National Science Foundation

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

UC San Diego
JACOBS SCHOOL OF ENGINEERING
Structural Engineering

UC San Diego
NHERI Joint Researcher Workshop
Lehigh & SimCenter

December 16-17, 2019
UC San Diego, La Jolla, CA

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

General Housekeeping Items

- Light breakfast available in Cymer Conference Center (SME 248) both days.
- SME 248 will be used for all presentations
- Tour will be given of the NHERI@UCSD large outdoor shake table experimental facility
- Lunch will be available both days in courtyard adjacent to the Cymer Conference Center
- Restrooms
- Wireless
- Workshop slides

Workshop Objectives

- Disseminate information on the use of the NHERI@UC San Diego EF, NHERI Lehigh EF, and NHERI SimCenter to conduct state-of-the-art research in natural hazards mitigation.
- Understand how these facilities can enhance participant research.
- Provide information for preparing competitive NSF research proposals which use these facilities, and particularly the NHERI@UCSD EF.
- Promote collaborative team research interests to use all three facilities (NHERI@UC San Diego, NHERI Lehigh, and NHERI SimCenter).
- Brainstorm on example uses at each facility given grand challenge discussions.

Workshop Program – Monday Morning

Day 1 (Dec 16, 2019): Facility Capabilities and Collaborative Research Planning

7:30 – 8:00am	Registration/light breakfast
8:00 – 8:15am	Welcome, introduction of each attendee & workshop schedule (Prof. Joel Conte, UC San Diego PI)
8:15 – 9:15am	NHERI@UC San Diego: Facility description and capabilities (Prof. Joel Conte, UC San Diego PI)
9:15 – 10:15am	NHERI@Lehigh: Facility description and capabilities (Prof. Jim Ricles, Lehigh PI)
10:15 – 10:30am	Break
10:30 – 11:10am	NHERI SimCenter: Capabilities (Prof. Laura Lowes, Univ. of Washington, SimCenter Co-PI)
11:10 – 11:50am	Example project: UCSD (Prof. Chia Ming Uang, UC San Diego)
11:50 – 12:30pm	Example projects: Lehigh (Prof. Jim Ricles, Lehigh PI)
12:30pm	Lunch & leave for tour (1:00 – 3:00pm) (Via Bus)

Workshop Program – Monday Afternoon

Day 1 (Dec 16, 2019): Facility Capabilities and Collaborative Research Planning

1:30 – 2:30pm	Tour of UCSD NHERI facility (Prof. Joel Conte, UC San Diego PI)
3:00 – 3:45pm	Example use of SimCenter/data/analysis tools for multiple collaborative projects (Dr. Adam Zsarnóczay, Post-doctoral researcher, Stanford, SimCenter)
3:45 – 4:15pm	DesignSafe tools and capabilities (Dr. Tim Cockerill, DesignSafe Deputy Project Director, Texas Advanced Computing Center)
4:15 – 4:45pm	Modular testbed building: opportunities for future research (Prof. Chris Pantelides, University of Utah)
4:45 – 5:15pm	Research planning in a nutshell (Prof. Tara Hutchinson, UC San Diego Co-PI)
5:15 – 5:30pm	Concluding remarks (Prof. Joel Conte, UC San Diego PI)
5:30pm	Dinner & poster session in courtyard

Workshop Program – Tuesday Morning

Day 2 (Dec 17, 2019): Grand Challenges in Earthquake Engineering

7:30 – 8:00am	Light breakfast
8:00 – 8:05am	Opening remarks (Prof. Joel Conte, UCSD PI)
8:05 – 8:15am	NSF NHERI Facilities and Research Programs (Dr. Joy Pauschke, NSF)
8:15 – 9:15am	GC1: Structural Systems (Prof. José Restrepo, UCSD)
9:15 – 10:15am	GC2: Community Resilience (Prof. John van de Lindt, Colorado State University)
10:15 – 10:30am	Break
10:30 – 11:30am	GC3: Nonstructural Components and Systems (Prof. Manos Maragakis, Dean of Engineering, Univ. of Nevada, Reno)
11:30 – 12:30pm	GC4: Soil Liquefaction & Soil-Structure Interaction (Prof. Bruce Kutter, UC Davis)
12:30 – 12:40pm	Concluding remarks (Prof. Joel Conte, UCSD PI)
12:40pm	Wrap up lunch

