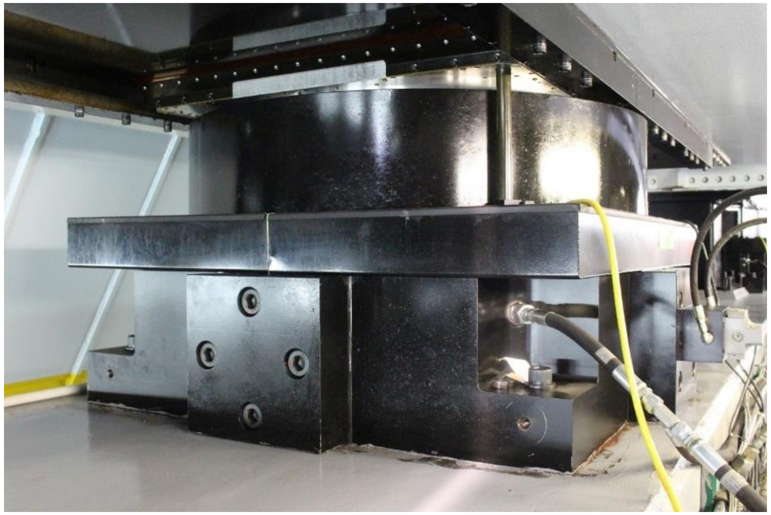


Courtesy of MTS Systems Corporation

Vertical Actuators

VERTICAL ACTUATORS SPECIFICATION		
	1-DOF Configuration	**6-DOF Configuration**
Piston Diameter	32 in (0.81 m)	32 in (0.81 m)
Effective area	798.31 in^2 (0.515 m^2)	798.31 in^2 (0.515 m^2)
Piston Stroke	± 0.25 in (± 0.0064 m)	± 5.0 in (± 0.127 m)
Piston Tilt	N/A	± 2°
Force Rating	3,000 psi (20.7 MPa)	3,000 psi (20.7 MPa)
Compression	2,200 kips (10.0 MN)	2,200 kips (10.0 MN)
Valve Flow	15 gpm (56.8 lit/min)	5,000 gpm (18,927 lit/min)





Hold-down Struts

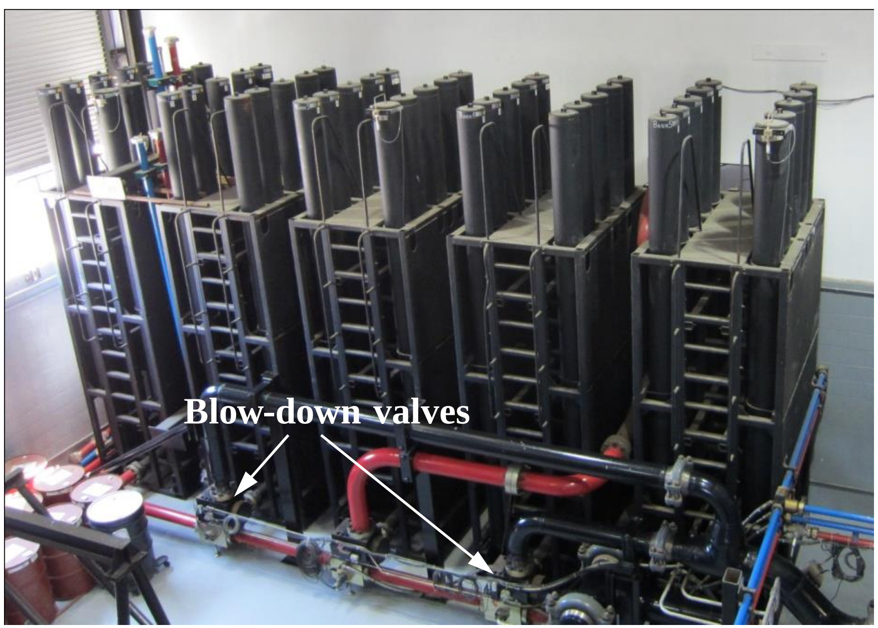
Hold-Down Struts (Qty. 2)	
Nitrogen Pressure	13.8 MPa
Uni-axial Stroke	2 m
Pin-to-Pin Length	3.3 m
Hold-down Force	**2.1 MN**
Effective Tension Area	0.15 m^2

Hydraulic Power System

Pumps

Hydraulic Power System	
Accumulator swept displacement	7.5 m
Accumulator bank pressure	35 MPa
System pressure	20.7 MPa
Blow-down maximum flow rate	38,000 lt/min
HPU flow rate @ 35 MPa (5,000 psi)	431 lt/min
HPU flow rate @ 20.7 MPa (3,000 psi)	718 lt/min
Surge tank capacity	20,000 lt

Accumulator bank

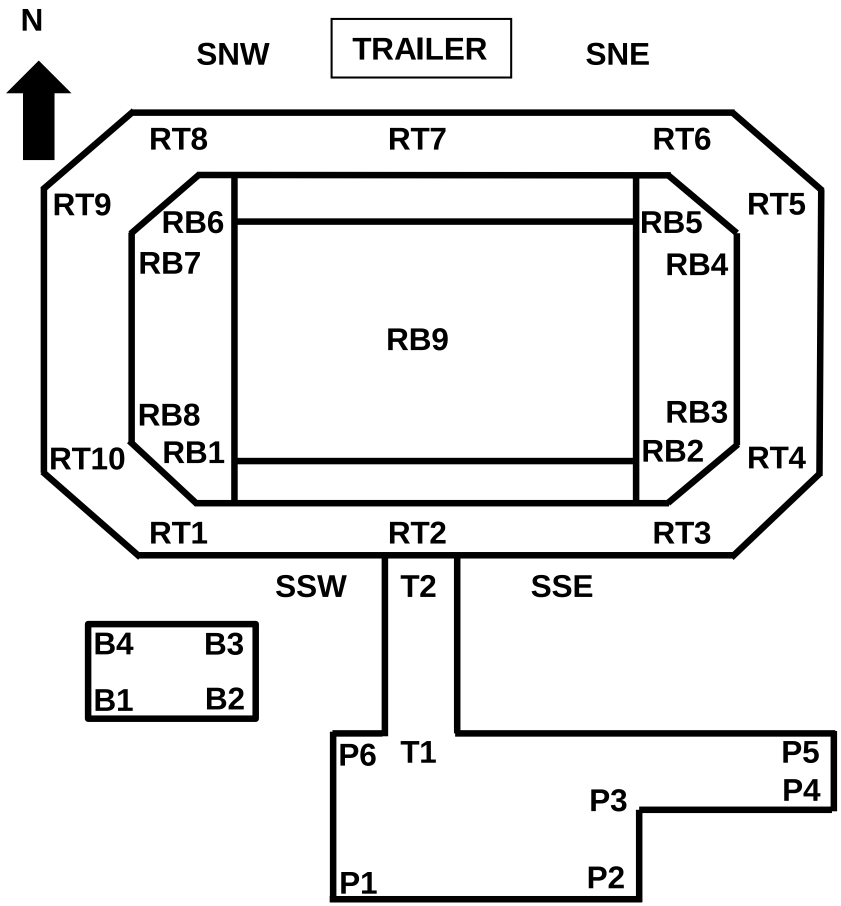


Surge tank

Bare Table Motions

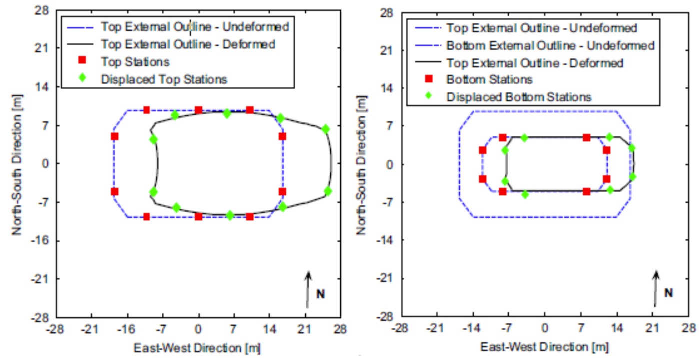
Forced Vibration Tests of the Reaction Mass at the NEES-UCSD Shake Table

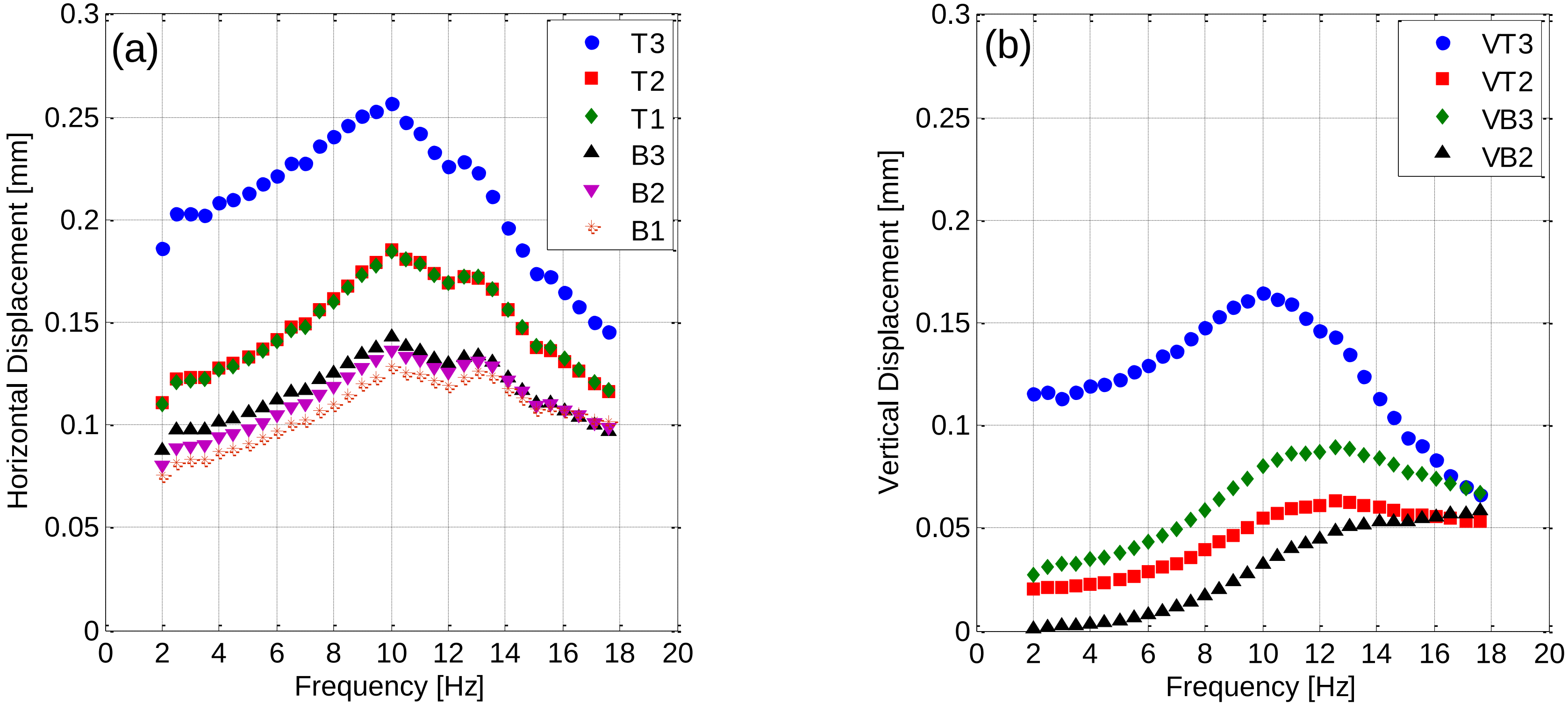
Commissioning Tests



Instrument locations on Reaction Block and adjacent foundations

Frequency Response Functions of Reaction Mass





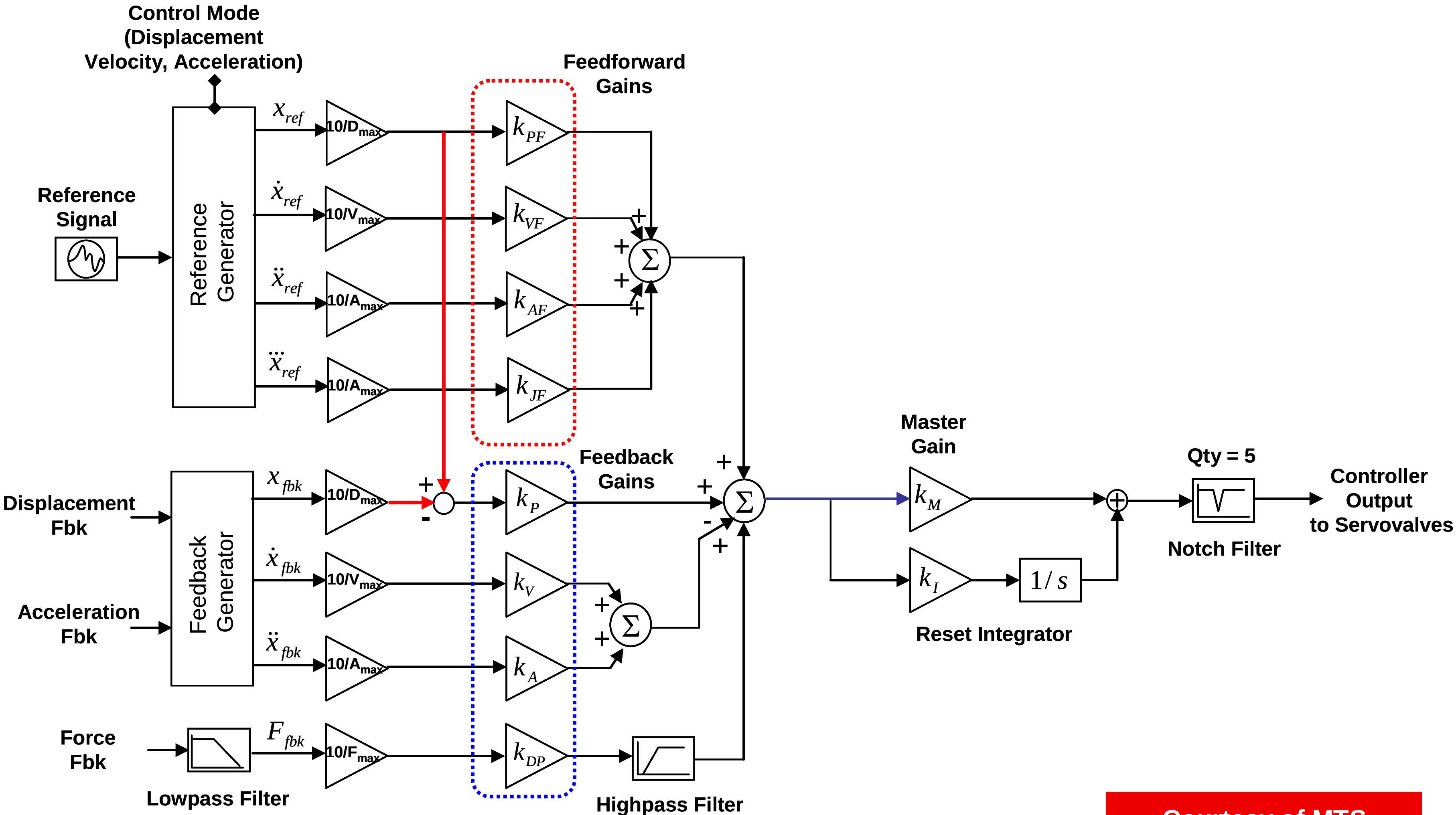
Amplitudes of the EW (a) and vertical (b) frequency response functions of the reaction block for EW excitation. The results shown are based on Test 2 and correspond to scaled displacement amplitudes for a harmonic force of constant amplitude 6.8 MN.

MTS Three-Variable Controller (TVC)

- **MTS Controller Model 469D** used on all large shake tables manufactured by MTS worldwide.
- TVC is a linear **state variable controller**. The three **state variables controlled by TVC** are:
  - Displacement
  - Velocity
  - Acceleration

  TVC can be set to run under displacement, velocity or acceleration mode.
- TVC has **special features to compensate for linear/nonlinear sources of signal distortions** within the system for both harmonic and broadband command signals:
  - Amplitude/phase control
  - Adaptive harmonic cancellation
  - Adaptive inverse control (AIC)
  - On-line iteration (OLI): Iterative signal matching technique
  - Notch filters
- Depending on the control mode, only one state variable becomes the **primary control variable** with the others serving only as compensation signals to improve the damping and stability of the system.

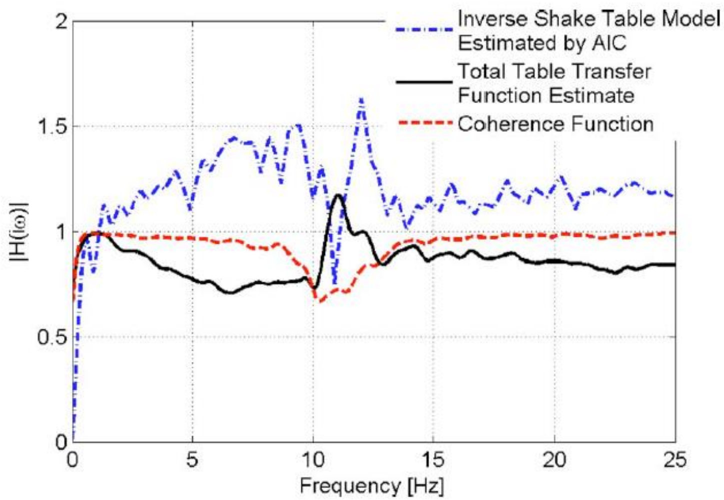
MTS Three-Variable Controller (TVC)



Courtesy of MTS
Systems Corporation

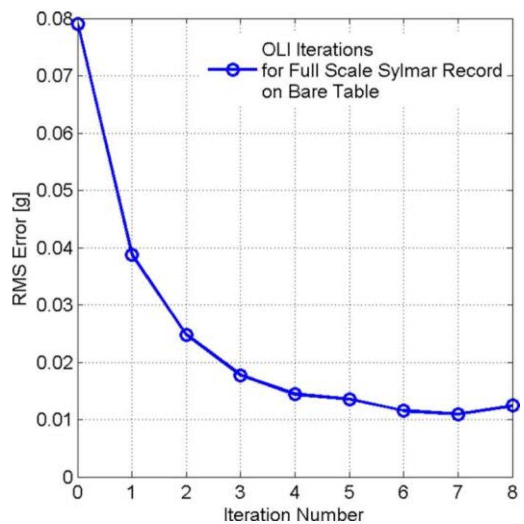
Tuning of LHPOST Controller (MTS 469D)

Tuning: Process of adjusting multiple control parameters (e.g., feedback and feedforward gains) and of preconditioning the input motion (through OLI) to optimize signal reproduction (tracking) capability of the shake table system.



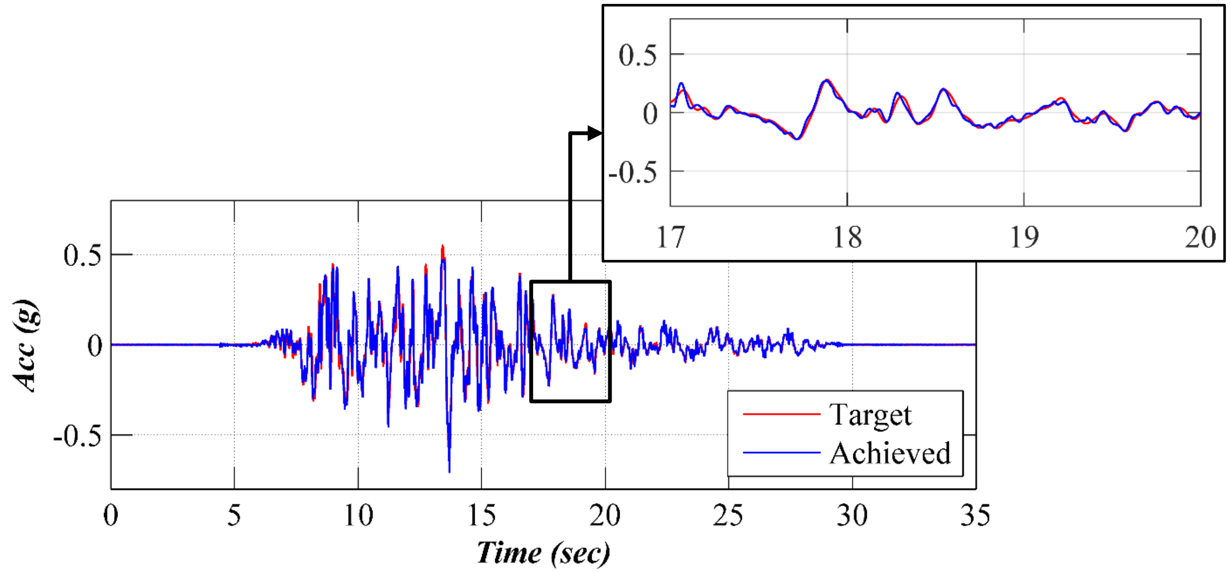
Step 1: Iterative process in which the control parameters of the controller are manually adjusted iteratively in small increments while the (bare or loaded) table is in motion, until the total table transfer function (estimated recursively) is deemed satisfactory.

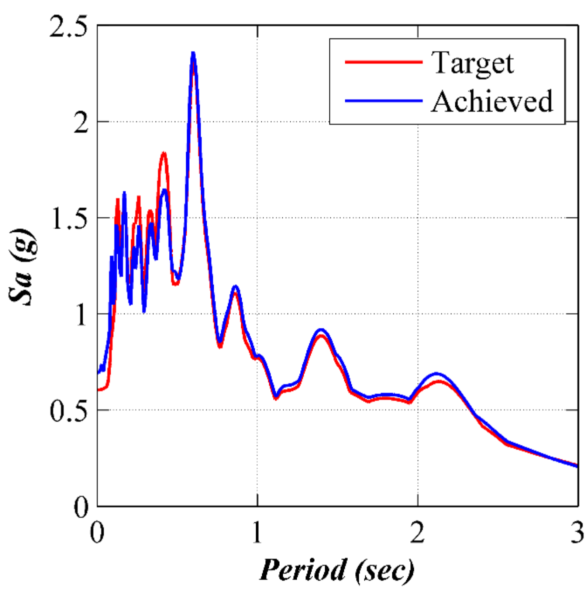
Step 2: Estimation of the inverse model of the plant using the adaptive inverse controller (AIC) technique.

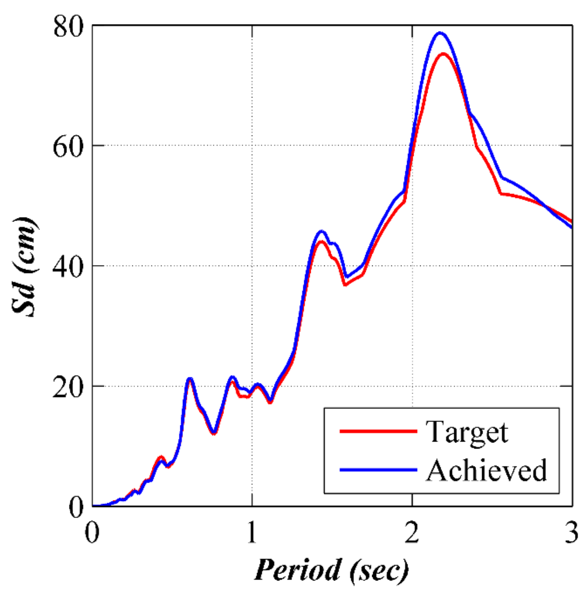


Step 3: Application of iterative time history matching technique called online iteration (OLI). The command input to the shake table controller (drive file) is repeatedly modified to optimize the match between the actual table motion and the desired/target motion.