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: Facility Description and Capabilities

Joel Conte, Professor
University of California, San Diego

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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

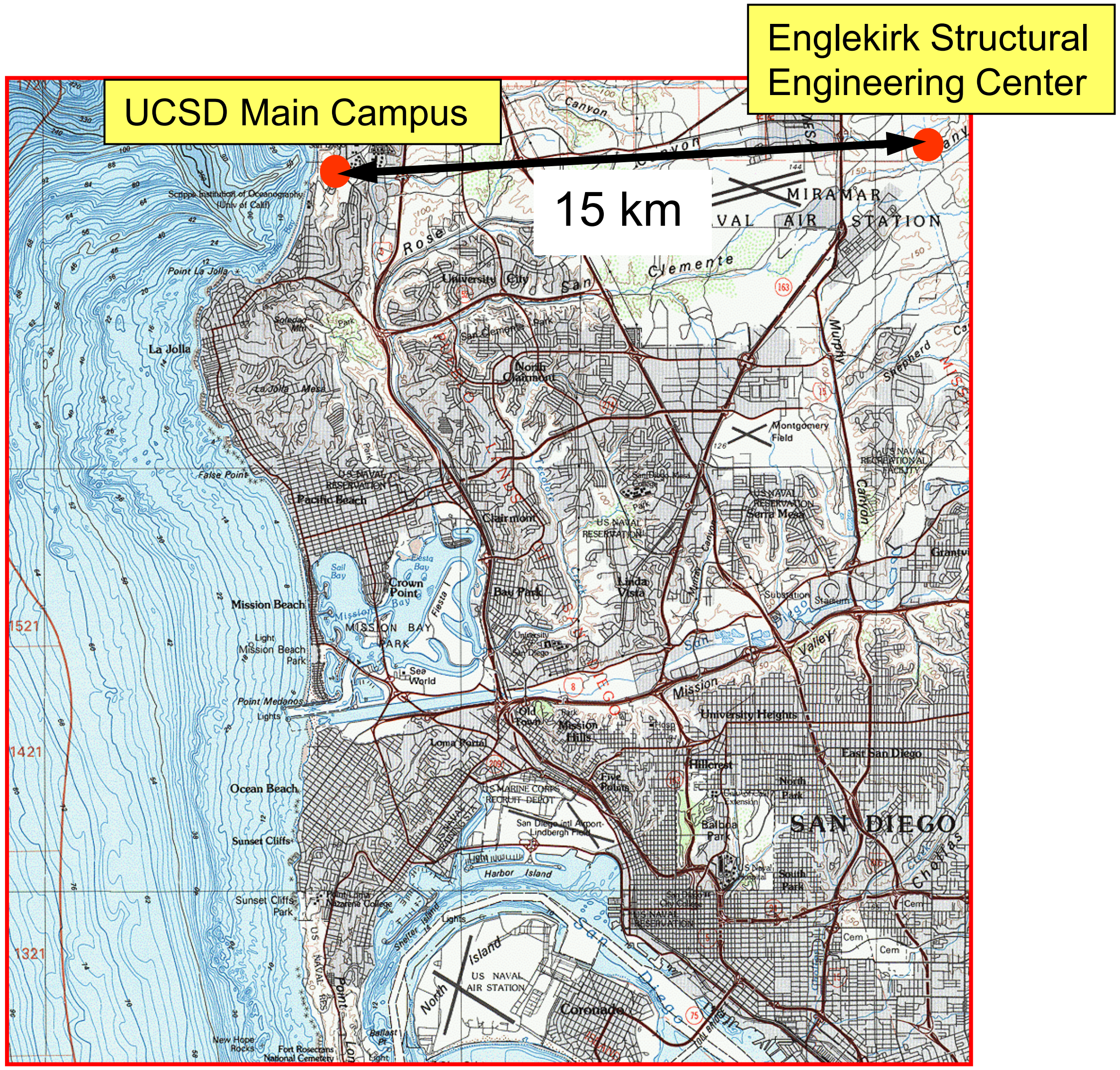
Natural Hazards Engineering Research Infrastructure (NHERI) Network

Outline

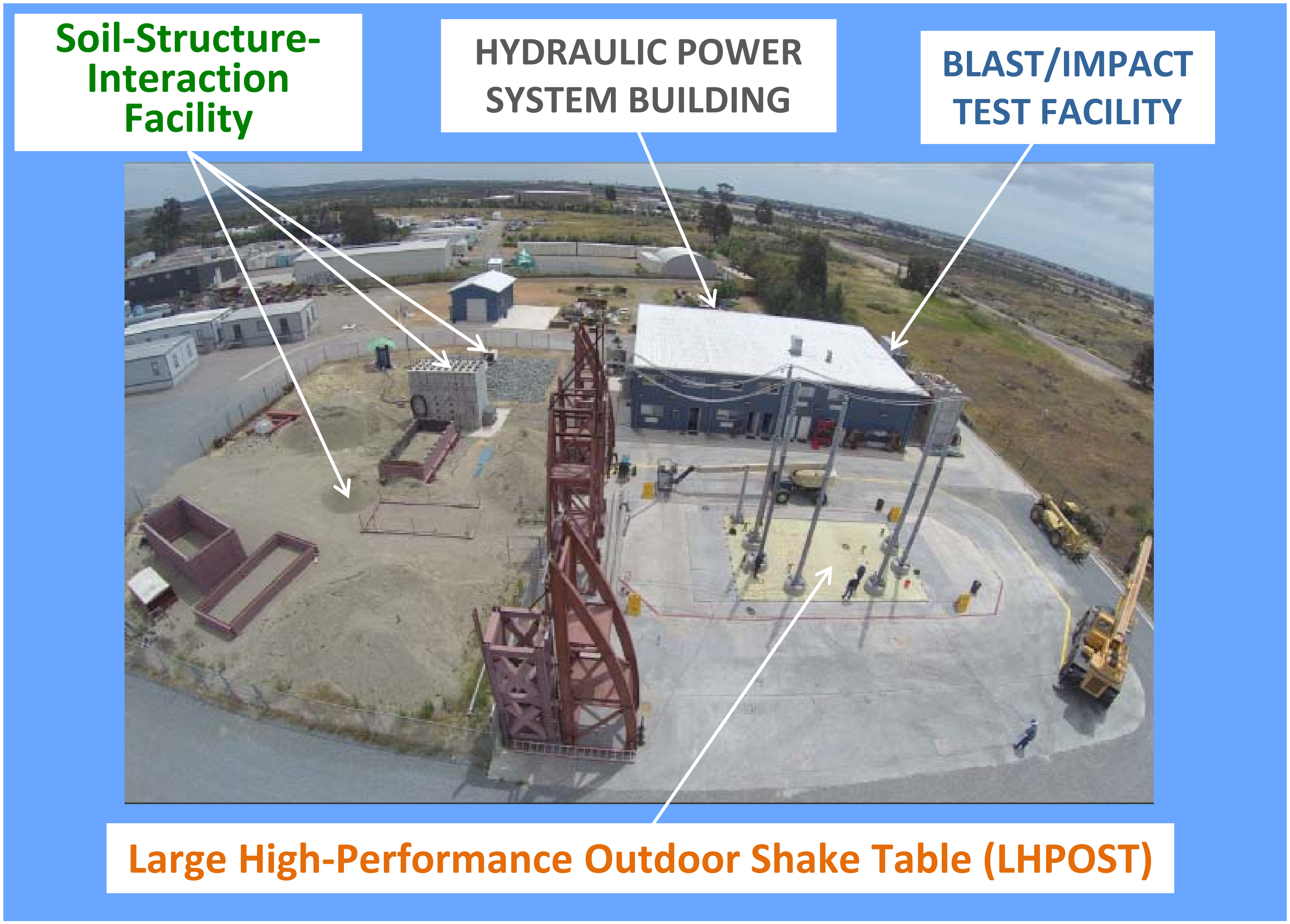
- Overview of NHERI@UC San Diego Large High-Performance Outdoor Shake Table (LHPOST) Experimental Facility
  - Description of Facility
  - Performance Characteristics
  - Capabilities and Limitations
- Select Set of Large-Scale Shake Table Tests Performed on the NHERI@UC San Diego Shake Table
- Six Degree-of-Freedom (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.