Tracking Performance of NHERI@UCSD Shake Table







1994 Northridge Earthquake
Canoga Park (comp. 196)
Amplitude scaling: 1.55

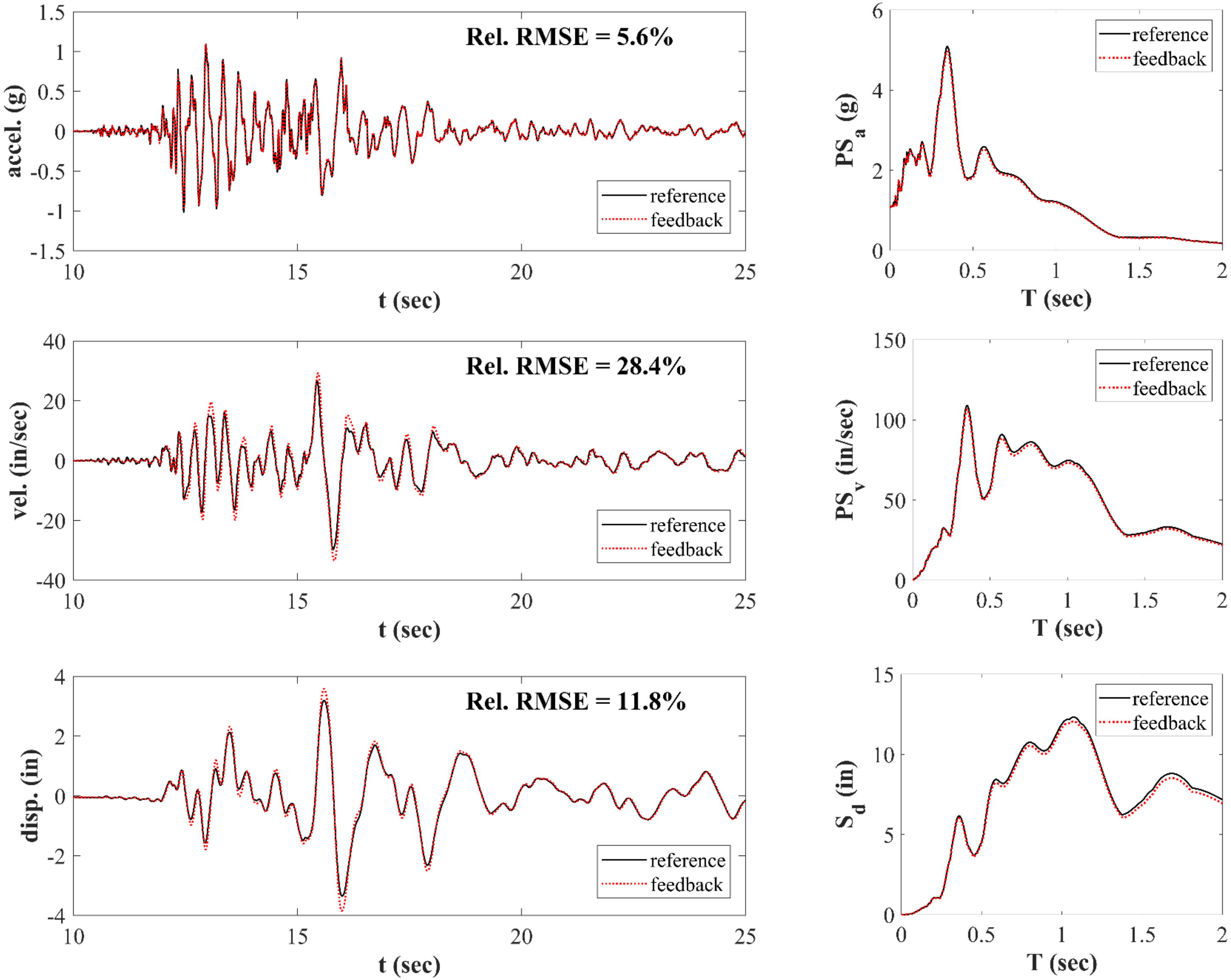
Tracking Performance of NHERI@UCSD Shake Table

- ➢ Specimen and safety pedestals as constructed on the shake table platen:

- ➢ Total weight on the table: 142 kips

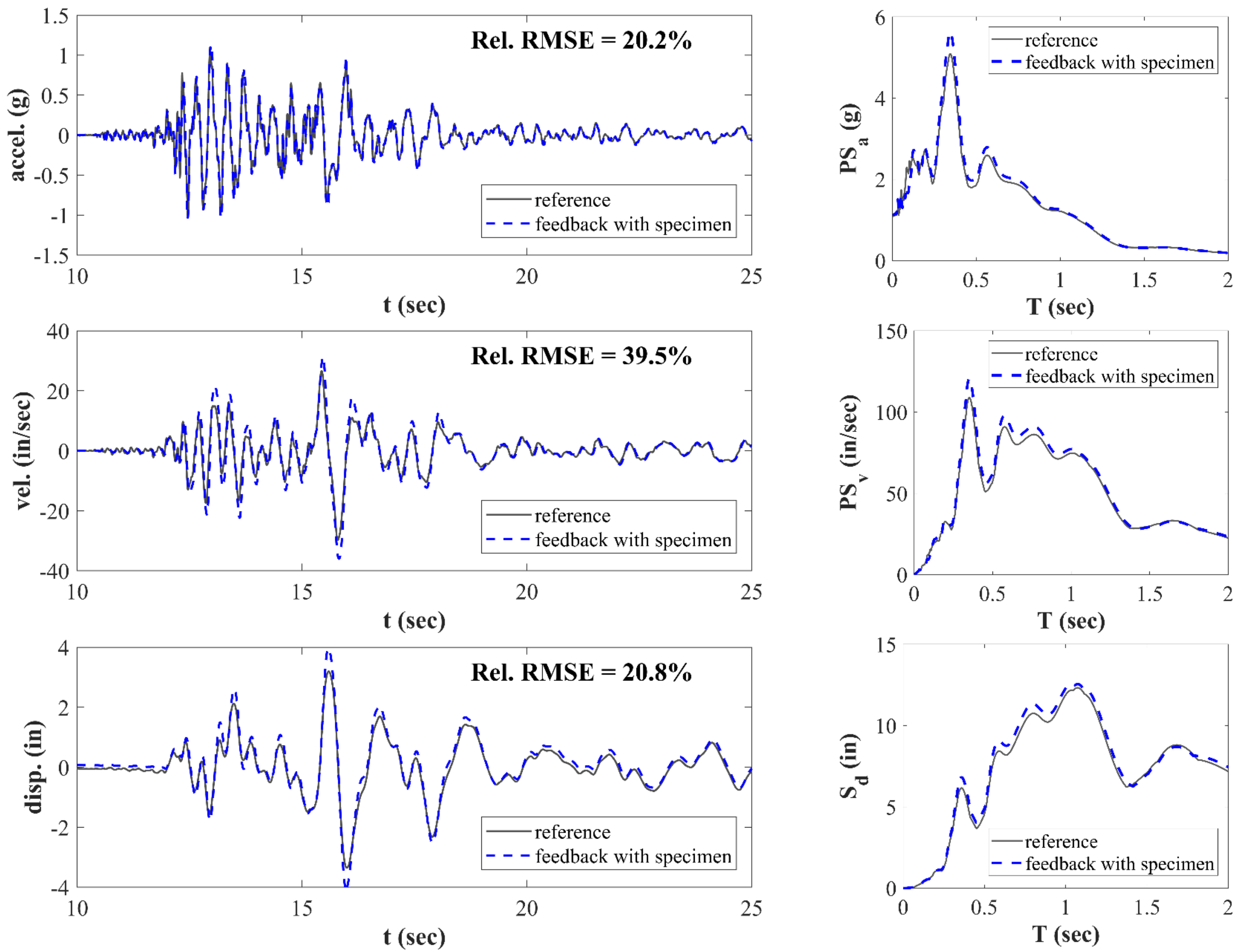
Tracking Performance of NHERI@UCSD Shake Table

1994 Northridge, Mulholland-279 at 90% (iteration 6)
(Bare table condition)



Tracking Performance of NHERI@UCSD Shake Table

1994 Northridge, Mulholland-279 at 90% (iteration 6) (Loaded table)



Instrumentation for LHPOST

- **Data Acquisition**
  - **12 DAQ nodes with 64 channels each** sampling up to **500 sps** with A/D conversion at 16 bits

- 130 MEMS-based **Accelerometers**
- 125 Linear **Displacement Transducers**
- 153 **String Potentiometer** Displacement Transducers

- Strain Gages (disposable)
- 4 **Load Jacks**
- 24 **Load Cells** (0 – 20,000 lbs).
- 32 **Soil Pressure Transducers**

- **GPS System** with RTD_NET Software by Geodetics with 3 Receivers Operating at **50 Hz**
- **High-Speed Cameras**
  - 15 GoPros 1080p, 4 Axis 240Q/241Q video servers streaming, 3 IQeye streaming/time lapse video (all at **30 fps**)
- Fully Configured, End-to-End, **Live Video Streaming Production System**
- **Calibration Equipment** for Data Acquisition Systems and Sensors

Selected Set of Specimens tested on the LHPOST









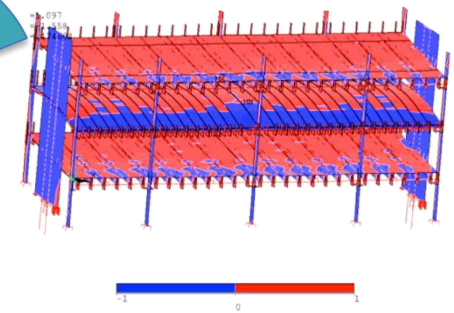




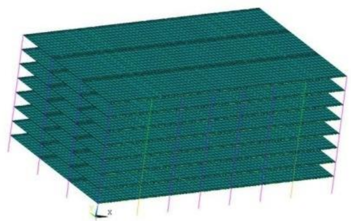
Integrated Experimental-Analytical Approach

Experimental Research
- Materials
- Structural components
- Structural systems

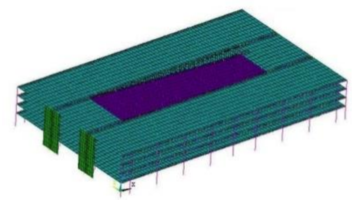
Computational Simulation
- Model development
- Model calibration
- Model validation



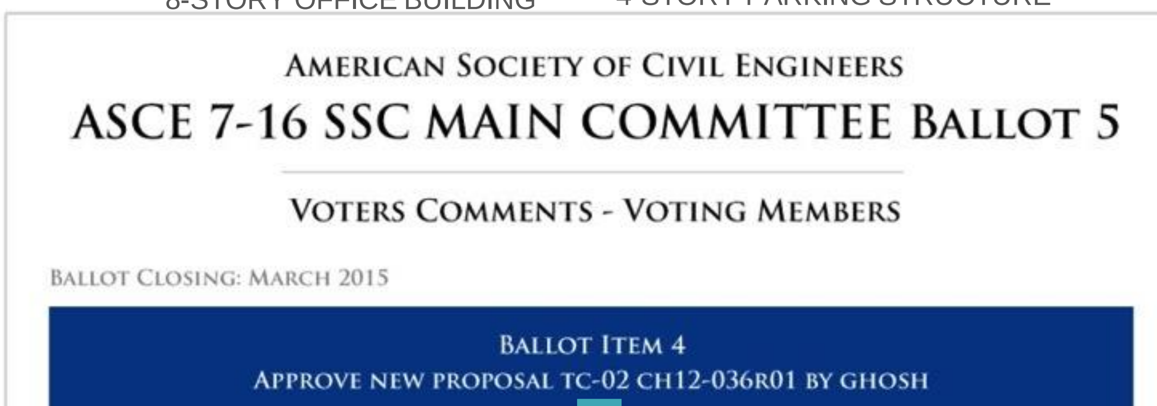
Design Provisions and Assessment Methods
- Development
- Verification through numerical simulation



8-STORY OFFICE BUILDING



4-STORY PARKING STRUCTURE



AMERICAN SOCIETY OF CIVIL ENGINEERS

ASCE 7-16 SSC MAIN COMMITTEE BALLOT 5

VOTERS COMMENTS - VOTING MEMBERS

BALLOT CLOSING: MARCH 2015

BALLOT ITEM 4

APPROVE NEW PROPOSAL TC-02 CH12-036R01 BY GHOSH

EARTHQUAKE RESILIENT INFRASTRUCTURE

Select Large-Scale Shake Table Tests Performed on the LHPOST

Development of a Seismic Design Methodology for Precast Building Diaphragms

PI – Prof. Robert B. Fleischman, University of Arizona


NEES

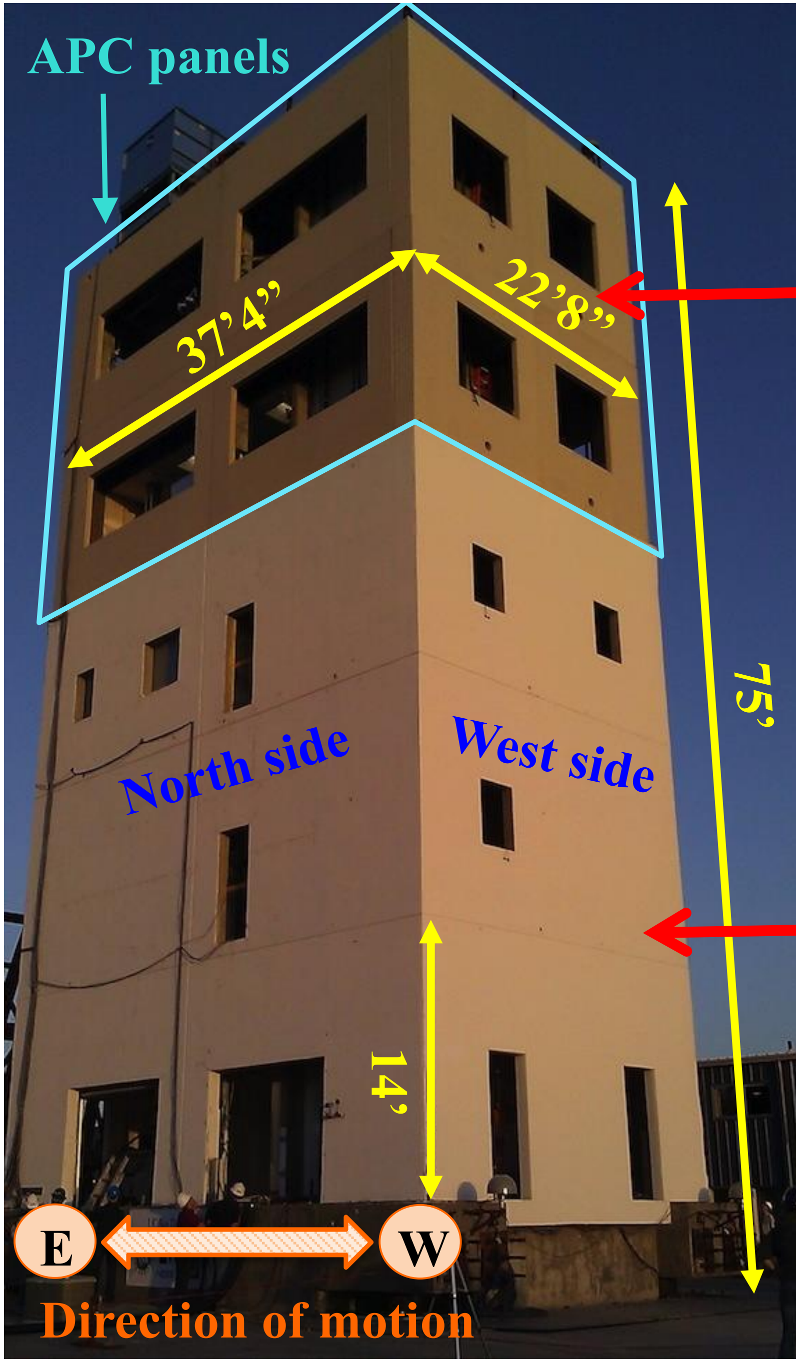
Collapse Vulnerability and Seismic Design of Metal Buildings

PI – Prof. Chia-Ming Uang, UC San Diego

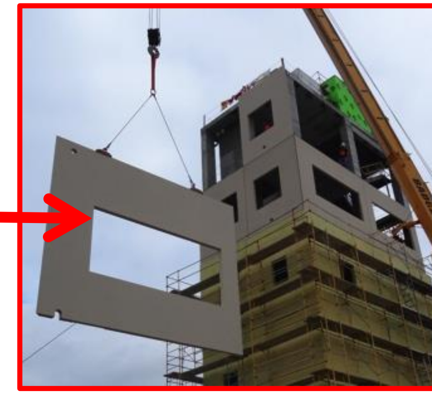
Full-scale Structural and Non-structural Building System Performance During Earthquakes

PI – Prof. Tara Hutchinson, UC San Diego

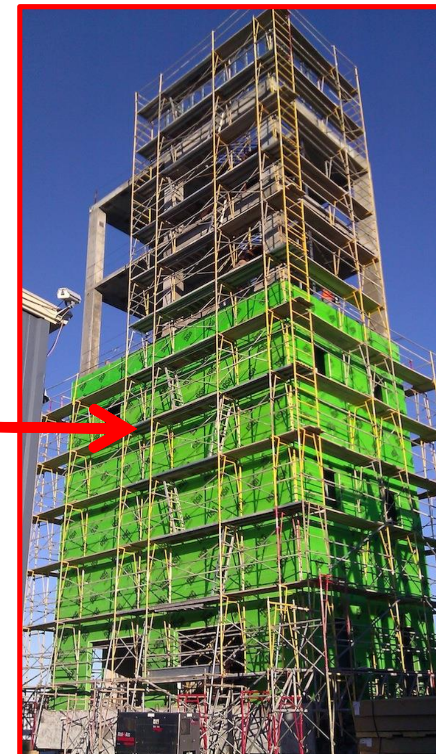
Exterior Facades



Architectural Precast Concrete Cladding

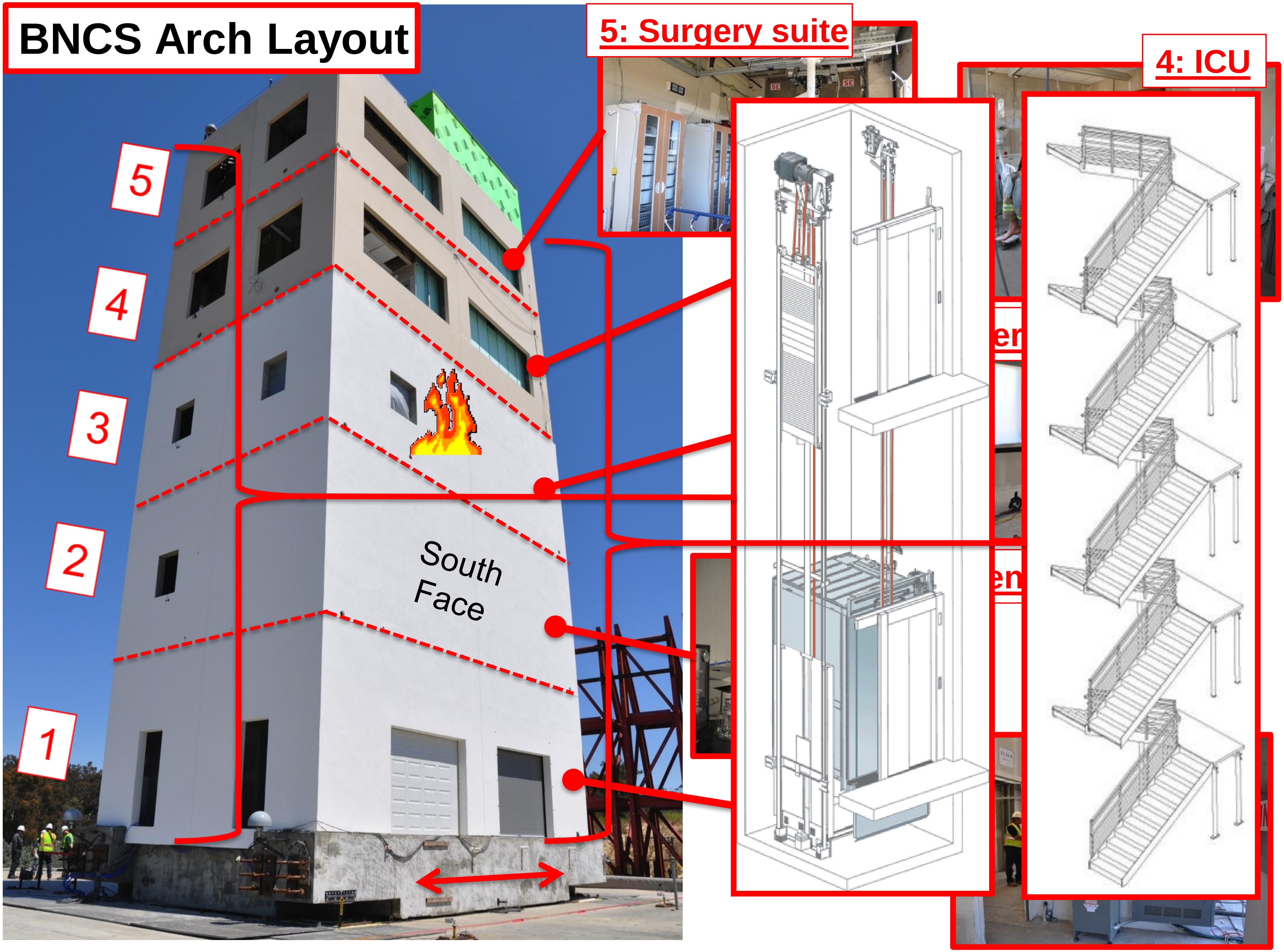


Balloon-framed metal stud+EIFS

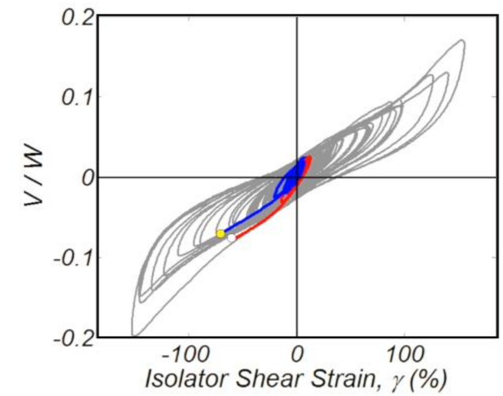


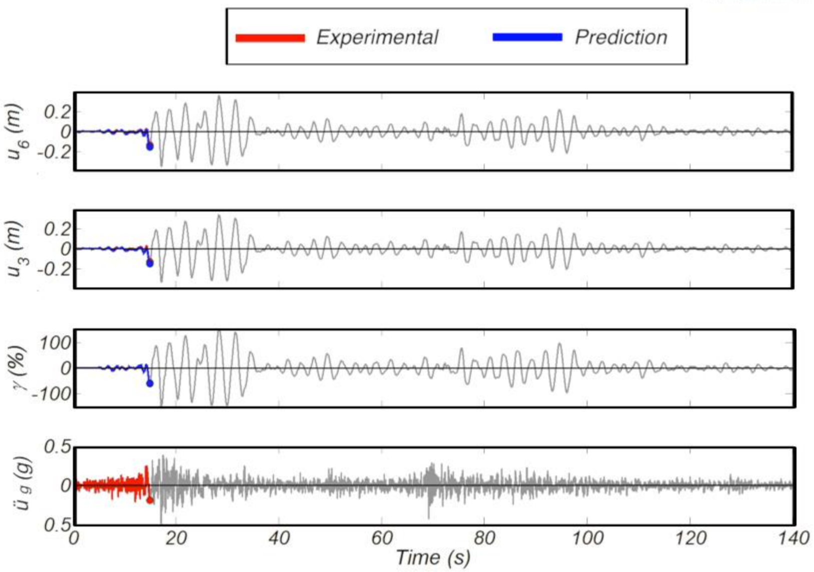
NW View

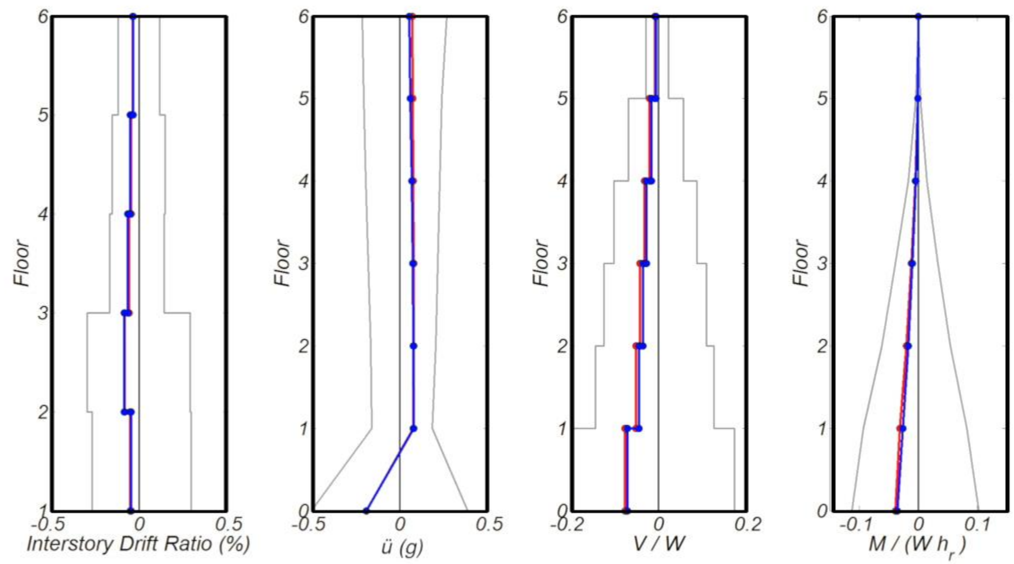
BNCS Arch Layout



Full-Scale Structural and Nonstructural Building System Performance – Base Isolated







Full-Scale Structural and Nonstructural Building System Performance – Fixed Base

Seismic Risk Reduction for Soft-Story Woodframe Buildings

PI - Prof. John W. van De Lindt, Colorado State University

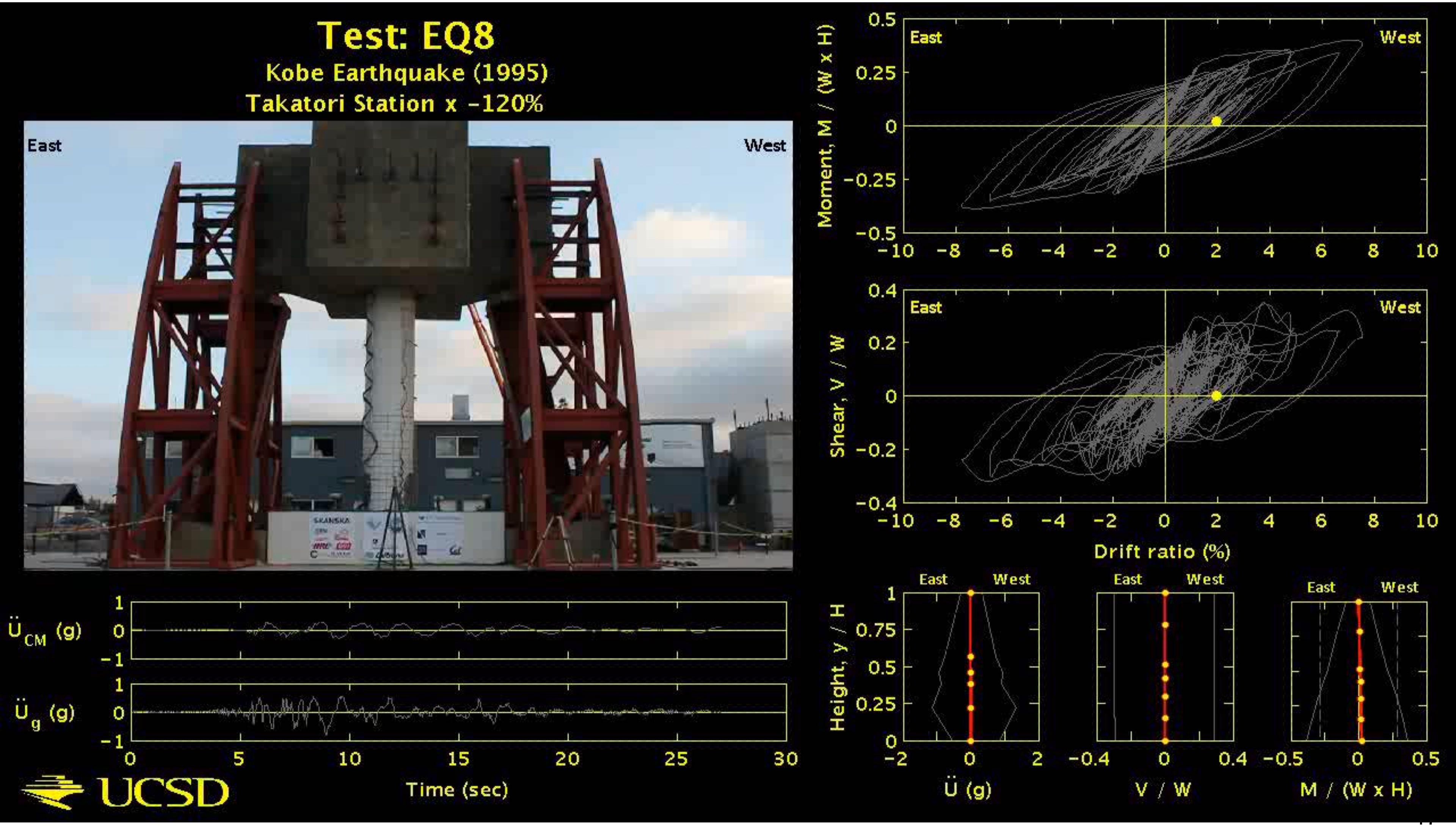
- Full-scale testing allowed to **validate the new evaluation techniques and higher performance levels** that were key to the success of the **San Francisco's mandatory soft story retrofit program** (6000 buildings in San Francisco undergoing the rigors of that program)

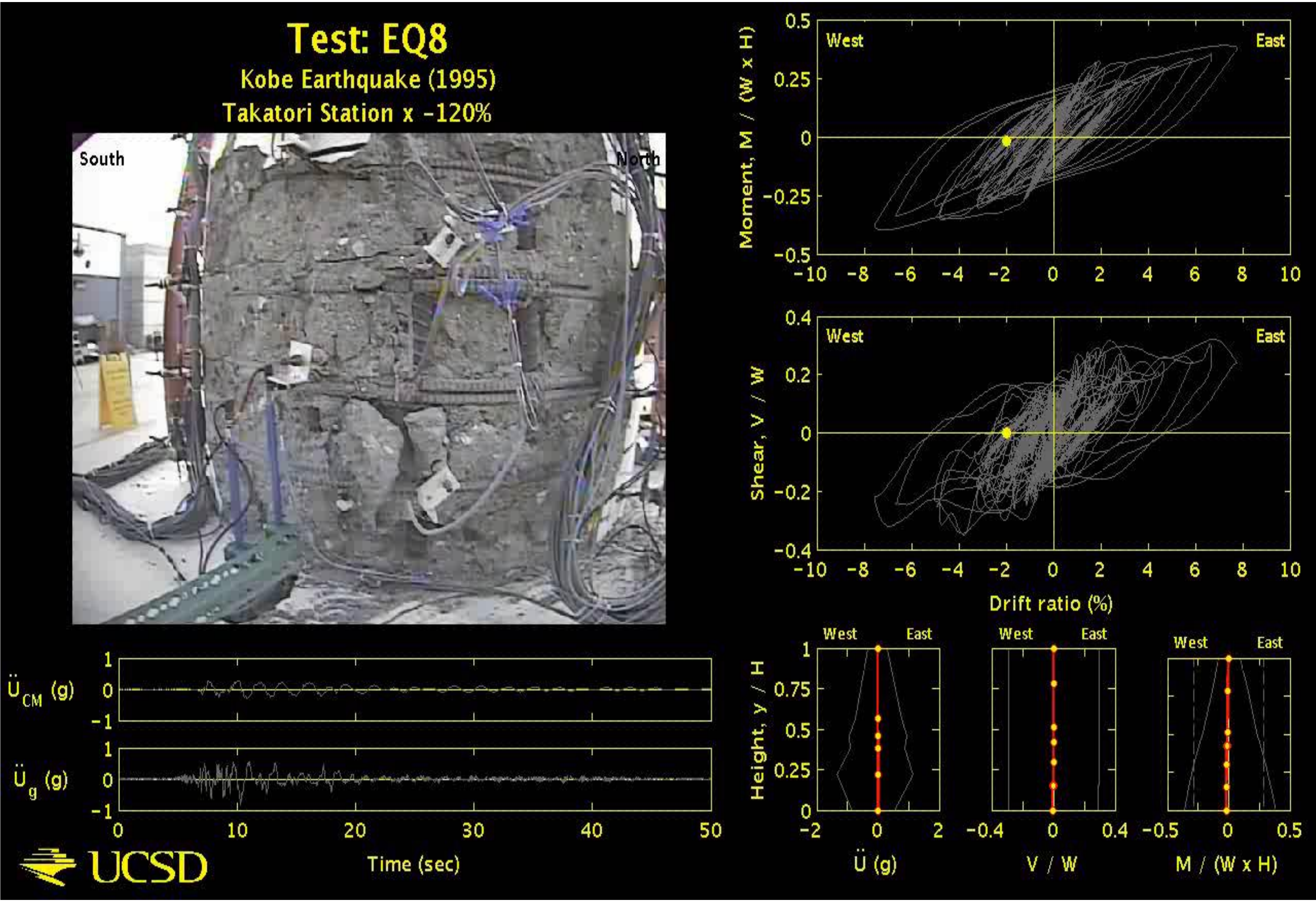
Seismic Risk Reduction for Soft-Story Woodframe Buildings

PI - Prof. John W. van De Lindt, Colorado State University

Large Scale Validation of Seismic Performance of Bridge Columns

PI - Prof. Jose I. Restrepo, UC San Diego




Test: EQ8
Kobe Earthquake (1995)
Takatori Station x -120%
South
North
West
East
Moment, M / (W x H)
Shear, V / W
Drift ratio (%)
Ü_CM (g)
Ü_g (g)
Time (sec)
Height, y / H
Ü (g)
V / W
M / (W x H)
UCSD

Earthquake and Post-Earthquake Fire Performance of Mid-Rise Light-Gauge Cold-Formed Steel Framed Buildings

PI – Prof. Tara Hutchinson, UC San Diego

Earthquake and Post-Earthquake Fire Performance of Mid-Rise Light-Gauge Cold-Formed Steel Framed Buildings

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Earthquake and Post-Earthquake Fire Performance of Mid-Rise Light-Gauge Cold-Formed Steel Framed Buildings

PI – Prof. Tara Hutchinson, UC San Diego

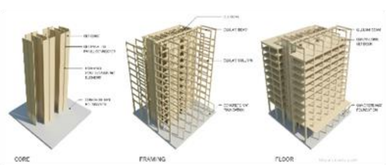
Earthquake and Post-Earthquake Fire Performance of Mid-Rise Light-Gauge Cold-Formed Steel Framed Buildings

PI – Prof. Tara Hutchinson, UC San Diego

Collaborative Research: A Resilience-based Seismic Design Methodology for Tall Wood Buildings

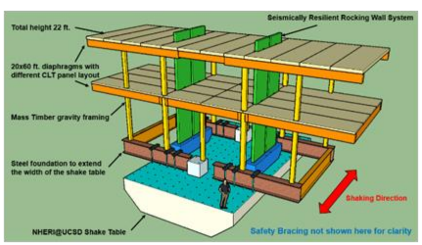
NHERI TallWood

Nheritallwood.mines.edu **spei@mines.edu**

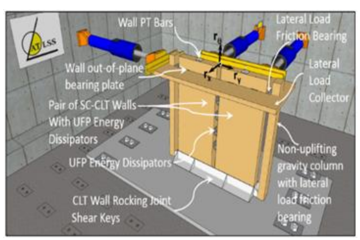


Define Tall Wood Archetypes

Investigative testing at system level



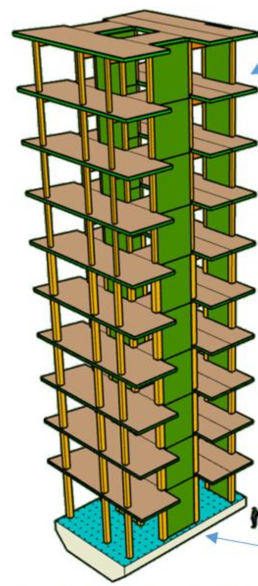
Two-story test at NHERI@UCSD 2017 Summer



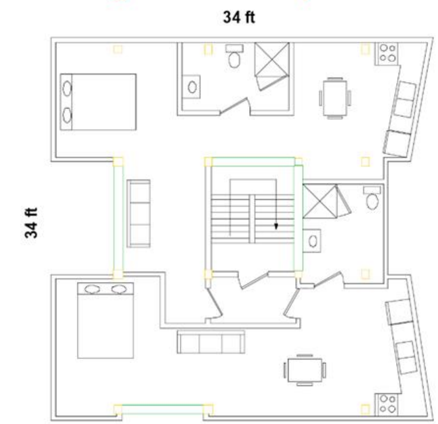
Assembly test at NHERI@Lehigh 2019

Seismic R & D
(2018~2020)

Full-scale 10-story validation Test (2021)



Mixed-Use building w/ CLT rocking wall lateral system



UCSD Shake Table

Collaborative Research: A Resilience-based Seismic Design Methodology for Tall Wood Buildings

UC San Diego

JACOBS SCHOOL OF ENGINEERING

July 2017 Earthquake Shake Tests at UC San Diego

Toward 20-story earthquake-safe buildings made from wood

The tests are being conducted at NHERI@UCSD, the shake table experimental facility at the University of California San Diego funded by the National Science Foundation (NSF) as part of its Natural Hazard Engineering Research Infrastructure (NHERI) program.

Use of LHPOST in Combination with Large Soil Boxes

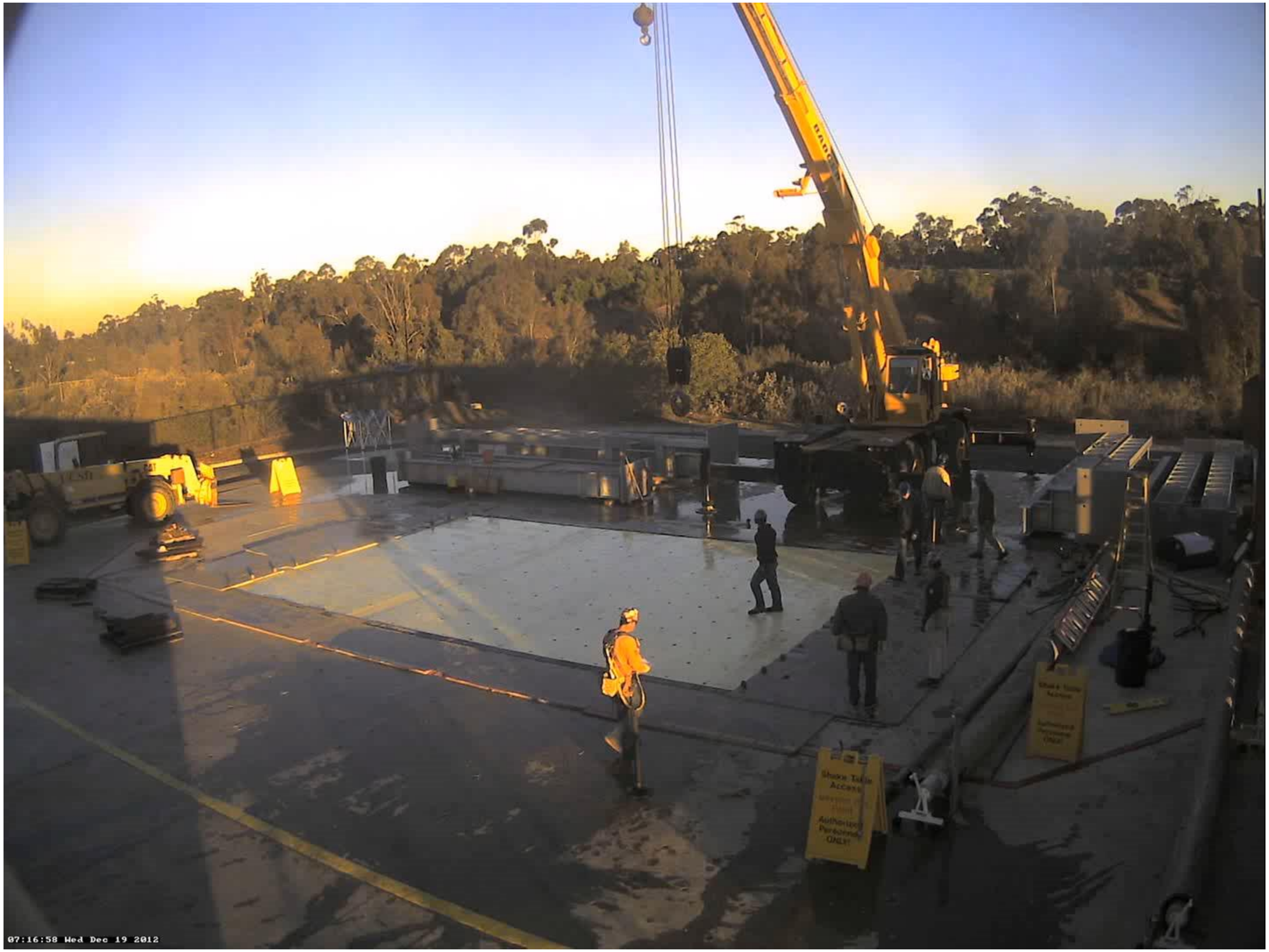
Laminar soil shear box:
6.7m (L) × 3.0m (W) × 4.7m (H)

Stiff soil confinement box:
10.0m (L) × 4.6 or 5.8m (W) × 7.6m (H)

- To investigate the seismic response of soil-foundation-structural systems
- To complement centrifuge tests in order to validate computational models
- To study the performance of **bridge abutments**, **earth retaining walls, slope stability in hillside construction,** and **underground structures**
- To investigate **soil liquefaction** and its effect on the seismic response of soil-foundation-structural systems

Assembly of Laminar Soil Shear Box

Assembly of Stiff Soil Confinement Box



Disassembly of Stiff Soil Confinement Box

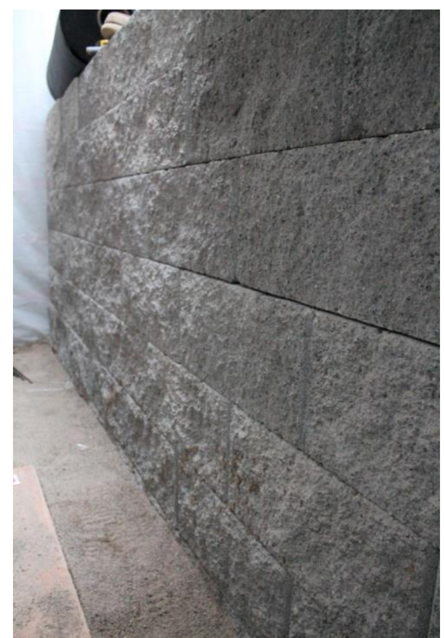
Liquefaction-Induced Lateral Spread Displacements and Soil-Pile Interaction in Multi-Layer Soil Strata

PI – Prof. Ahmed Elgamal, UC San Diego

Seismic Performance Tests of Full-Scale Retaining Walls

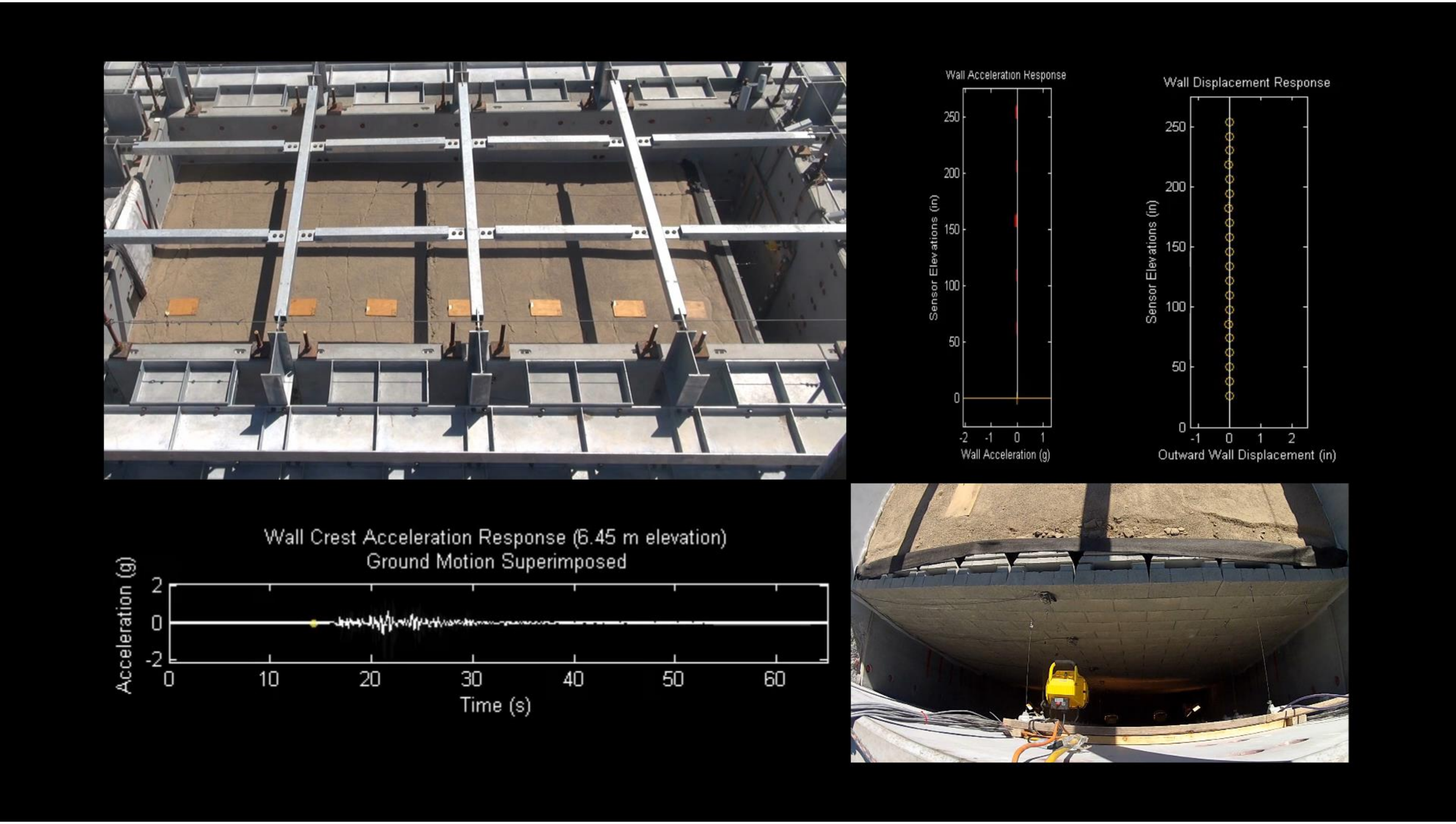
PI – Prof. Patrick Fox UCSD

22 ft. Above Table Elevation



Earthquake Performance of Full-Scale Reinforced Soil Walls

PI – Prof. Patrick Fox UCSD



Soil-Foundation-Structure Interaction Test

PI – Prof. Marios Panagiotou, UC Berkeley

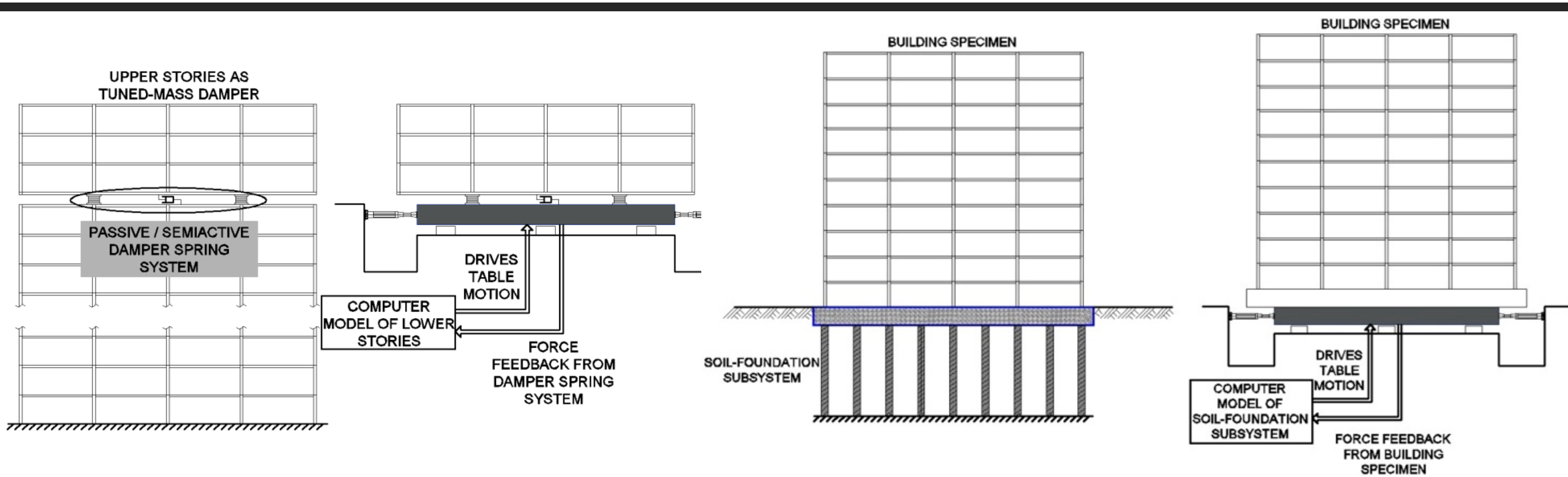
Staging Facility

- In an effort to increase throughput at the NHERI@UCSD facility, a reinforced concrete staging slab with dimensions of 13.4 m × 8.8 m × 0.914 m deep (44 ft × 30 ft × 3 ft deep) was built near the shake table.
- Small to moderate size specimens (weighing up to 100 tons) can be constructed on the staging area then lifted onto the shake table platen, or partial assembly of components for large specimens can reduce construction time.

Staging Facility

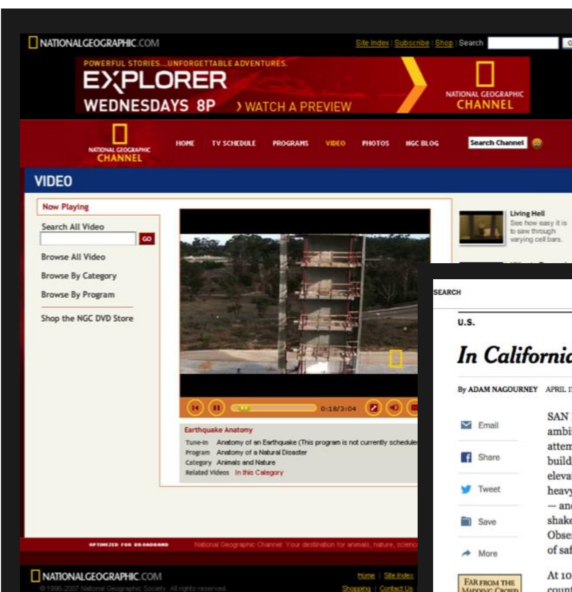
Hybrid Shake Table Testing

➢ **Basic hardware and software in place for real-time hybrid shake-table testing:**
- Multi-channel MTS FlexTest controller
- SCRAMNet ring for real-time communication and synchronization of data flow between shake-table controller, FlexTest controller, and real-time target PC running the Matlab/SIMULINK Real-time Workshop and xPC Target software
- Easy integration of OpenSees/OpenFresco open-source software framework
- 50-ton dynamic actuator
- Portable hydraulic power system



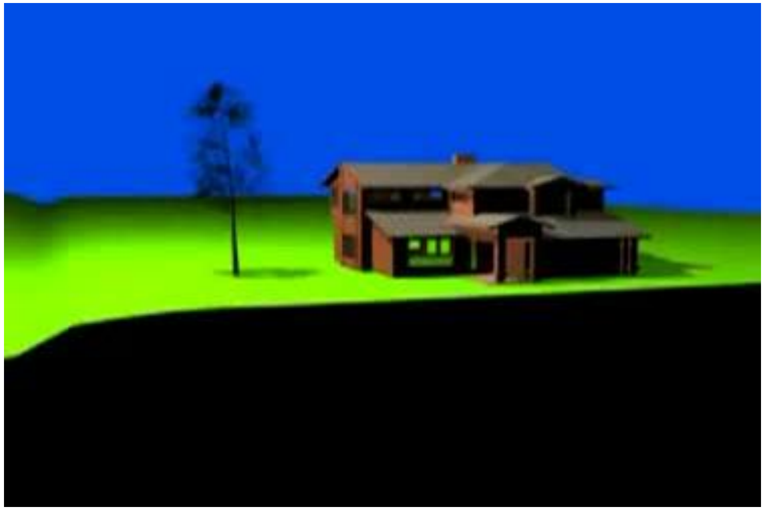
Broad Public Dissemination

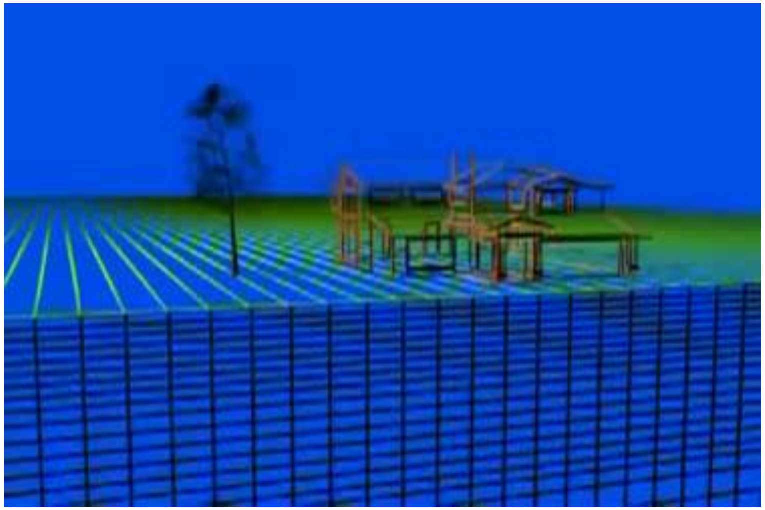
- Jacobs School of Engineering Communications and Media Relations
- International, National, Regional, and Local Exposure