INTERNATIONAL ACCREDITATION SERVICE®

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Raj Nathan
President

15-12065

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:	**K. Loftizadeh:**	**Acting Site Operation Manager**
	D. McKay:	**Research & Development Engineer**
	A. Sherman:	**Senior Development Technician & Site Foreman**
	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

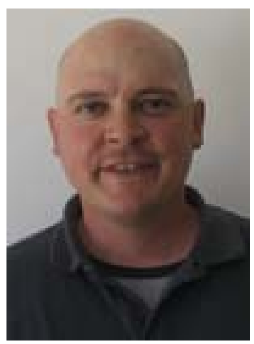
Benson Shing
Co-PI
Site Operations

Lelli Van Den Einde
Co-PI
Education and
Community Outreach

José Restrepo
Senior Personnel

Enrique Luco
Senior Personnel

Koorosh
Loftizadeh
Acting 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@UC San Diego Shake Table experimental facility** is rooted on **three critical needs** for advancing the science, technology, and practice in earthquake disaster mitigation and prevention:

  (1) 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**.

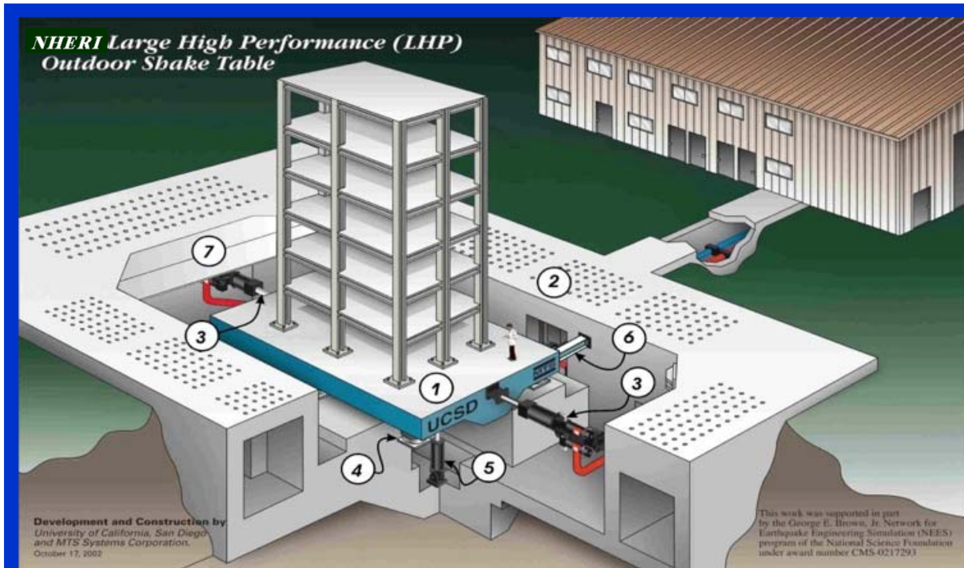
  (2) Experimental data to support the **development, calibration and validation of high-fidelity physics-based computational models** of structural/geotechnical/soil-foundation-structural systems that will progressively shift the current reliance on physical testing to model-based simulation for the seismic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