Need for Upgrade of LHPOST to Multi-Degree-of-Freedom Capabilities

Multi-Directional Nature of Earthquake Ground Motions

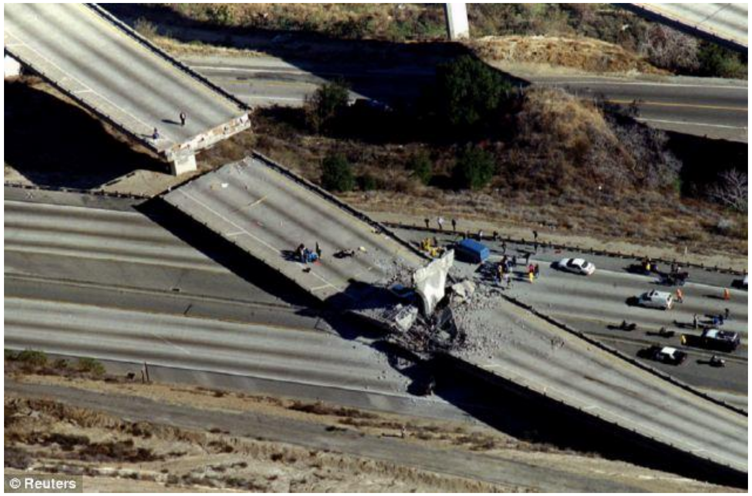




Multi-Directional Nature of Earthquake Ground Motions

California,1994 Northridge Earthquake
Overpass Bridge Pier

California,1994 Northridge Earthquake
Northridge Overpass

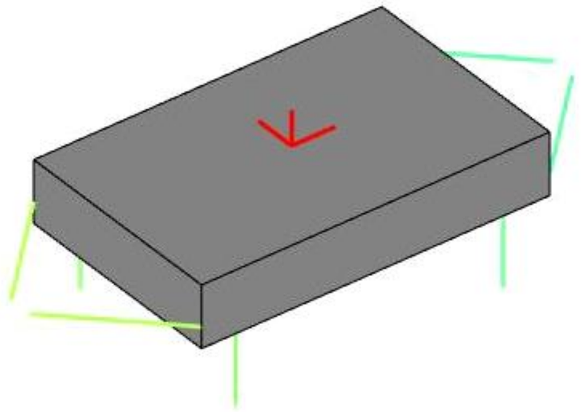


Chile, 2010 Maule Earthquake
Alto Rio Building

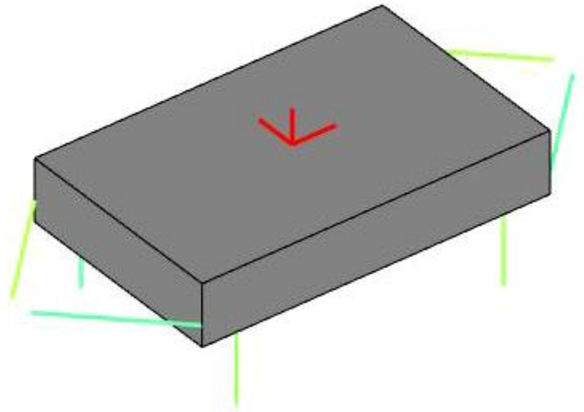
New Zealand, 2011 Christchurch Earthquake

Upgrade to 6 DOF-Configuration

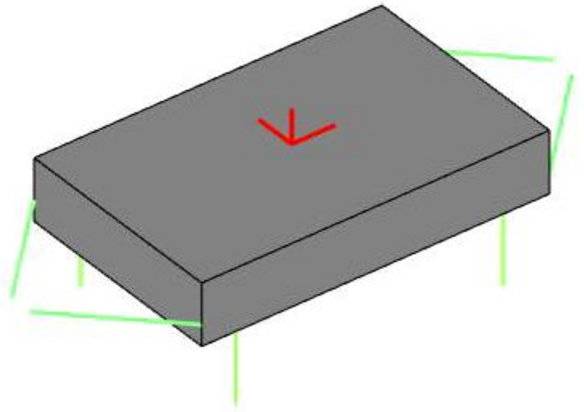
Longitudinal DOF (East-West)



Transversal DOF (South-North)

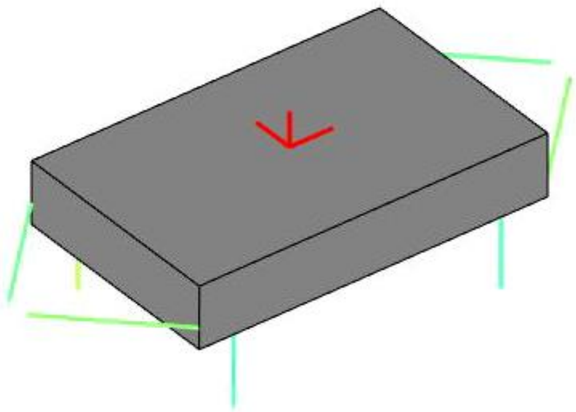


Vertical DOF (Up-Down)

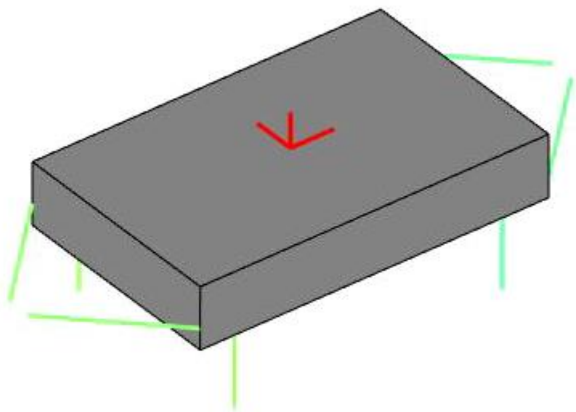


Upgrade to 6 DOF-Configuration

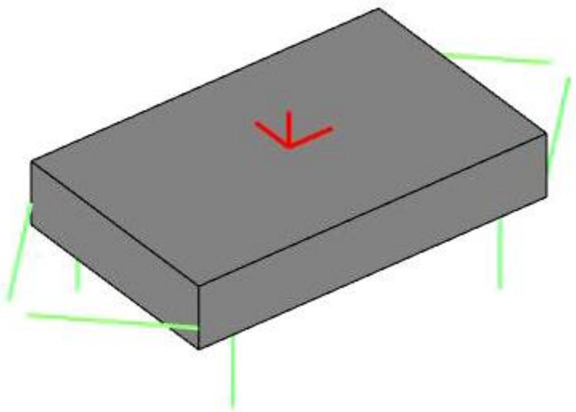
Roll DOF



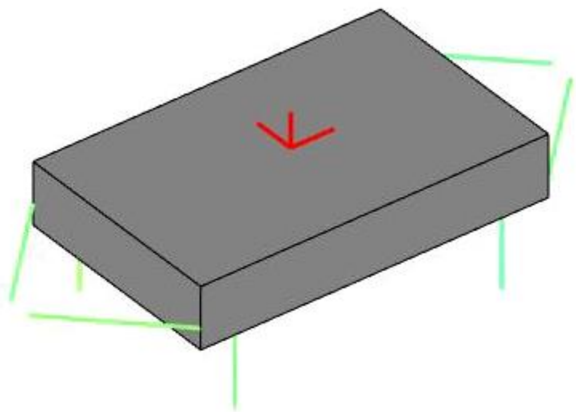
Pitch DOF



Yaw DOF



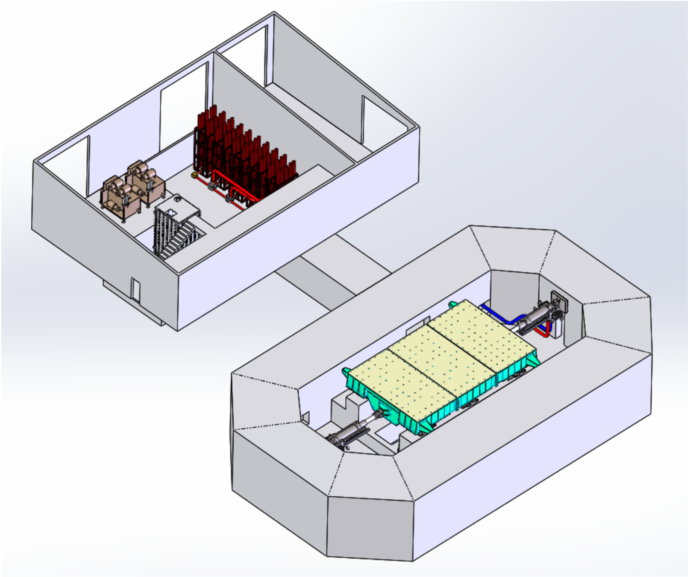
Roll + Pitch DOFs

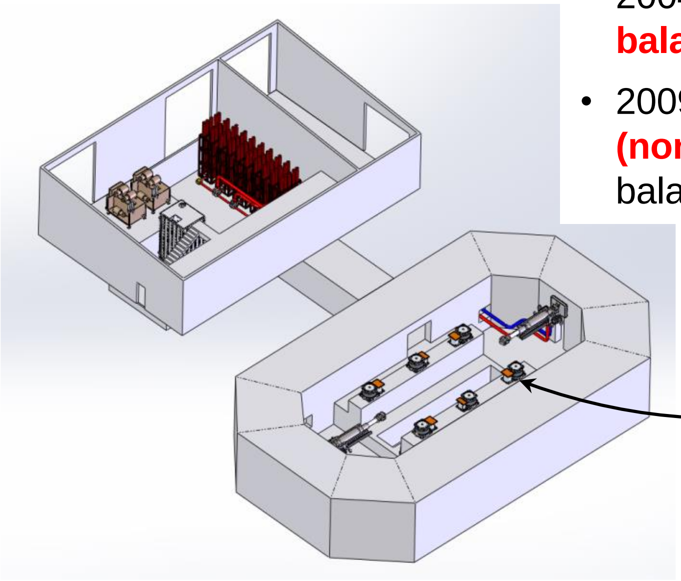


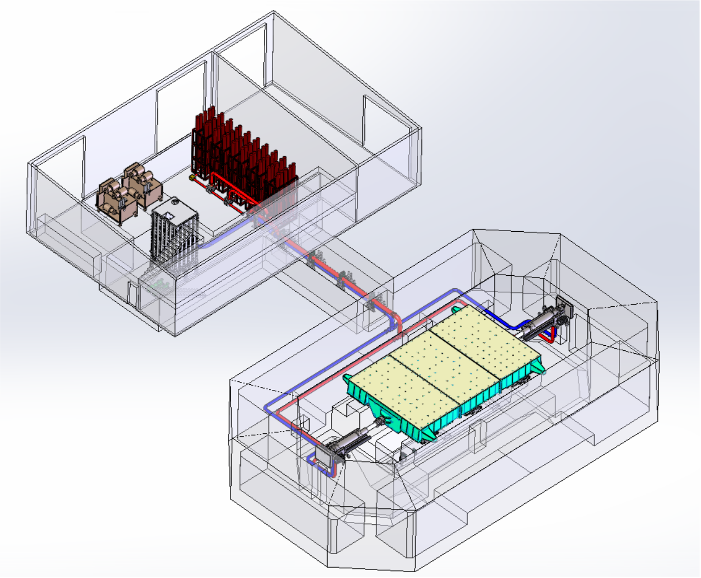
Six Degree-of-Freedom (6-DOF) Upgrade of LHPOST

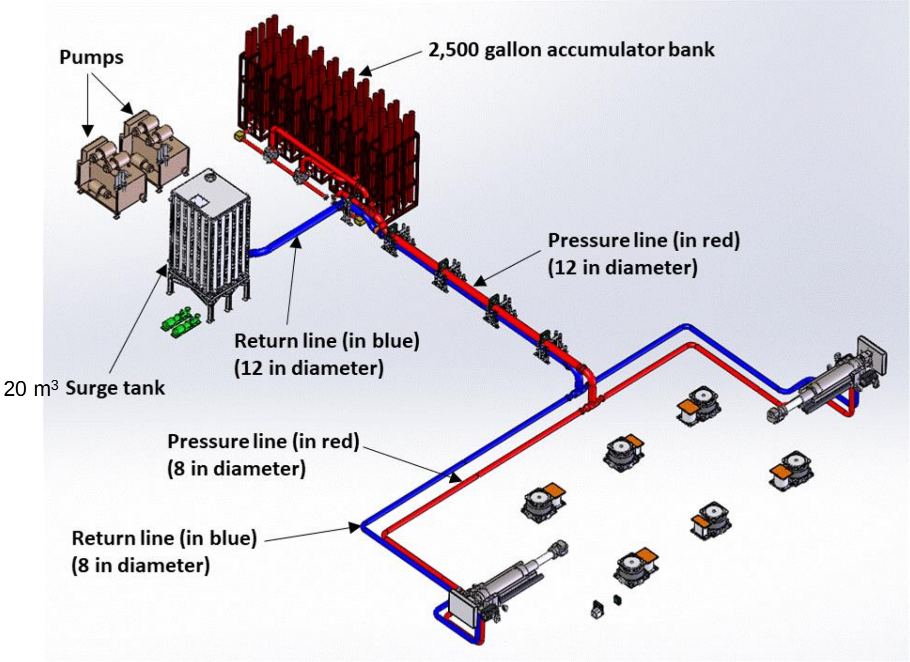
Hydraulic Power System for 1-DOF LHPOST

- 2004-2009 **Pressure balanced bearings**
- 2009-current **Actuators (non-ported)** with Pressure balanced bearing