  (3) **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.
- 34 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)

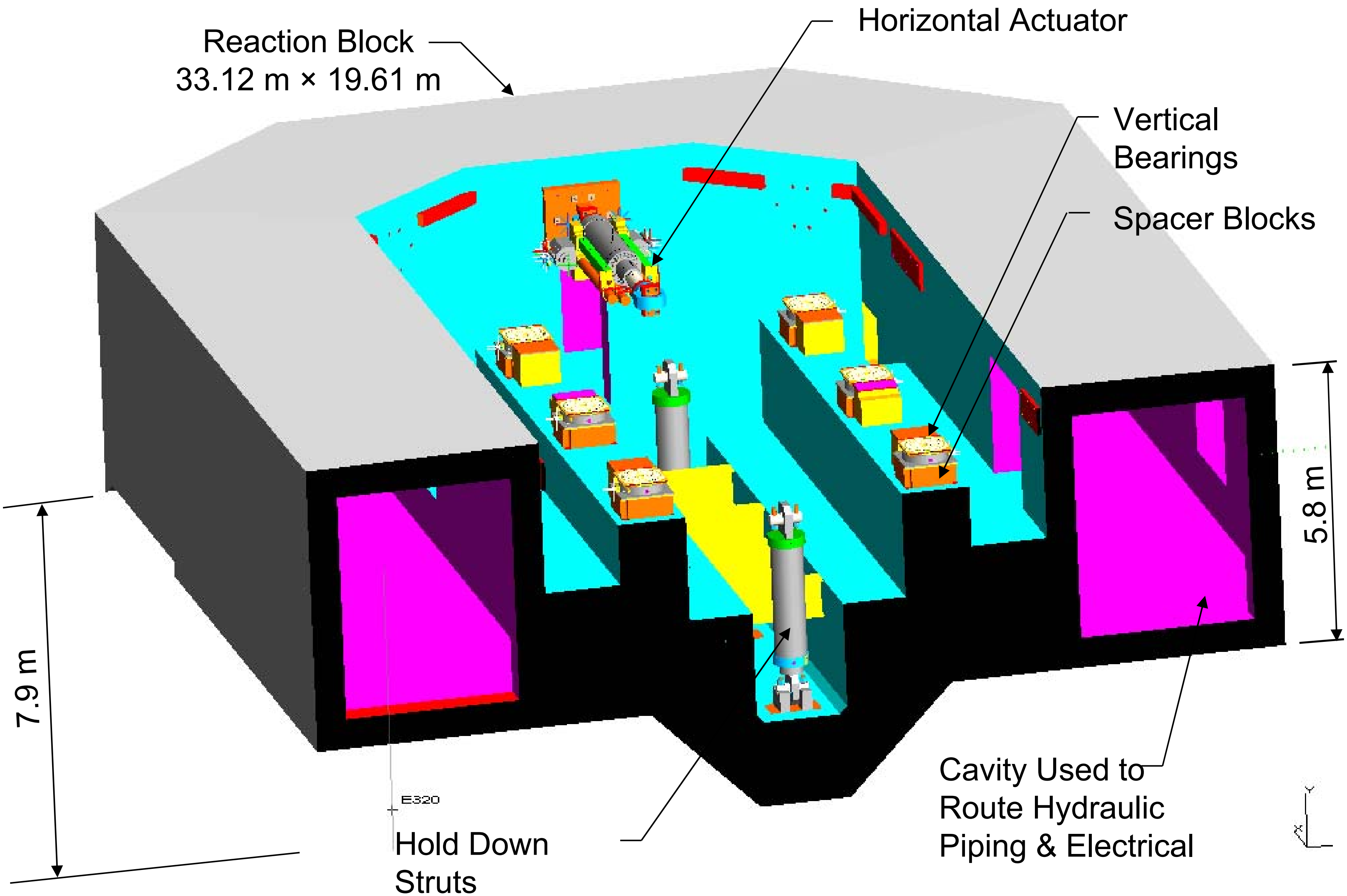


Performance Characteristics in Current 1-DOF Configuration	
Designed as a 6-DOF shake table, but built as a 1-DOF system to accommodate funding available	