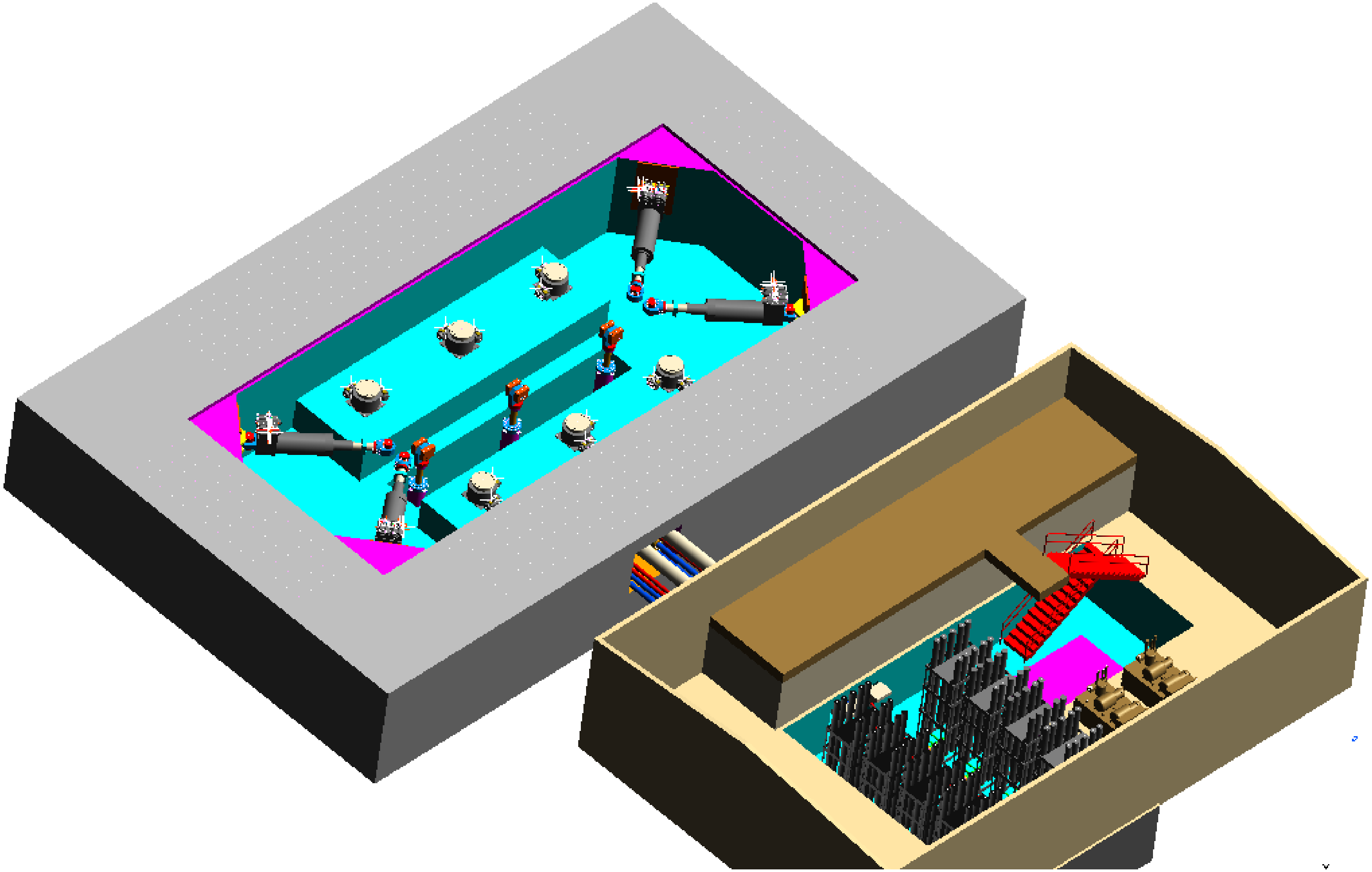




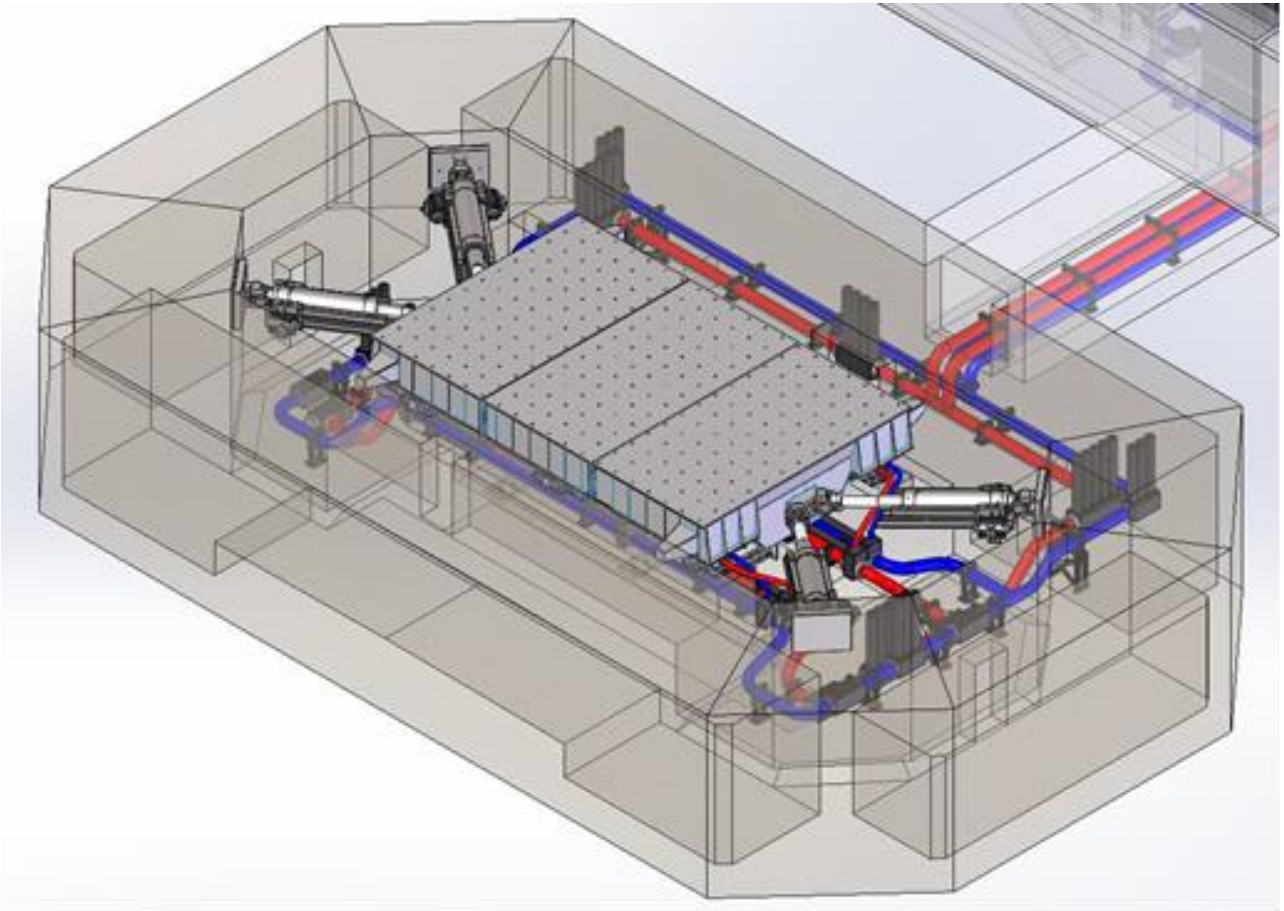




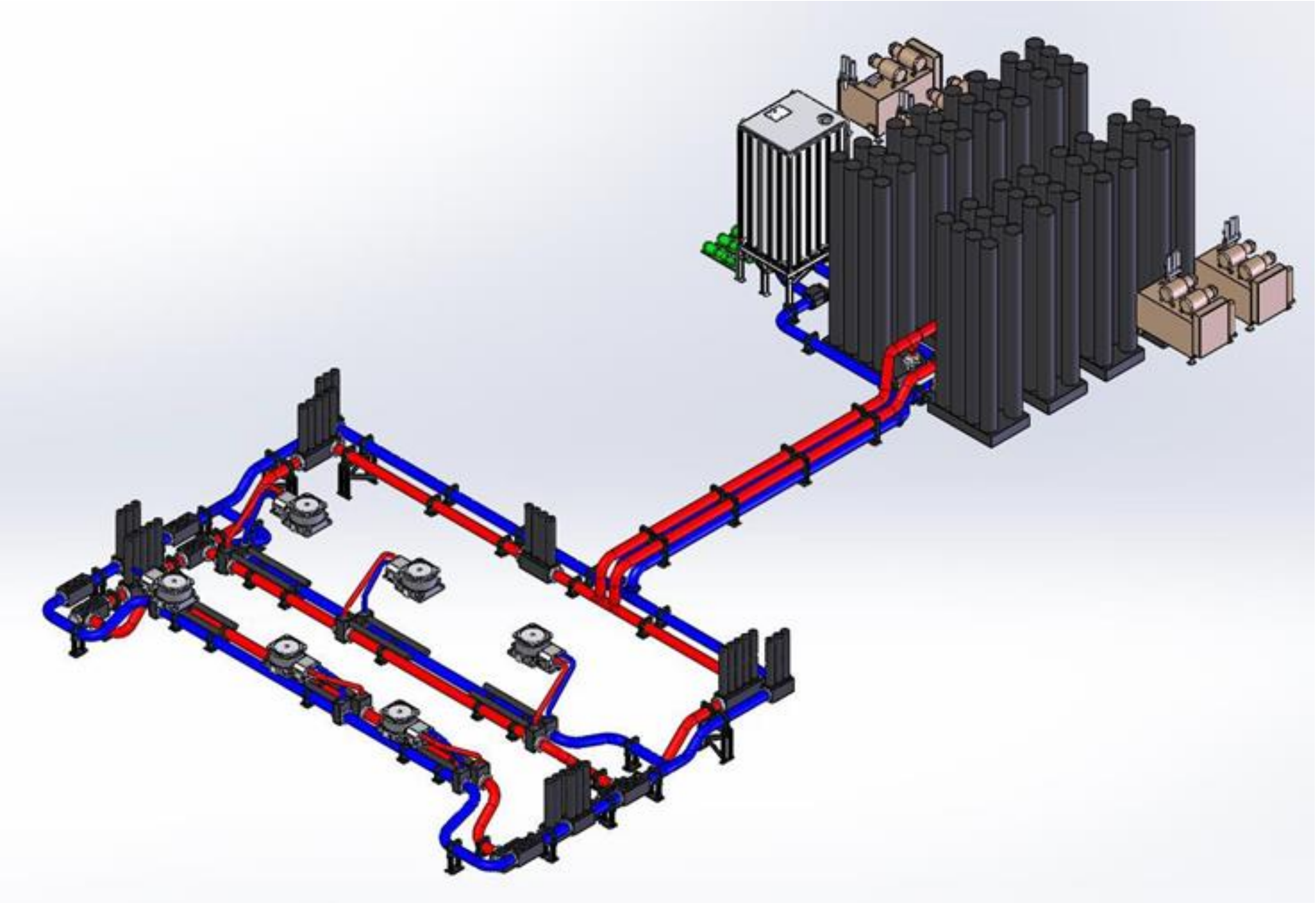
Upgrade to 6-DOF Configuration



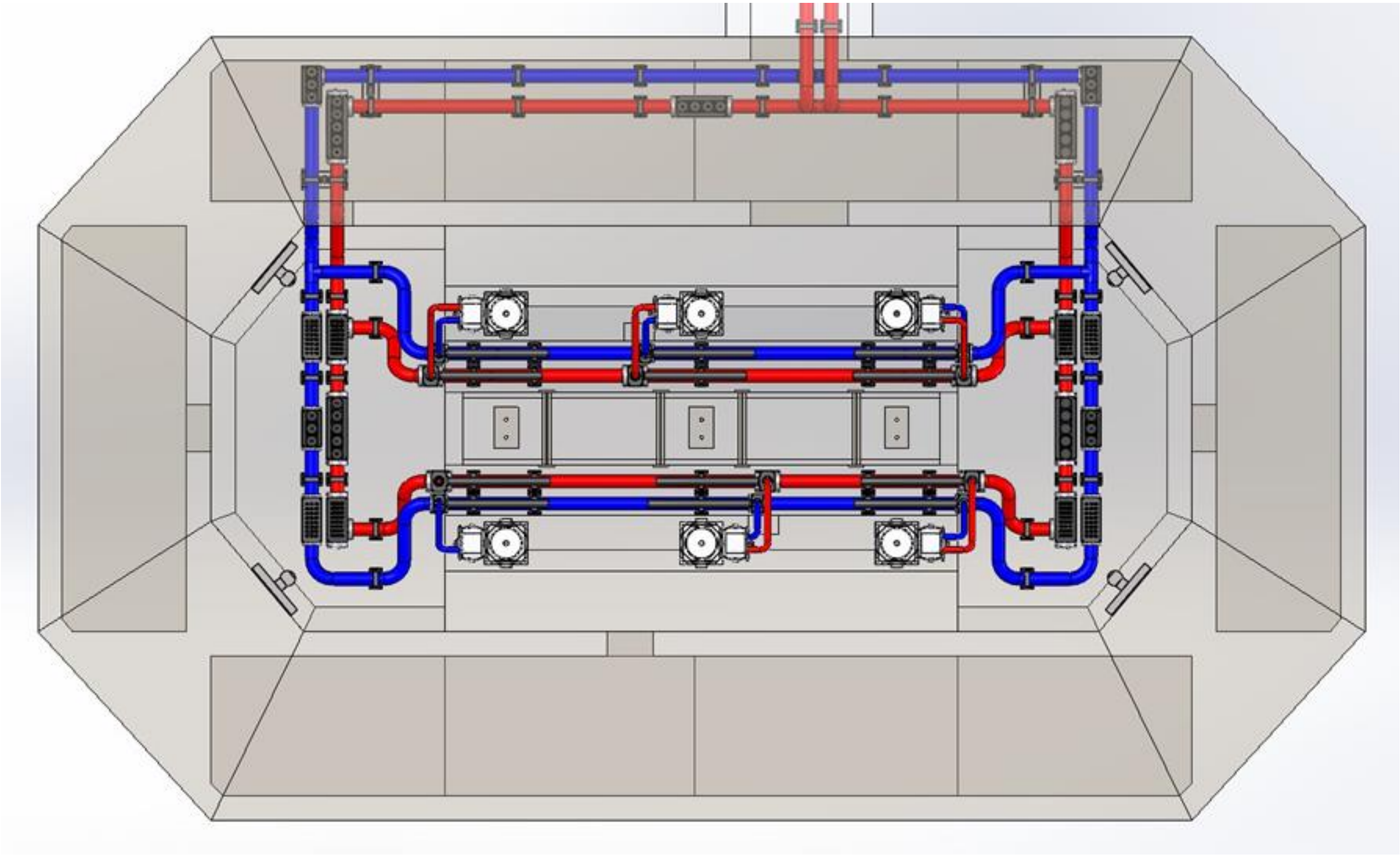
Upgrade to 6-DOF Configuration



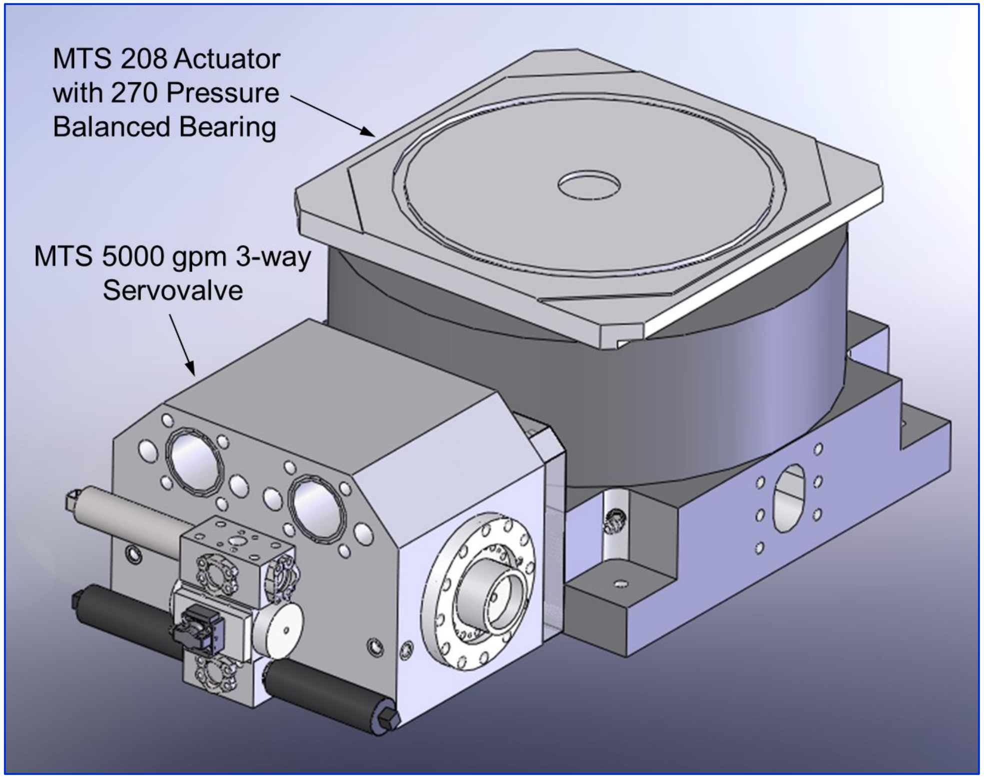
Upgrade to 6-DOF Configuration

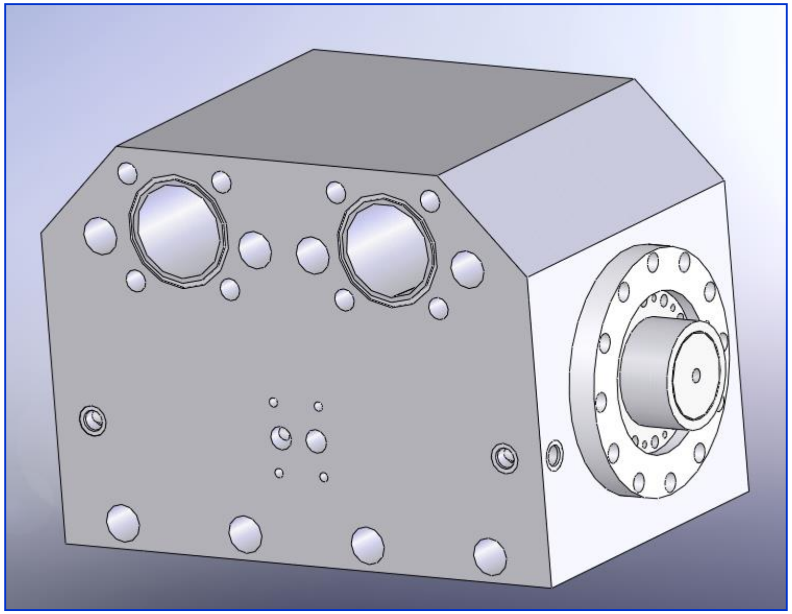


Upgrade to 6-DOF Configuration



High-Flow Servovalves for Vertical Actuators





Uni-axial Performance Characteristics of 6-DOF LHPOST

Platen size	12.2 m × 7.6 m (40 ft × 25 ft)		
Frequency Bandwidth	0 – 33 Hz		
Vertical Payload Capacity	20 MN (4,500 kip)		
	Horizontal X	Horizontal Y	Vertical Z
Peak Translational Displacement	±0.89 m (±35 in)	±0.38 m (±15 in)	±0.127 m (±5 in)
Peak Translational Velocity	2.5 m/sec (100 in/sec)	2.0 m/sec (80 in/sec)	0.6 m/sec (25 in/sec)
Peak Translational Force*	10.6 MN (2,380 kip)	8.38 MN (1,890 kip)	54.8 MN** (12,300 kip)
Peak Rotation*	2.5 deg	1.5 deg	4.0 deg
Peak Rotational Velocity*	21.0 deg/sec	12.4 deg/sec	40.5 deg/sec
Peak Moment*	37.2 MN-m (27,400 kip-ft)	49.0 MN-m (36,200 kip-ft)	47.0 MN-m (34,600 kip-ft)
Overturning Moment Capacity	45.1 MN-m (33,200 kip-ft)	50.0 MN-m (36,900 kip-ft)	

* peak demand obtained during sinusoidal motions

** peak compressive force in the compression-only vertical actuators

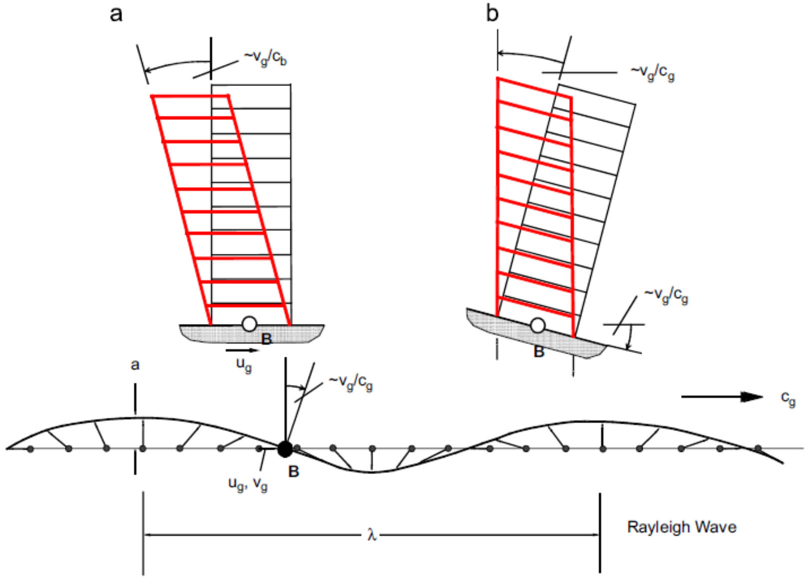
Table loaded with rigid payload of 1,100 kips (5 MN)

New Research Opportunities Made Possible by the Upgraded 6-DOF LHPOST

Research Made Possible by the 6-DOF Upgraded LHPOST

- Investigate many important aspects of the seismic response behavior of civil infrastructure systems:
  - **Effects of three-directional translational ground motions**
  - **Effects of rotational ground motion components**
  - **Effects of six-degree-of-freedom earthquake ground motions**

- Investigate in full 3D and at large- or full-scale the **combined effect of realistic near-field translational and rotational ground motions** applied as dynamic excitation to a **structural, geotechnical, or soil-foundation-structural system**, including the **effects of SSI** (both kinematic and inertial), **nonlinear soil and structural responses**, and **soil liquefaction**.



Geometric interpretation of how horizontal translation and rocking can contribute to the total drift in a simple building during passage of a Rayleigh wave [Trifunac, 2009]

Research Made Possible by the 6-DOF Upgraded LHPOST

- **Understanding inherent damping** in structures to settle the issue of **which is the best damping model** to be used in linear and nonlinear time history analyses.
    - **Shake table experiments with 6-DOF seismic base excitation on large-scale building specimens with and without non-structural components and systems and large-scale bridge sub-structures (e.g., bridge bents) will guide in the selection of different inherent damping models.**

- Experimental study of Dynamic Soil-Structure Interaction
    - **Kinematic interaction of the foundation with the soil (in the absence of the superstructure)**
    - **Inertial interaction (resulting in additional rocking and torsional components of motion of the foundation)**

- Three general types of experimental SSI studies become possible:
    - **Verification studies under three-axial or six-axial excitation**
    - **Hybrid tests**
    - **Large soil box studies under tri-axial or six-axial excitation**

Research Made Possible by the 6-DOF Upgraded LHPOST

- **Real-Time Hybrid Shaking Table Testing**
  - Expand the complexity of the large-scale geotechnical and structural systems that can be tested.
- **Seismic safety of unreinforced masonry buildings**
  - URM walls subjected to uni-axial in-plane forces tend to exhibit a much better performance than under bi-axial seismic loading conditions (out-of-plane collapse).
  - Vertical ground acceleration could also play an important role on the strength capacity (arching mechanism) and stability of URM walls.
- **Seismic performance of reinforced concrete and reinforced masonry wall structures**
  - Design provisions for RC and reinforced masonry shear walls are primarily based on in-plane horizontal loading tests of wall components.
  - Effects of simultaneous bi-horizontal and vertical ground excitation could play a significant role on the seismic performance of a building with RC or reinforced masonry walls.
  - Multi-axial shake table tests are needed to investigate this problem and to improve current design codes.

Research Made Possible by the 6-DOF Upgraded LHPOST

- **Non-structural components and systems (NSCs).**
  - **Architectural, mechanical, electrical and plumbing, or building contents.**
  - **Improve our understanding of the seismic response of NCSs under multi-directional earthquake excitation.**
  - **Advance the development of a reliable, unified design strategy accounting for multi-directional earthquake excitation.**
- **Damage-free, maintenance-free earthquake protective systems (e.g., rocking, self-centering systems), accelerated bridge construction.**
  - **Investigate the response behavior of these high-performance systems (with complex kinematics) under multi-directional earthquake input excitation.**

THANK YOU !

NSF

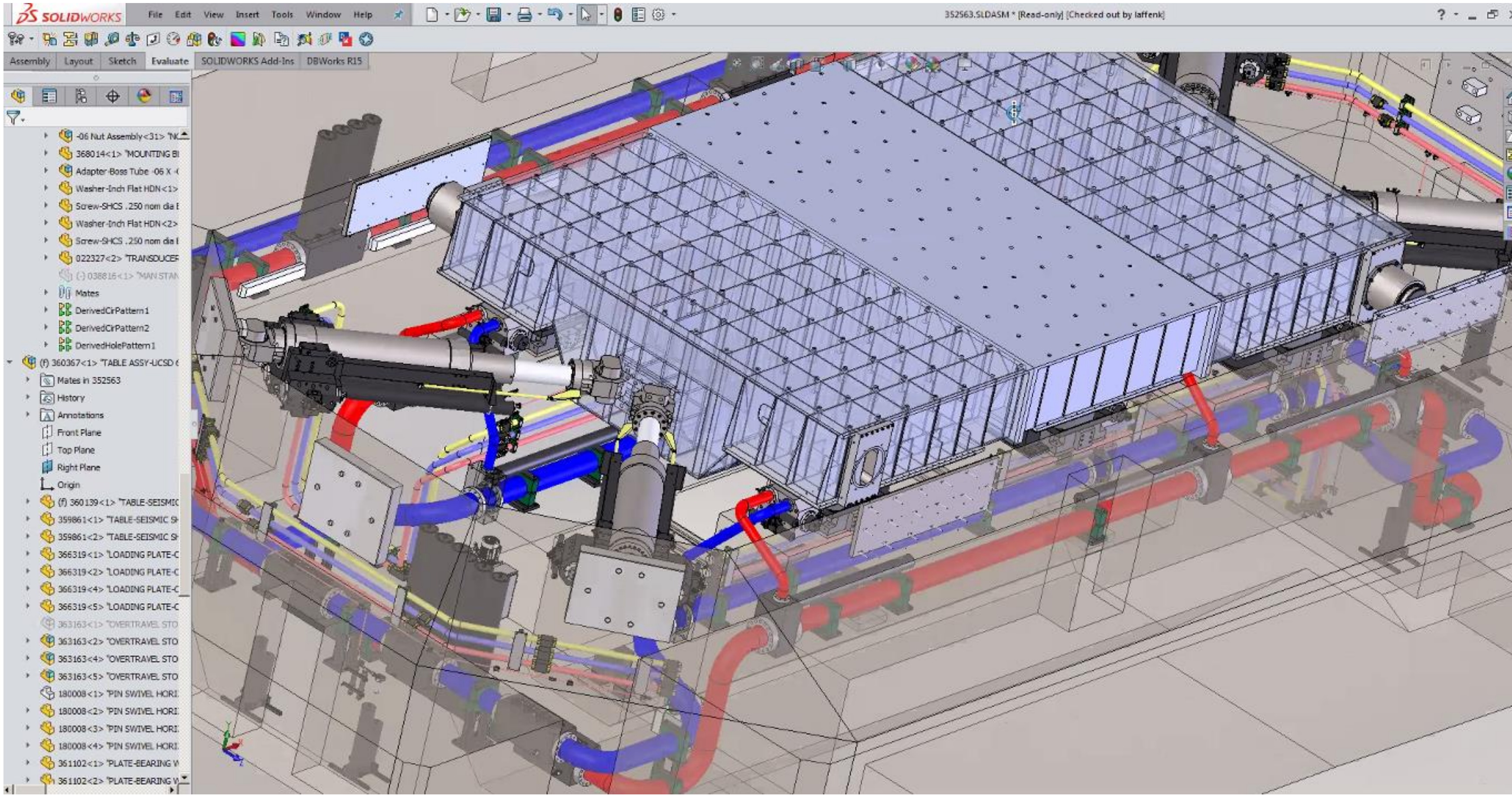
NHERI@
UC San Diego

Benchmarking

	Facility[1]	LHPOST	SRMD	UCB	UNR	SUNY-Buffalo	E-Defense	NIED	ILEE	CGS	Pavia
	Country	USA	USA	USA	USA	USA	Japan	Japan	China	Algeria	Italy
	Max Payload (MN)	20	4	0.75	0.45	1	12	5	0.7	0.6	0.3
	DOFs	6	6	6	6	6	6	6	2	6	4
	Platen Size L x W (m)[2]	12.2 x 7.6	4 x 5	6.1 x 6.1	2.8 x 2.8	(2) 3.7 x 3.7	20 x 15	14.5 x 15	(4) 6 x 4	6.1 x 6.1	4.8 x 4.8
X-Dir	Velocity (± m/s)	3.00	1.80	0.64	1.52	0.75	2.00	1.30	1.00	1.10	2.00
X-Dir	Displacement (± m)	0.89	1.22	0.15	0.30	0.15	1.00	0.50	0.50	0.25	0.50
Y-Dir	Velocity (± m/s)	3.50	0.80	0.64	1.52	0.75	2.00	0.70	1.00	1.10	2.00
Y-Dir	Displacement (± m)	0.43	0.61	0.15	0.30	0.15	1.00	1.00	0.50	0.15	0.50
Z-Dir	Velocity (± m/s)	0.50	0.25	0.25	1.40	0.75	0.70	0.20	-	1.00	0.50
Z-Dir	Displacement (± m)	0.13	0.13	0.05	0.10	0.08	0.50	0.50	-	0.10	0.14

[1]Performance metric that matches or exceeds that of the proposed upgraded LHPOST

[2](#) denotes number of tables, for multi-table facilities (note: UNR also offers (3) 4-DOF tables as well as a new 6-DOF table)


SOLIDWORKS
File Edit View Insert Tools Window Help
352563.SLDASM * [Read-only] [Checked out by laffenk]
Assembly Layout Sketch Evaluate SOLIDWORKS Add-Ins DBWorks R15
-06 Nut Assembly<31>
368014<1> "MOUNTING BI
Adapter-Boss Tube -06 X
Washer-Inch Flat HDN<1>
Screw-SHCS .250 nom dia
Washer-Inch Flat HDN<2>
Screw-SHCS .250 nom dia
022327<2> "TRANSDUCER
Mates
DerivedCirPattern1
DerivedCirPattern2
DerivedHolePattern1
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Mates in 352563
History
Annotations
Front Plane
Top Plane
Right Plane
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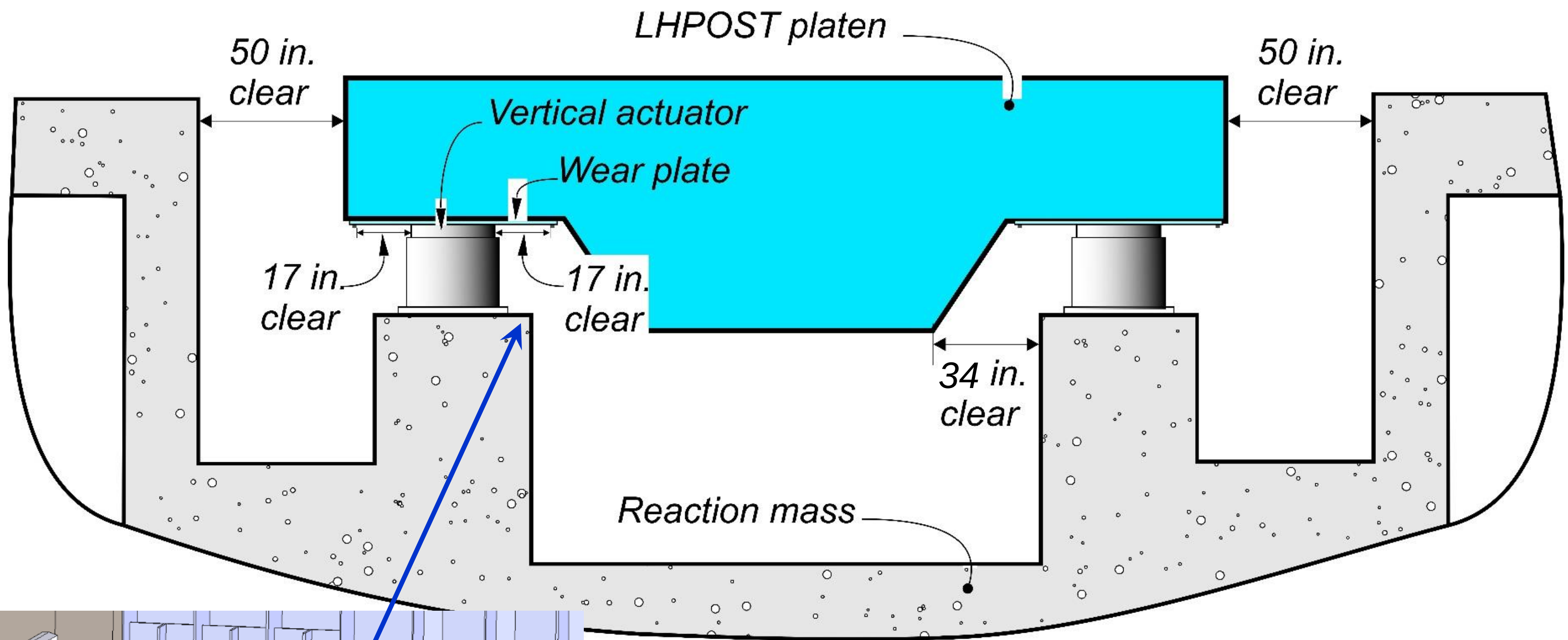
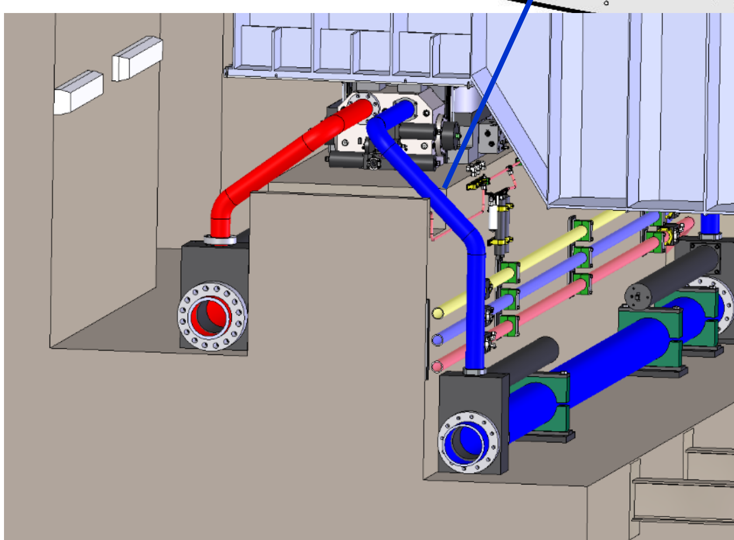
361102<1> "PLATE-BEARING W
361102<2> "PLATE-BEARING W

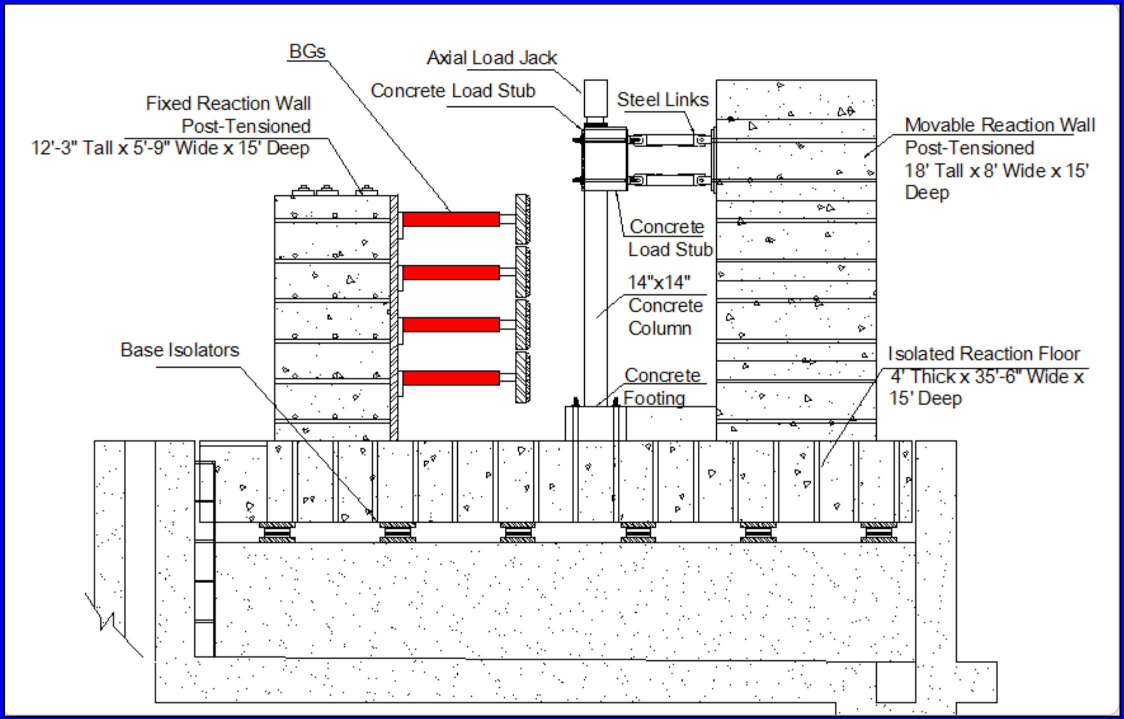
Displacement Limit in the Transverse (North-South) Direction

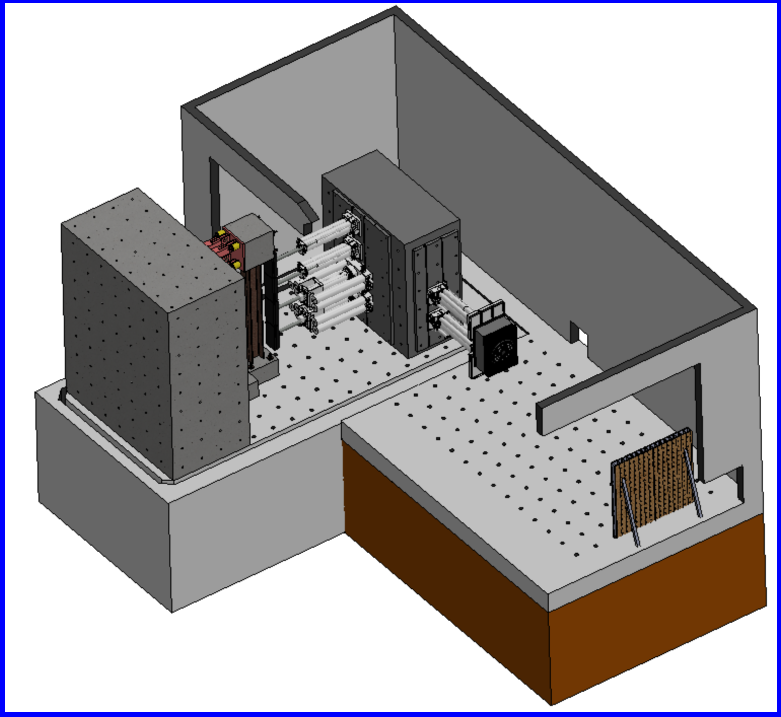




- More on travel limit issues along the N-S as well as the E-W direction to be presented later (**Crash Protection System Design**).

Blast / Impact Simulator

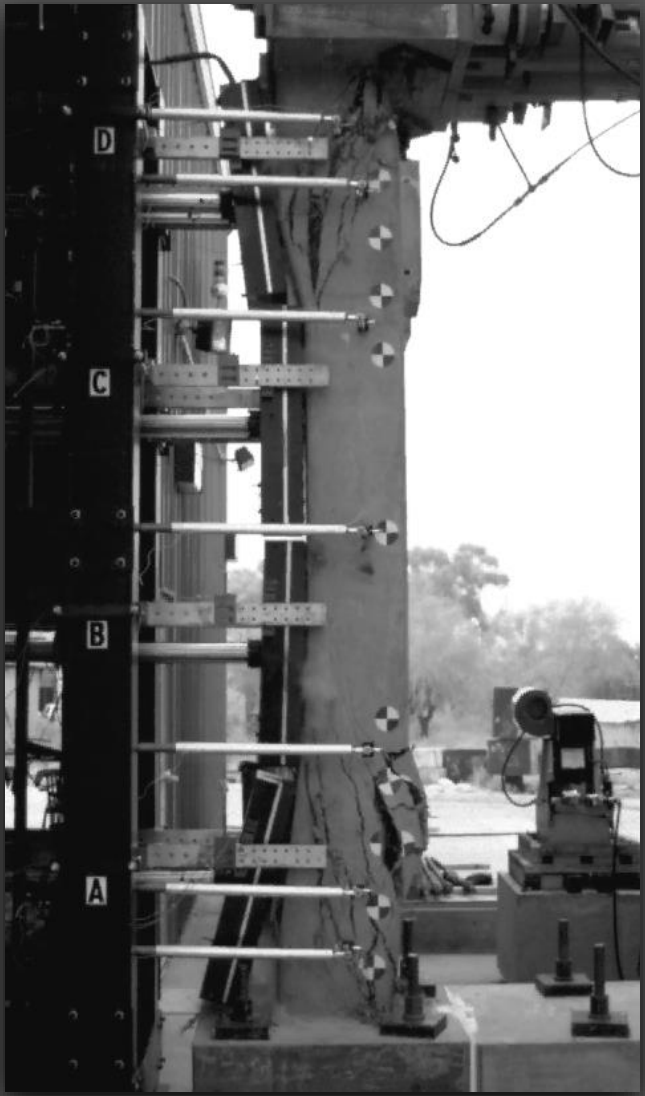




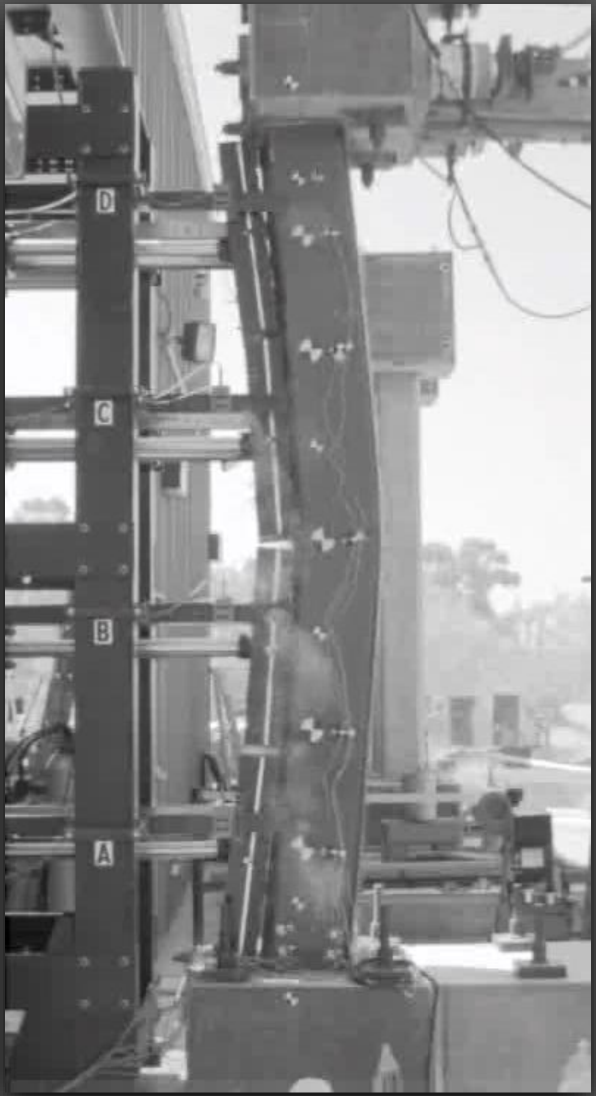
EES Performance Specifications		
BG Type	Number	Impact Velocity Range
BG25	4	1 – 30 m/s (2 – 67 mph)
BG50	2	4 – 66 m/s (9 – 140 mph)

- Multi-configurable hydraulic-pneumatic high-speed facility designed to operate in BLAST and LAUNCH modes
- Can launch debris of various sizes/shapes:
  - Masses of 100 kg (220 lb) at maximum velocity of 140 mph
  - Masses of 400 kg (880 lb) at maximum velocity of 100 mph
- Test specimens can be tied down to strong floor

Blast Loading of Reinforced Concrete Columns



AS-BUILT



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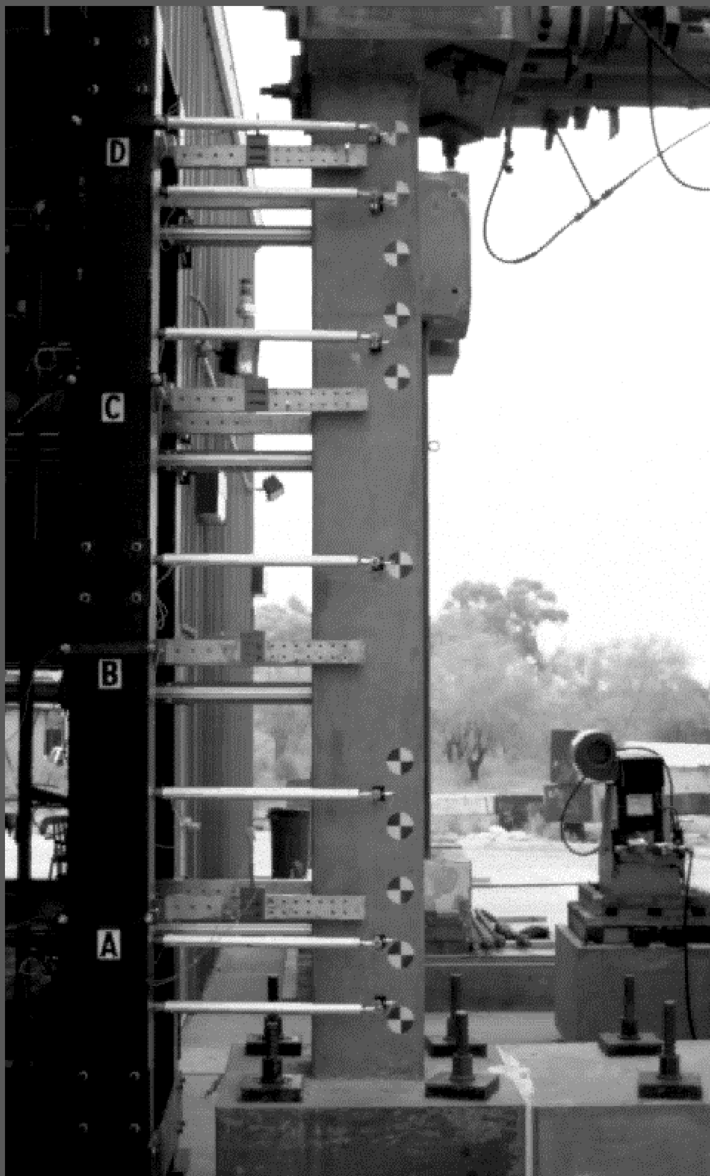
D
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D
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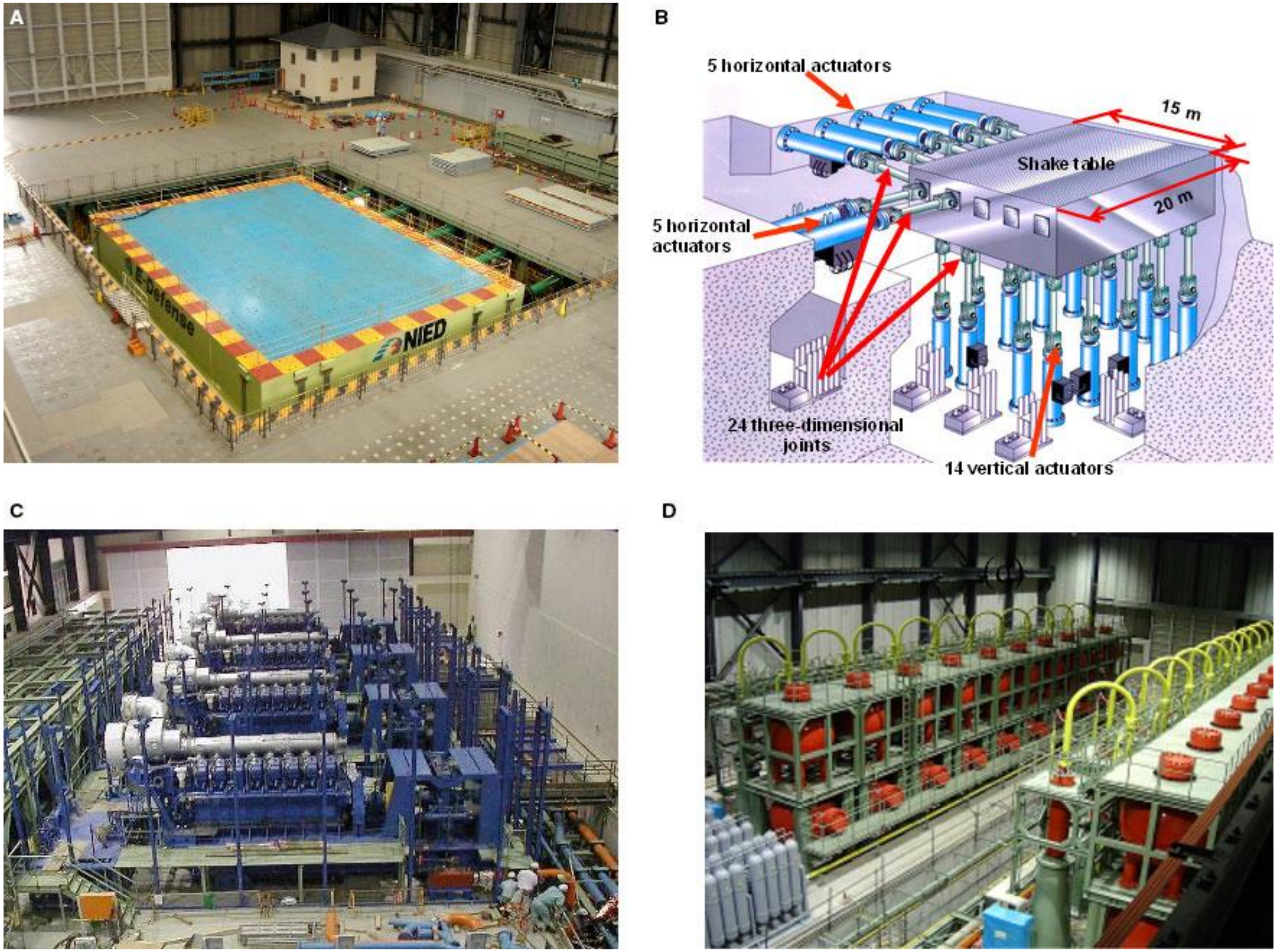
Benchmarking

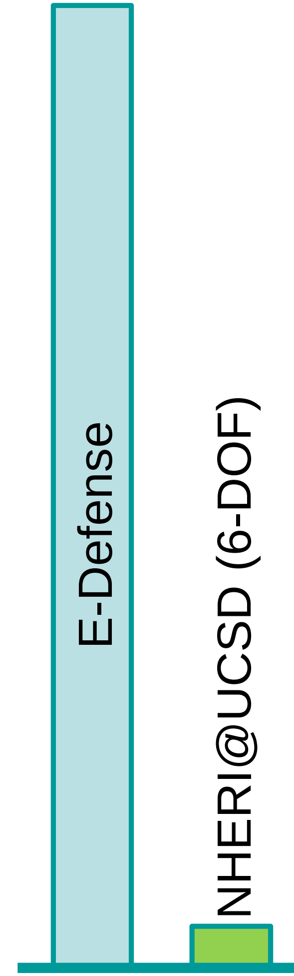
	Facility [1]	LHPOST	SRMD	UCB	UNR	SUNY-Buffalo	E-Defense	CGS	Pavia
	Country	USA	USA	USA	USA	USA	Japan	Algeria	Italy
	Max Payload (MN)	20	4	0.75	0.45	1	12	0.6	0.3
	DOFs	6	6	6	6	6	6	6	4
	Platen Size L x W (m) [2]	12.2 x 7.6	4 x 5	6.1 x 6.1	2.8 x 2.8	(2) 3.7 x 3.7	20 x 15	6.1 x 6.1	4.8 x 4.8
X-Dir	Velocity (± m/s)	3.00	1.80	0.64	1.52	0.75	2.00	1.10	2.00
X-Dir	Displacement (± m)	0.89	1.22	0.15	0.30	0.15	1.00	0.25	0.50
Y-Dir	Velocity (± m/s)	3.50	0.80	0.64	1.52	0.75	2.00	1.10	2.00
Y-Dir	Displacement (± m)	0.43	0.61	0.15	0.30	0.15	1.00	0.15	0.50
Z-Dir	Velocity (± m/s)	0.50	0.25	0.25	1.40	0.75	0.70	1.00	0.50
Z-Dir	Displacement (± m)	0.13	0.13	0.05	0.10	0.08	0.50	0.10	0.14

[1] *Performance quantity that matches or exceeds that of proposed upgraded LHPOST*

[2] *(#) denotes number of tables, for multi-table facilities (note: UNR also offers (3) 4-DOF tables as well as a new 6-DOF)*

Comparison with E-Defense





Relative Investment
~ 17 : 1

Nakashima, M., et al. "Experiences, accomplishments, lessons, and challenges of E-defense — Tests using world's largest shaking table." *Japan Architectural Review* 1.1 (2018): 4-17.

Benchmarking

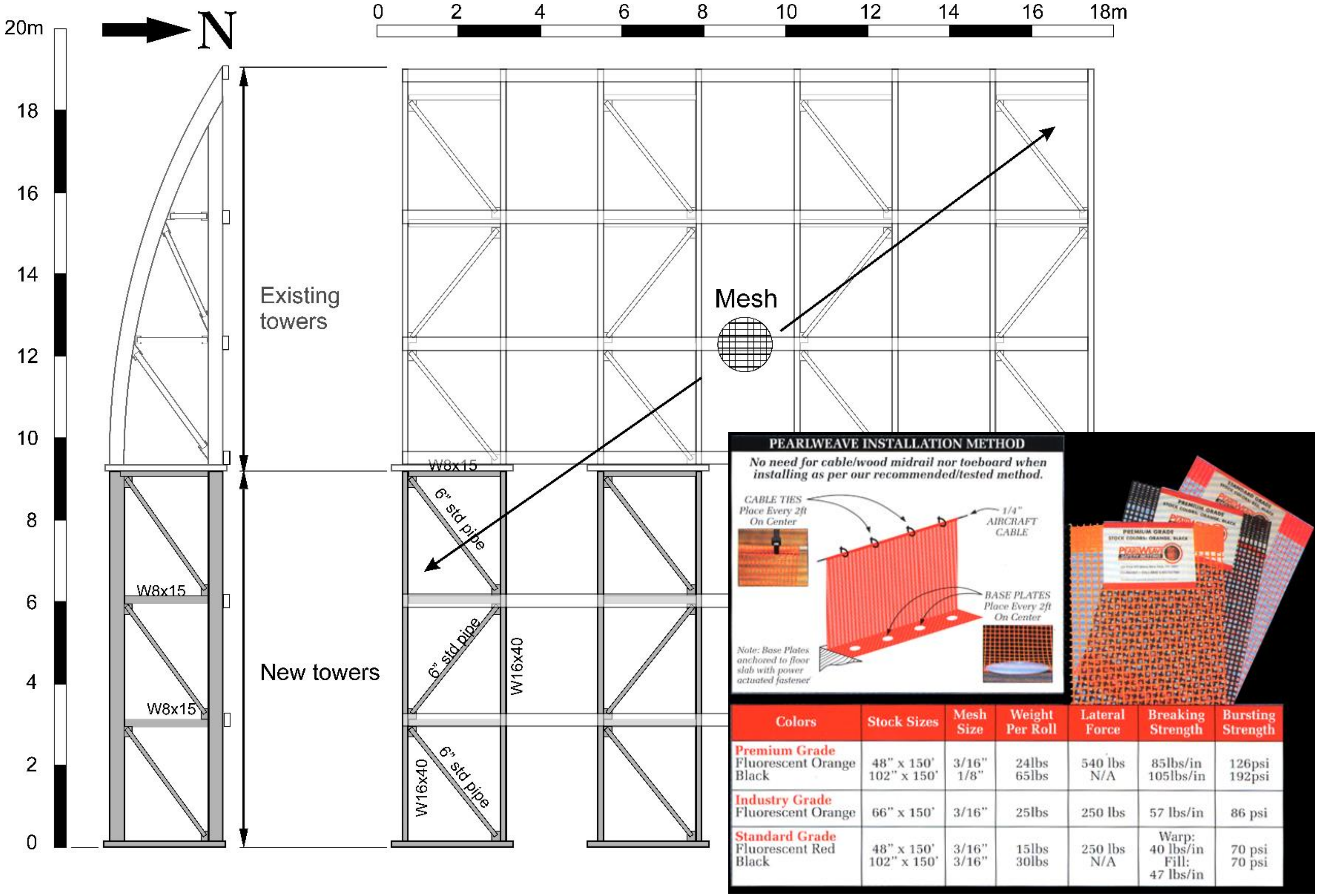
	Facility[1]	LHPOST	SRMD	UCB	UNR	SUNY-Buffalo	E-Defense	NIED	ILEE	CGS	Pavia
	Country	USA	USA	USA	USA	USA	Japan	Japan	China	Algeria	Italy
	Max Payload (MN)	20	4	0.75	0.45	1	12	5	0.7	0.6	0.3
	DOFs	6	6	6	6	6	6	6	2	6	4
	Platen Size L x W (m)[2]	12.2 x 7.6	4 x 5	6.1 x 6.1	2.8 x 2.8	(2) 3.7 x 3.7	20 x 15	14.5 x 15	(4) 6 x 4	6.1 x 6.1	4.8 x 4.8
X-Dir	Velocity (± m/s)	3.00	1.80	0.64	1.52	0.75	2.00	1.30	1.00	1.10	2.00
	Displacement (± m)	0.89	1.22	0.15	0.30	0.15	1.00	0.50	0.50	0.25	0.50
Y-Dir	Velocity (± m/s)	3.50	0.80	0.64	1.52	0.75	2.00	0.70	1.00	1.10	2.00
	Displacement (± m)	0.43	0.61	0.15	0.30	0.15	1.00	1.00	0.50	0.15	0.50
Z-Dir	Velocity (± m/s)	0.50	0.25	0.25	1.40	0.75	0.70	0.20	-	1.00	0.50
	Displacement (± m)	0.13	0.13	0.05	0.10	0.08	0.50	0.50	-	0.10	0.14

[1]Performance metric that matches or exceeds that of the proposed upgraded LHPOST

[2](#) denotes number of tables, for multi-table facilities (note: UNR also offers (3) 4-DOF tables as well as a new 6-DOF table)

Conceptual Design of the New Safety Towers

Conceptual Design of the New Safety Towers



Colors	Stock Sizes	Mesh Size	Weight Per Roll	Lateral Force	Breaking Strength	Bursting Strength
Premium Grade Fluorescent Orange Black	48" x 150' 102" x 150'	3/16" 1/8"	24lbs 65lbs	540 lbs N/A	85lbs/in 105lbs/in	126psi 192psi
Industry Grade Fluorescent Orange	66" x 150'	3/16"	25lbs	250 lbs	57 lbs/in	86 psi
Standard Grade Fluorescent Red Black	48" x 150' 102" x 150'	3/16" 3/16"	15lbs 30lbs	250 lbs N/A	Warp: 40 lbs/in Fill: 47 lbs/in	70 psi 70 psi

Side View

Elevation

Full-scale Structural and Non-structural Building System Performance During Earthquakes

PI – Prof. Tara Hutchinson UCSD

[redacted]

Seismic Performance Assessment and Retrofit of Non-Ductile RC Frames with Infill Walls Phase I

PI – Prof. Benson Shing UCSD

A Seismic Study of Wind Turbines for Renewable Energy

PI – Prof. Ahmed Elgamal, UC San Diego

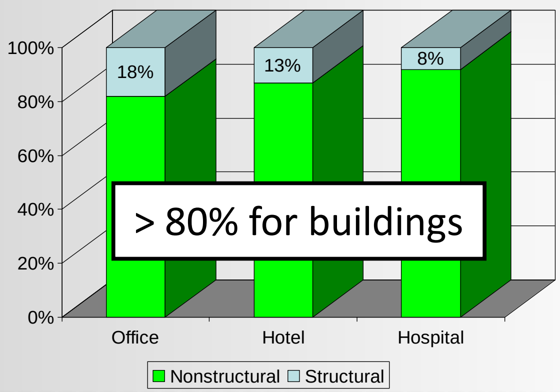
A Seismic Study of Wind Turbines for Renewable Energy

PI – Prof. Ahmed Elgamal, UC San Diego

Nonstructural Components & Systems (NCSs): Knowledge Gaps, Efforts & Impact

NCSs: Architectural, mechanical/ electrical/plumbing, contents

Role & Significance



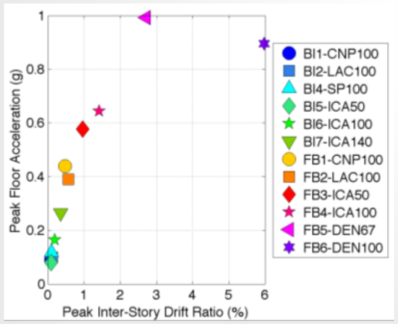
Issues:

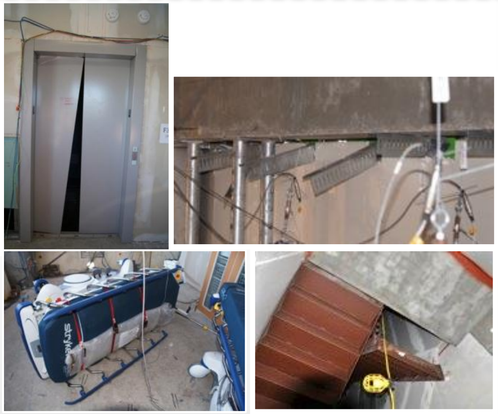
- Designed for functionality
- Lightweight & low stiffness
- Low damping (lack protection)
- Damaged at intensities much lower than that which would damage primary structure

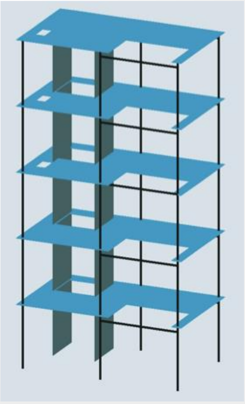
Consequences:

- Major problems during rescue operations
- Loss of functionality, facility downtime
- Excessive $ losses
- Threaten life safety

Total Building Test Program (BNCS)







System Demands → ***NCS Damage*** → ***Modeling*** → ***Design Code & Construction Impact***

Large body of important nonstructural component test data, however, these cannot:

- Capture interaction with building system
- Capture interaction with other NCSs
- Capture dynamic environment of building
- Numerous types, config., attachments remain unstudied

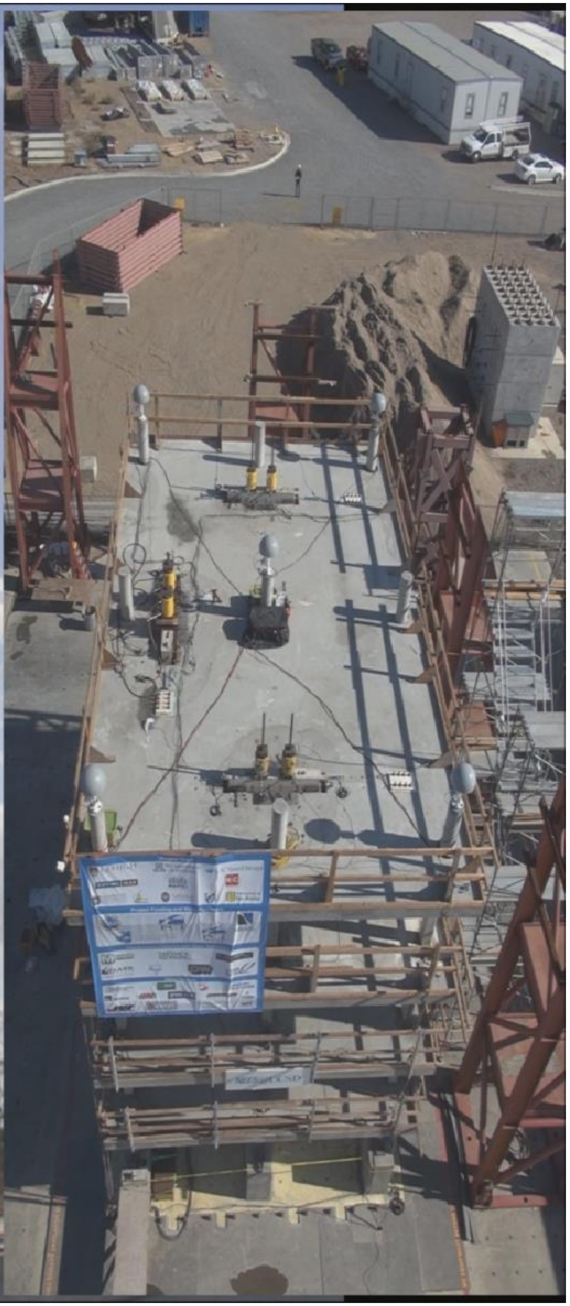
LSCB – Large Soil Confinement Box

PI – Prof. Patrick Fox, UC San Diego

- LSCB Dimensions: 15 ft or 19 ft width × 33 ft length × 25 ft height

Inertial Force – Limiting Anchorage Systems for Seismic Resistant Building Structures

PI - Prof. Robert B. Fleischman, University of Arizona




LEHIGH
TRITONS

Improving Seismic Performance of Partially Grouted Reinforced Masonry Construction

PI - Prof. P. Benson Shing, UC San Diego


1940 El Centro Earthquake at 214%
Test date: 4/22/2014
Base Shear (kips)
Drift Ratio (%)
Drift Ratio (%)
Time (s)
Input Acceleration (g)
Time (s)
UCSanDiego
South View [t=0.033s]
NEES@UCSD
North-East Inside View [t=0.033s]

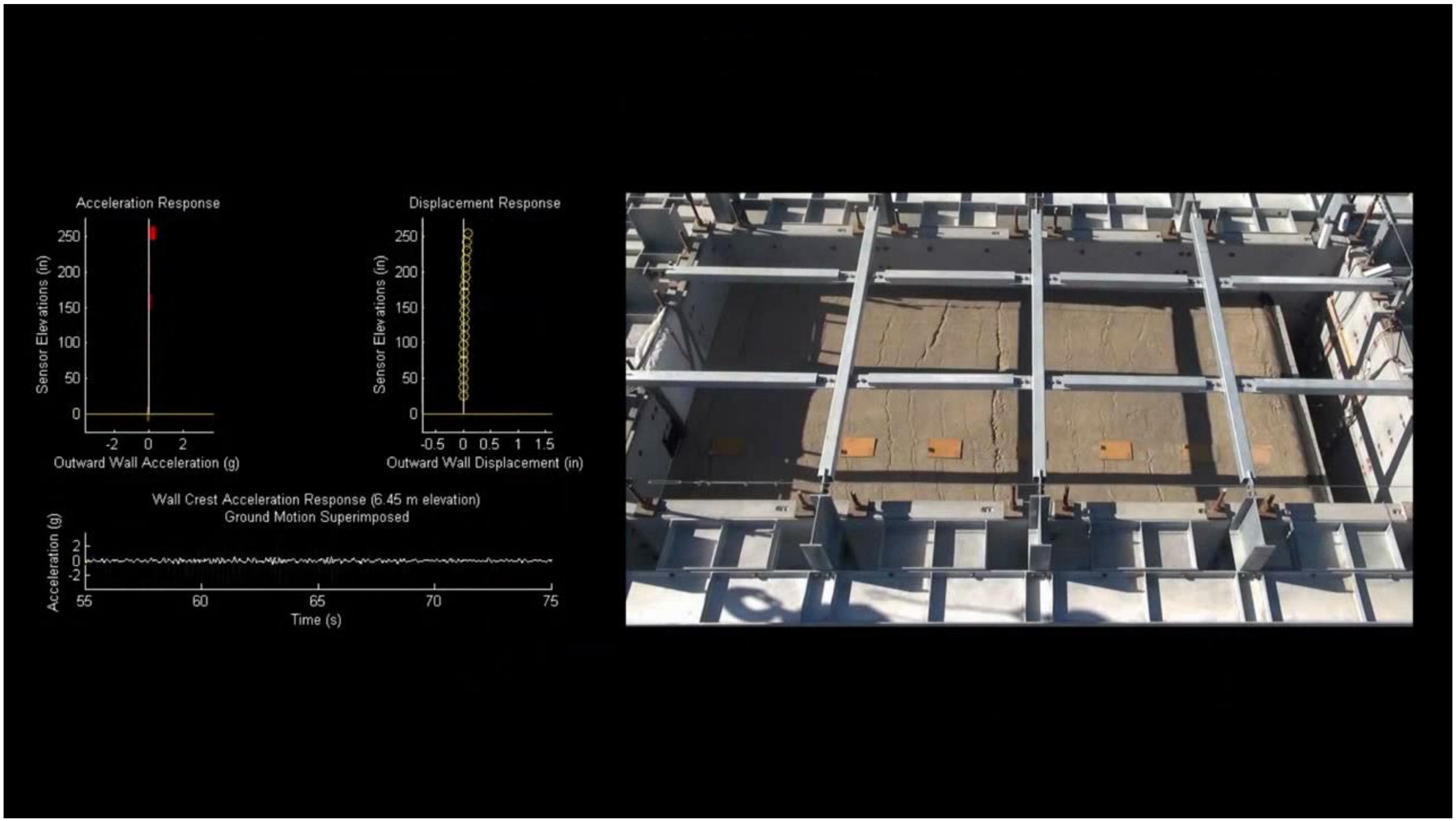
116

Earthquake Performance of Full-Scale Reinforced Soil Walls

PI – Prof. Patrick Fox UCSD

Earthquake Performance of Full-Scale Reinforced Soil Walls

PI – Prof. Patrick Fox UCSD



Staging Facility

- In an effort to increase throughput at the NHERI@UCSD facility, a reinforced concrete staging slab with dimensions of 13.4 m × 8.8 m × 0.914 m deep (44 ft × 30 ft × 3 ft deep) was built near the shake table.
- Small to moderate size specimens (weighing up to 100 tons) can be constructed on the staging area then lifted onto the shake table platen, or partial assembly of components for large specimens can reduce construction time.

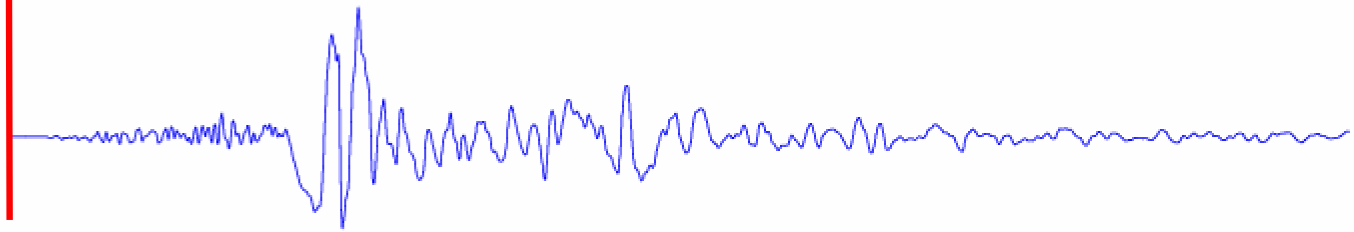
Staging Facility

Bare Table Commissioning Tests

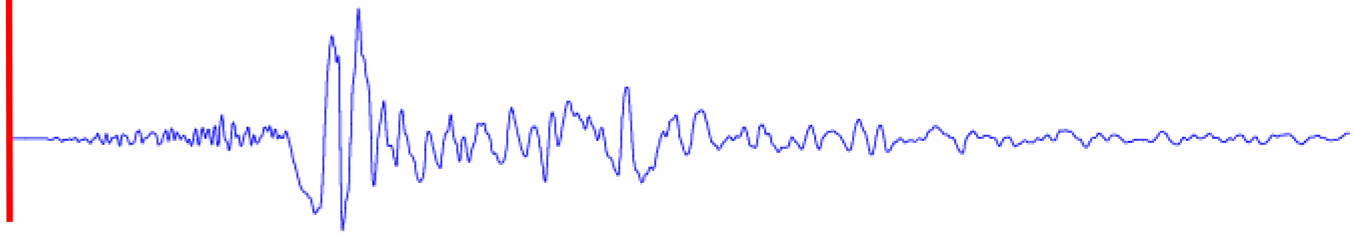
Seismic Response of a Seven Story Building

PI – Prof. Jose I. Restrepo, UC San Diego

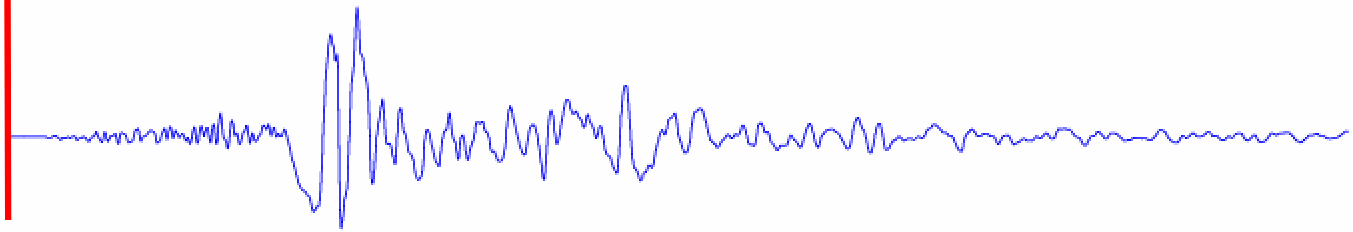
EQ4:

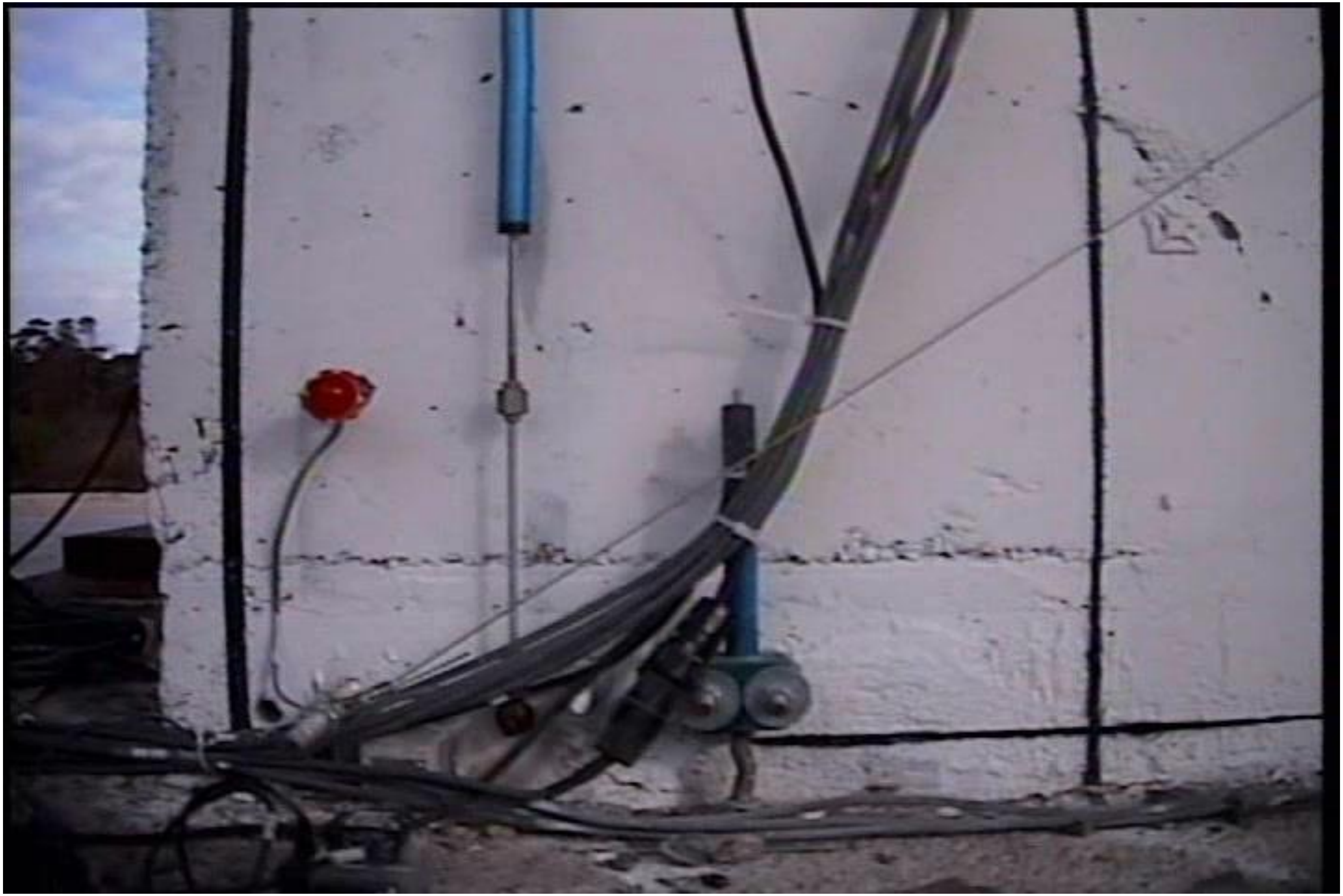


EQ4:



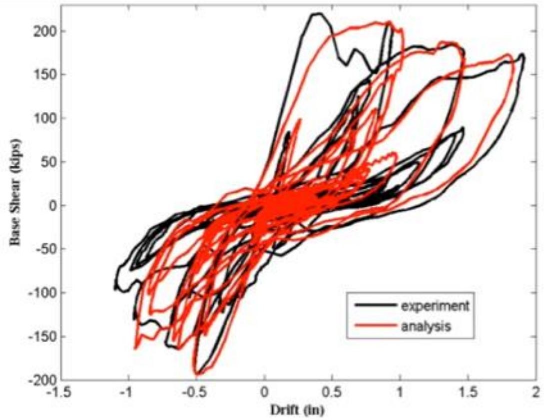
EQ4:

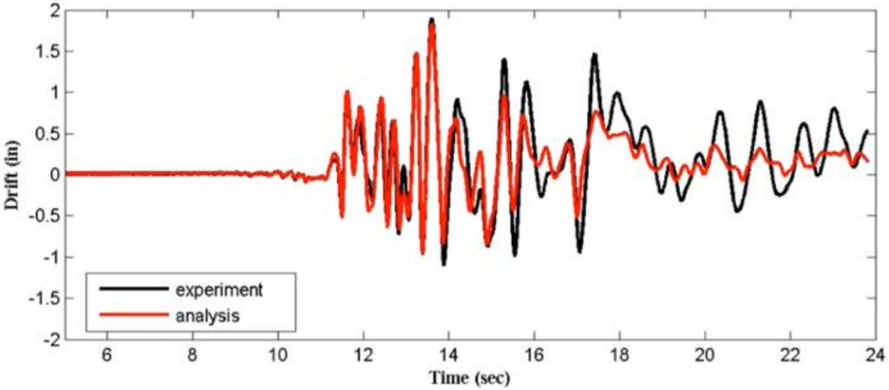


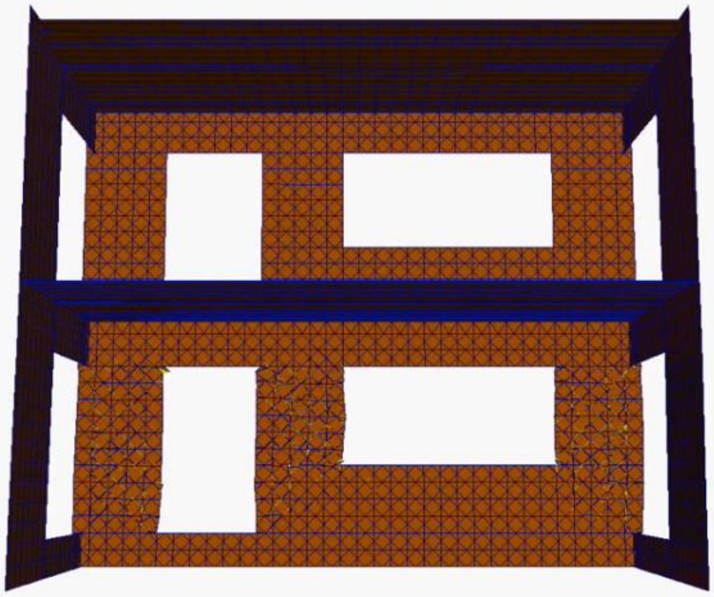


Performance-based Seismic Design Methods for Reinforced Masonry Shear-Wall Structures

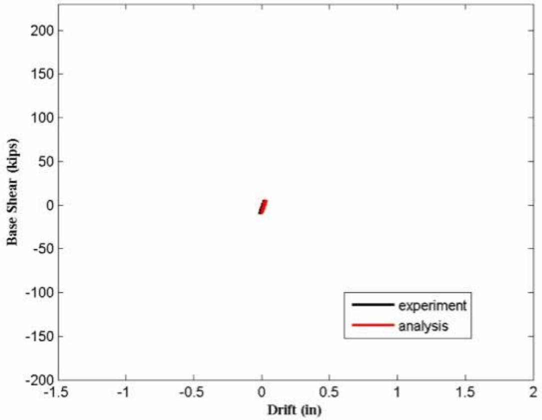
PI – Prof. Benson Shing, UC San Diego

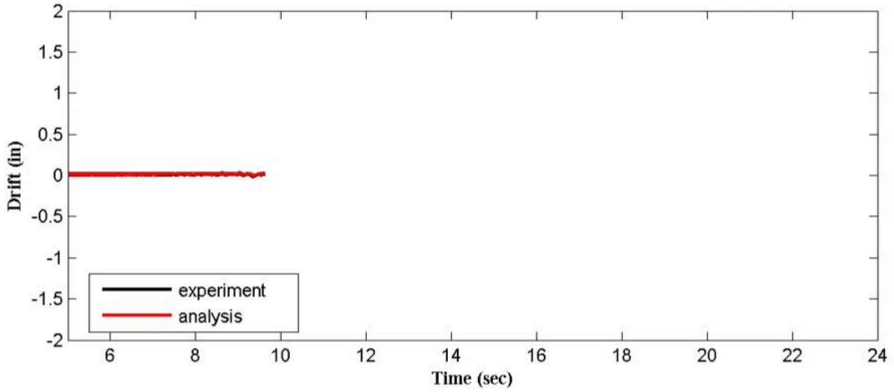


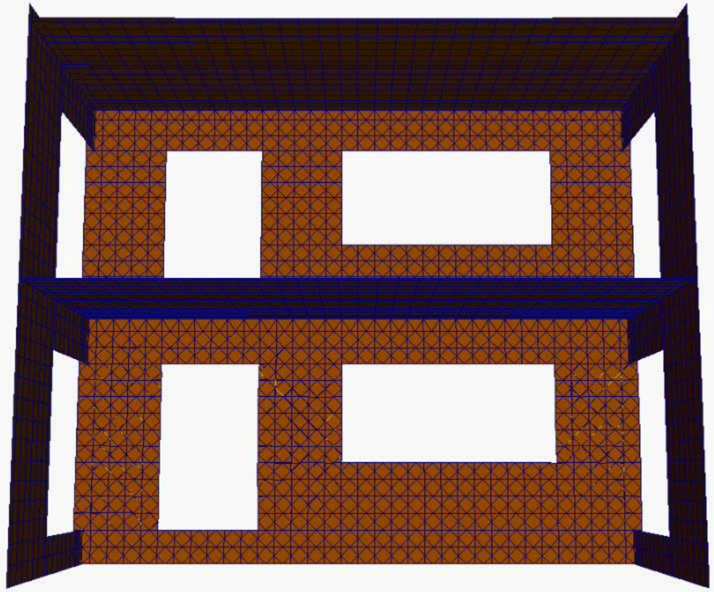





NEES @ UCSD
NIST
NEES
Shake Table Access
Beyond this Point
Authorized Personnel ONLY!

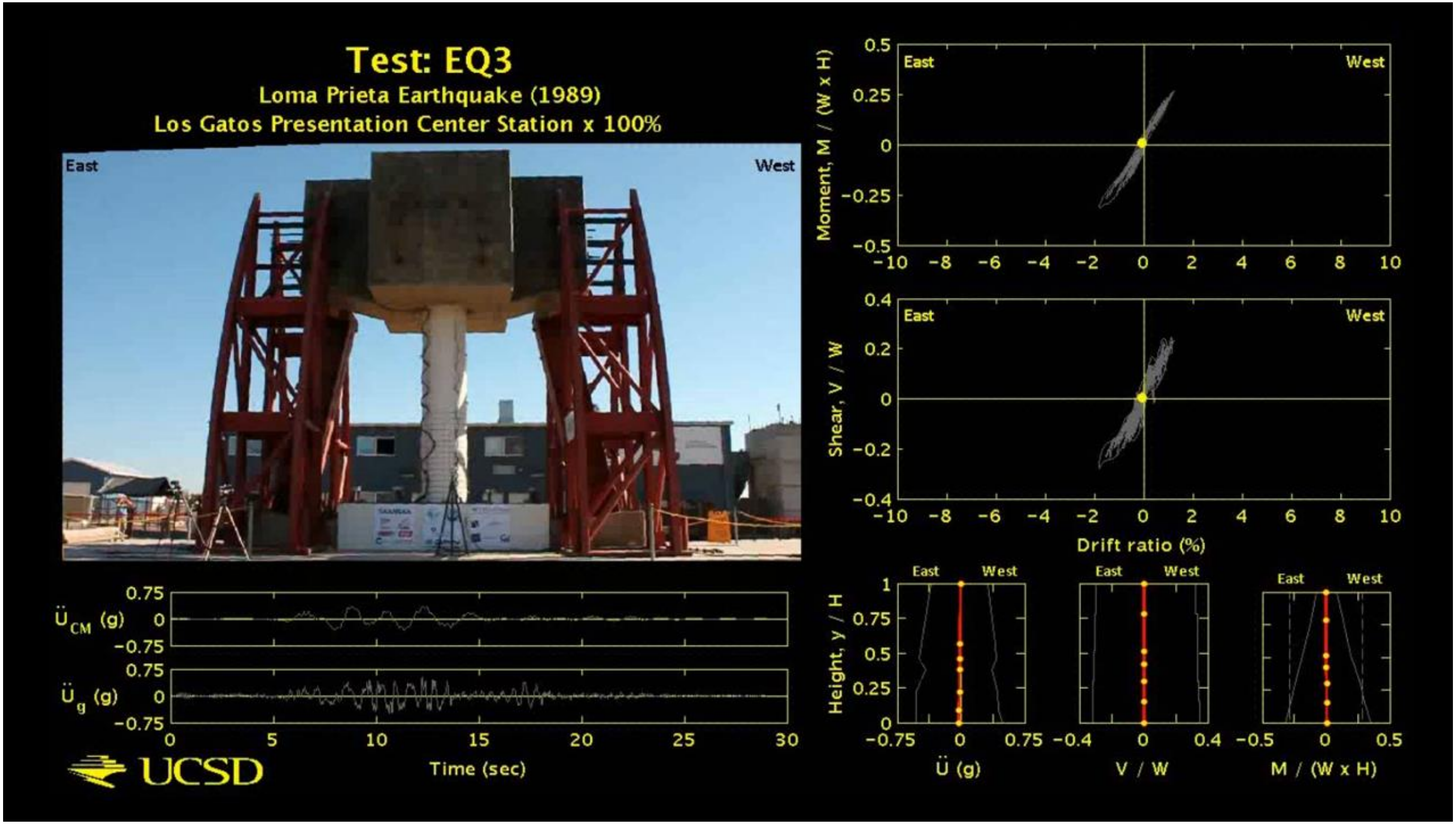

Base Shear (kips)
Drift (in)
experiment
analysis
200
150
100
50
0
-50
-100
-150
-200
-1.5
-1
-0.5
0
0.5
1
1.5
2

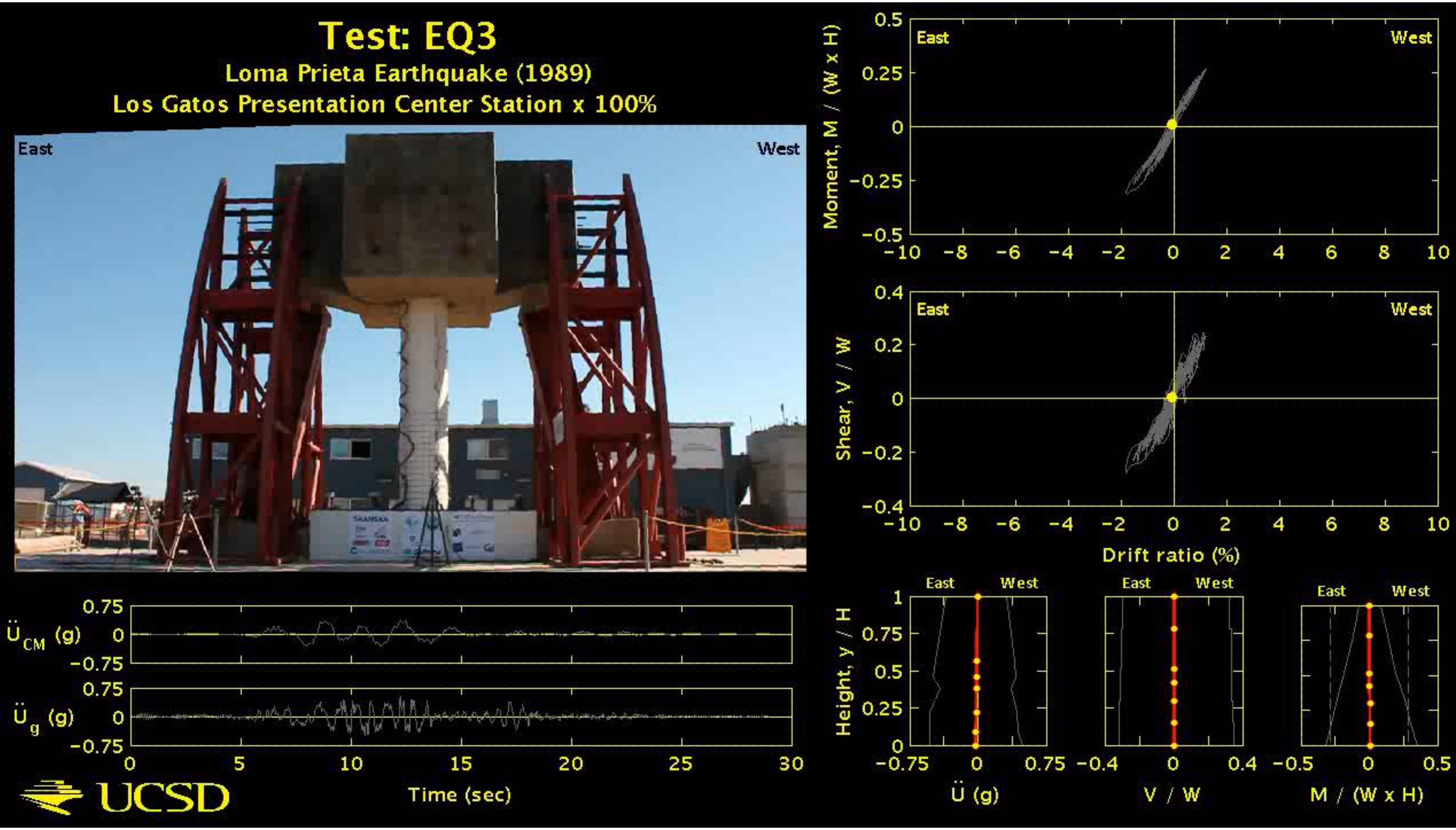

Drift (in)
Time (sec)
experiment
analysis
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
6
8
10
12
14
16
18
20
22
24



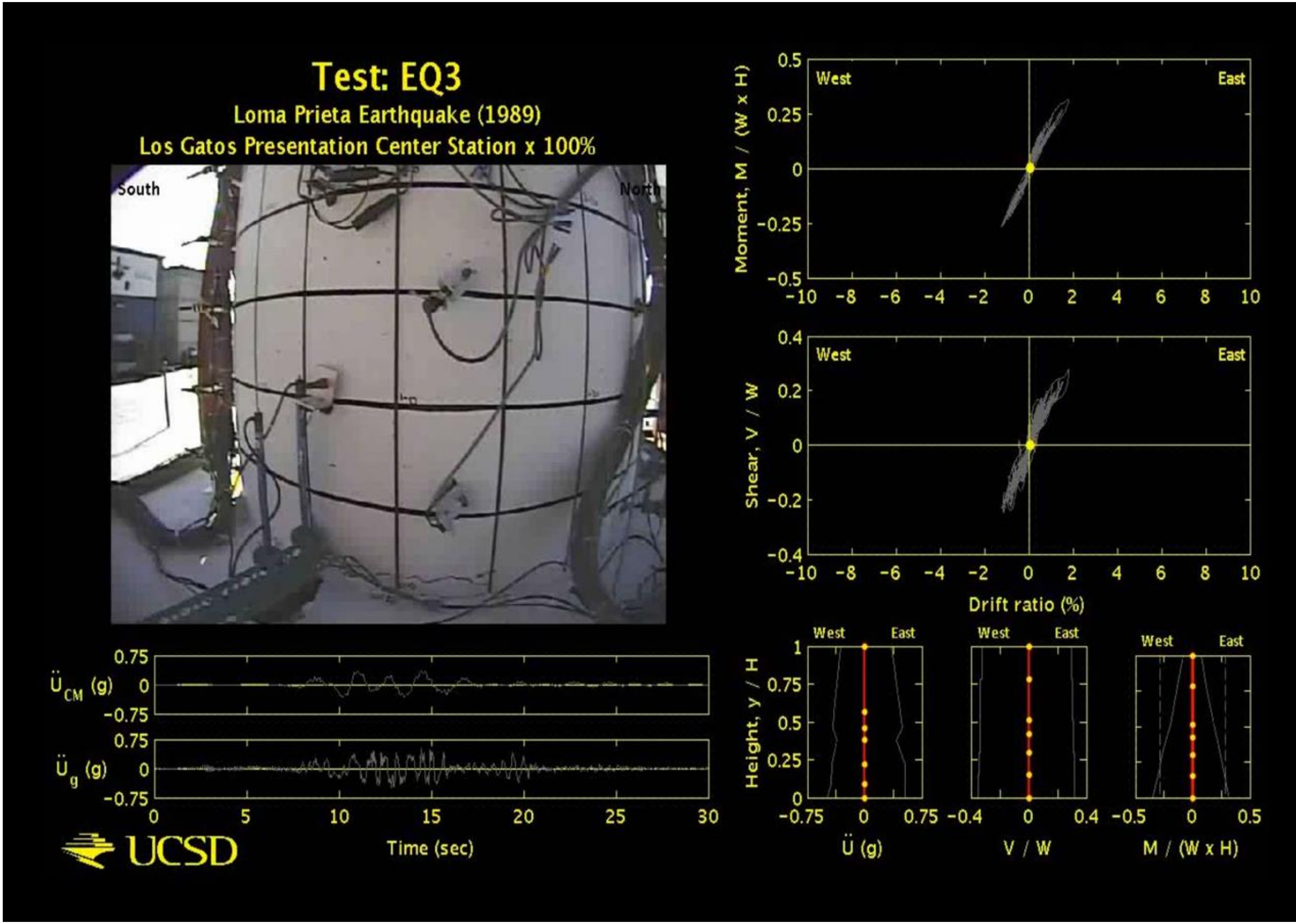
Large Scale Validation of Seismic Performance of Bridge Columns

PI - Prof. Jose I. Restrepo, UC San Diego

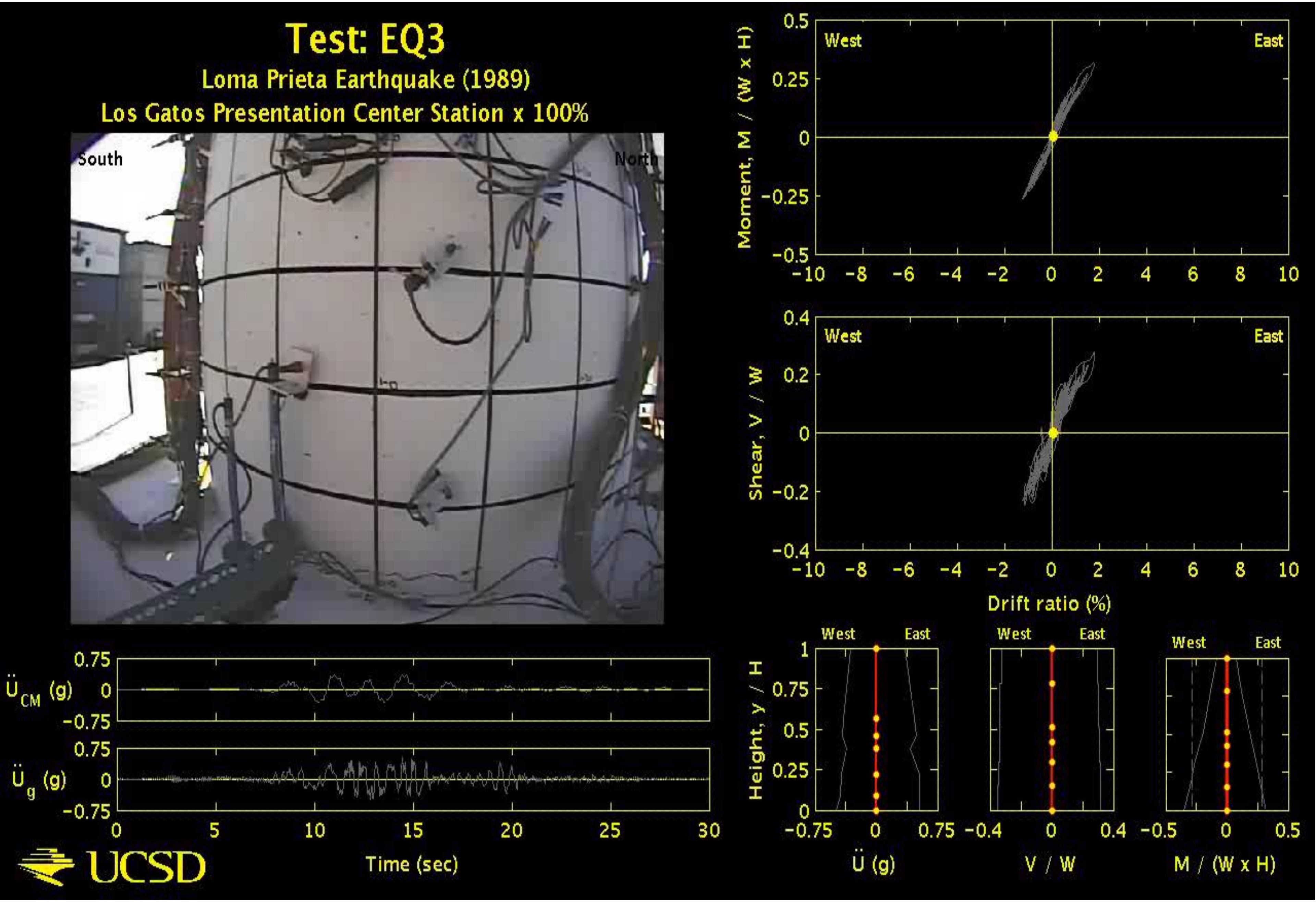




Test: EQ3
Loma Prieta Earthquake (1989)
Los Gatos Presentation Center Station x 100%
East
West
Moment, M / (W x H)
Shear, V / W
Drift ratio (%)
Height, y / H
Ü (g)
V / W
M / (W x H)
Ü_CM (g)
Ü_g (g)
Time (sec)
UCSD



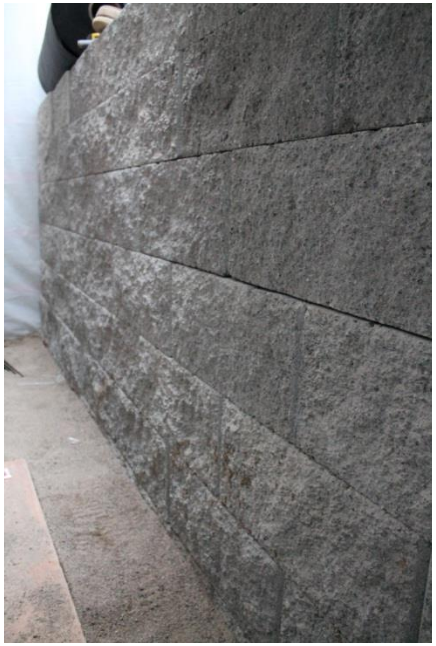
Test: EQ3
Loma Prieta Earthquake (1989)
Los Gatos Presentation Center Station x 100%
South
North
West
East
Moment, M / (W x H)
Shear, V / W
Drift ratio (%)
Height, y / H
Ü (g)
V / W
M / (W x H)
Time (sec)
UCSD


Test: EQ3
Loma Prieta Earthquake (1989)
Los Gatos Presentation Center Station x 100%
South
North
West
East
Moment, M / (W x H)
Shear, V / W
Drift ratio (%)
Height, y / H
Ü (g)
V / W
M / (W x H)
Ü_CM (g)
Ü_g (g)
Time (sec)
UCSD

Seismic Performance of Full-Scale Reinforced Soil Walls

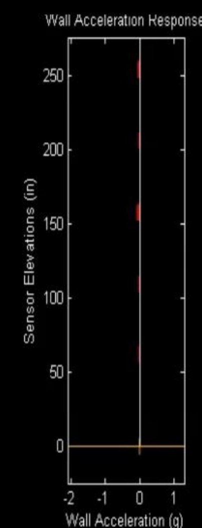
PI – Prof. Patrick Fox, UCSD

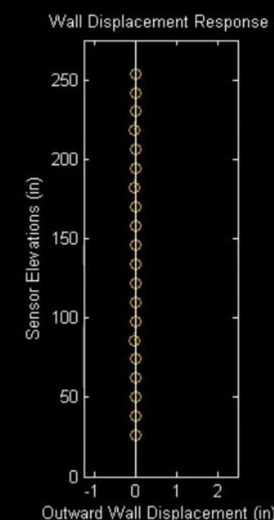
22 ft. Above Table Elevation

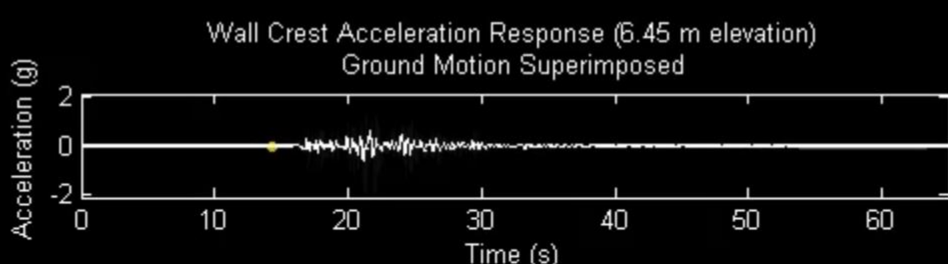


Earthquake Performance of Full-Scale Reinforced Soil Walls

PI – Prof. Patrick Fox, UC San Diego







Earthquake and Post-Earthquake Fire Performance of Mid-Rise Light-Gauge Cold-Formed Steel Framed Buildings

PI – Prof. Tara Hutchinson, UC San Diego

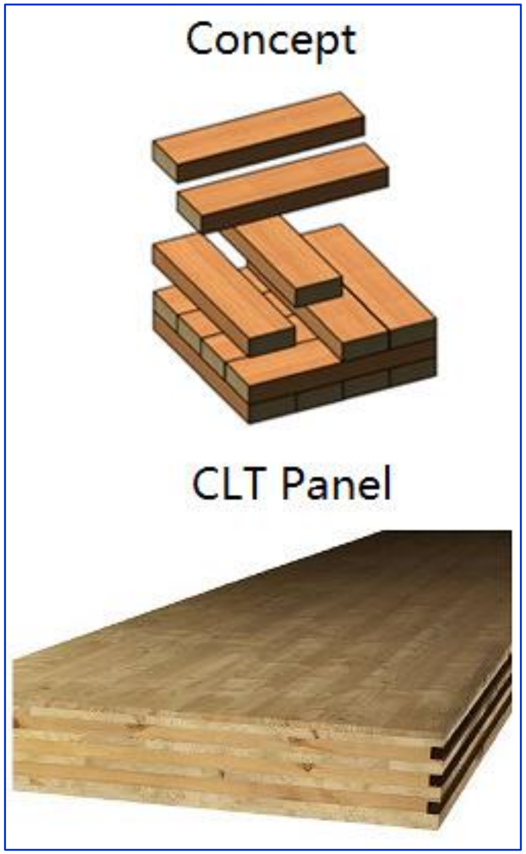
UC San Diego
Jacobs School of Engineering

Earthquake & Post-Earthquake Fire Performance of Mid-Rise Light-Gauge Cold-Formed Steel Framed Buildings

Compilation of Select
Earthquake & Post-Earthquake Fire Scenarios

UCSD WPI

Cross-Laminated Timber (CLT) and Tall Wood Buildings



UC San Diego

JACOBS SCHOOL OF ENGINEERING

July 2017 Earthquake Shake Tests at UC San Diego

Toward 20-story earthquake-safe buildings made from wood

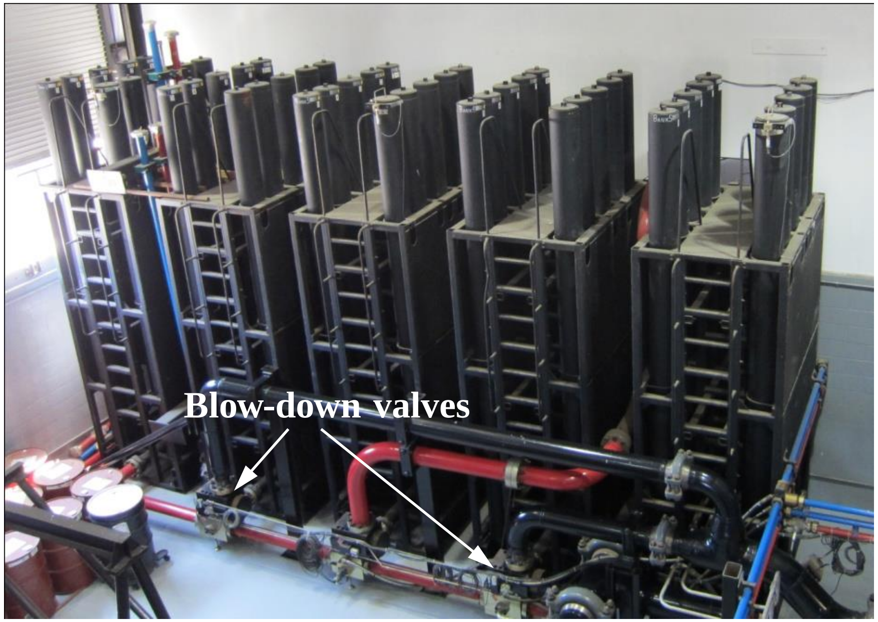
The tests are being conducted at NHERI@UCSD, the shake table experimental facility at the University of California San Diego funded by the National Science Foundation (NSF) as part of its Natural Hazard Engineering Research Infrastructure (NHERI) program.

Current Hydraulic Power System

Pumps

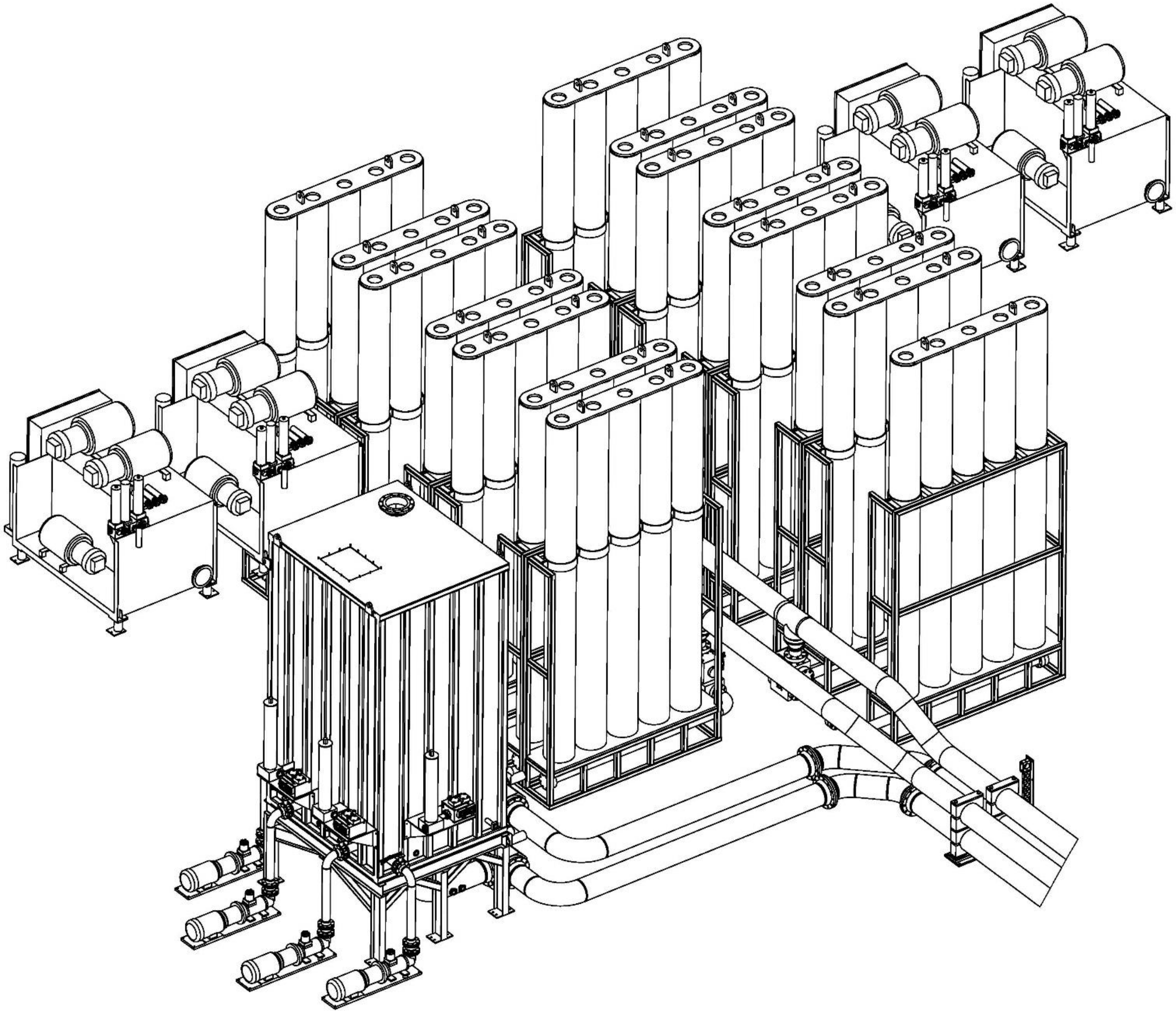
Hydraulic Power System	
Accumulator swept displacement	7.5 m
Accumulator bank pressure	35 MPa
System pressure	20.7 MPa
Blow-down maximum flow rate	38,000 lt/min
HPU flow rate @ 35 MPa	431 lt/min
HPU flow rate @ 20.7 MPa	718 lt/min
Surge tank capacity	20,000 lt

Accumulator bank



Surge tank

Hydraulic Power System for 6-DOF LHPOST



Value of the LHPOST to the State of California

Value of LHPOST to the State of California

- Increase the State of California’s ability to:
  - **Save lives**
  - **Improve emergency response**
  - **Reduce losses**

  in future destructive earthquakes.

- **Increase the seismic resilience of the State of California.**

- Large-scale experimental research is needed to **better understand the effects of seismic excitation on our infrastructure** and how to **increase its seismic resilience.**
  - “identifying an achievable path forward toward **improving the safety of earthquake-vulnerable buildings**” (Governor Brown’s recent veto of Bill 2681)

- **Seismic validation & qualification tests** required for:
  - **Seismic retrofit strategies**
  - **Nuclear industry**
  - **Health industry** (OSHPD)
  - **CA High-Speed Rail Project**
  - **Tunnels/levees** (e.g., Delta)

Value of LHPOST to the State of California

- **Seismic qualification tests require multi-directional seismic excitation.**
  - **Large hospital equipment cannot be qualified anywhere in the nation**
- **Education**:
  - **Students**
  - **Engineers**
  - **News media**
  - **Policy/Decision makers**
  - **Infrastructure owners**
  - **Insurance**
  - **General public (seismic performance provided by the design codes)**
- **Reduce the need to transfer large-scale shake table tests** (e.g., CA utility companies) **and research projects** to other countries (e.g., Japan, China, South Korea) at a much higher cost.

Tri-axial Strong Ground Motion Records Used for Preliminary Design of 6-DOF Upgraded LHPOST

Event Name	Station Name	M	PGA (g)			PGV (m/s)			PGD (m)			High pass freq. (Hz)
			EW	NS	UP	EW	NS	UP	EW	NS	UP	
Tabas, 1978	Tabas, Iran	7.4	0.97	0.88	0.72	1.0	0.87	0.33	0.62	0.33	0.11	0.16
Chi-Chi, Taiwan, 1999	TCU065	7.6	0.72	0.49	0.23	0.82	0.73	0.38	0.36	0.24	0.10	0.25
Kobe, 1995	Takatori, Japan	6.9	0.62	0.67	0.28	1.21	1.23	0.16	0.40	0.30	0.04	0.125
Northridge, 1994	Rinaldi Receiving Station	6.7	0.87	0.47	0.96	1.48	0.75	0.42	0.42	0.23	0.04	0.10
Nepal, 2015	Kathmandu, Nepal	7.8	0.16	0.17	0.15	0.43	0.40	0.26	0.30	0.20	0.10	0.25
AC-156 compatible earthquake		-	0.96	1.01	0.71	1.13	1.04	0.77	0.22	0.21	0.12	0.70

Near fault

Far field

Artificial

Intra-plate

Long duration inter-plate

Strike-slip

Thrust

EW component uses near total flow capacity for 1-DOF LHPOST

Collaborative Research: A Resilience-based Seismic Design Methodology for Tall Wood Buildings

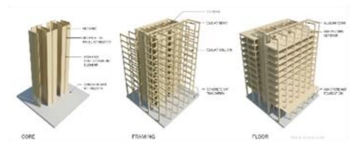
NHERI TallWood

A Six-University Collaboration to develop and validate resilient tall wood building design methodology.

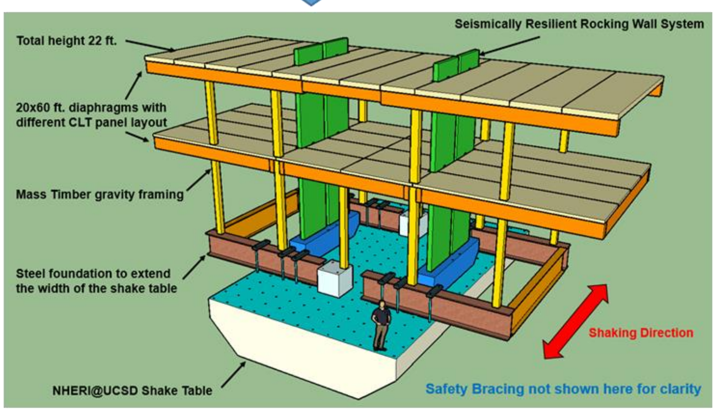
- Main contact:

Dr. Shiling Pei, Colorado School of Mines, spei@mines.edu

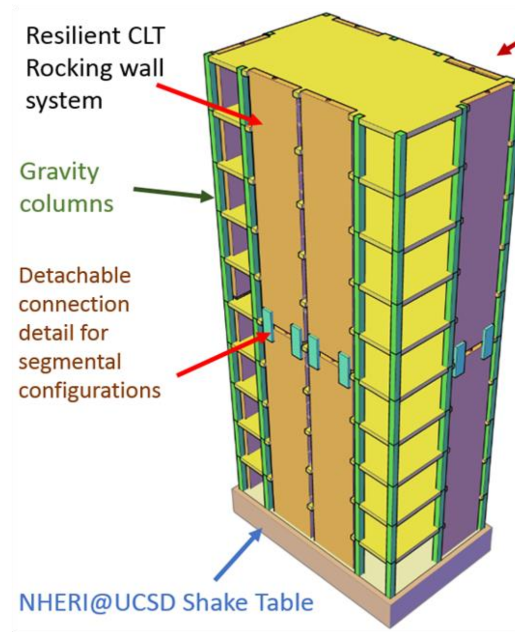
Project Website: Nheritallwood.mines.edu

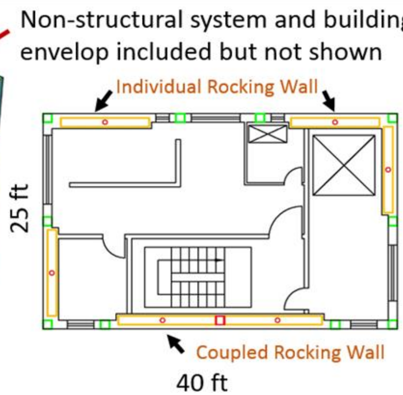


Archetype Meeting at Portland OR 11/2016



A full-scaled 2-story mass timber building with CLT rocking walls (July 2017 NHERI@UCSD)





- Both individual and coupled rocking walls included
- Intentional un-symmetric design to induce torsion
- Include two configurations: Monolithic and Segmental

Full-scale 10-story building test at NHERI@UCSD shake table (expected 2019~2020)

Colorado School of Mines 1874 · University of Washington · University of Nevada, Reno · Lehigh University · Washington State University · Colorado State University

Outline

- **Overview of Englekirk Structural Engineering Center (ESEC) and NHERI@UCSD Shake Table Experimental Facility (LHPOST)**
- **Select Large-Scale Shake Table Tests Performed on the LHPOST**
- **Need for Upgrade of LHPOST to Multi-Degree-of-Freedom Capabilities**
- **Six Degree-of-Freedom (6-DOF) Upgrade of Shake Table**
- **New Research Opportunities Made Possible by the 6-DOF LHPOST**

Outline

- Overview of NHERI@UC San Diego Shake Table Experimental Facility
  - Description of Facility
  - Performance Characteristics
  - Capabilities and Limitations
- Shake Table Dynamics and Control
  - Sources of Signal Distortion
  - Shake Table Controller
  - Fidelity in Signal Reproduction
- Select Set of Large-Scale Shake Table Tests Performed on the NHERI@UC San Diego Shake Table
- Six Degree-of-Freedom (6-DOF) Upgrade of Shake Table
- New Research Opportunities Made Possible by the 6-DOF LHPOST