Stroke	**± 0.75m**
Platen Size	40 ft × 25 ft (12.2 m × 7.6 m)
Peak Velocity	**1.8 m/sec**
Peak Acceleration	4.7g (bare table condition); 1.2g (4.0MN/400 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)

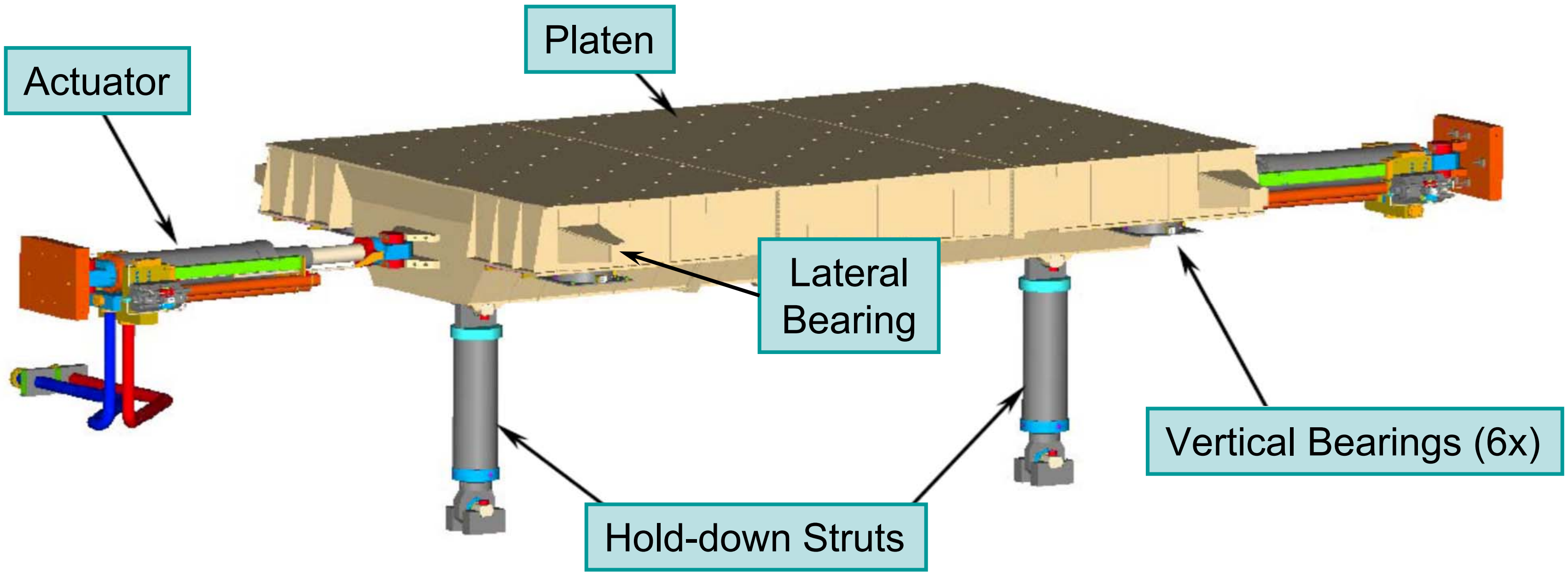
Capabilities/Provisions of NHERI@UCSD Site

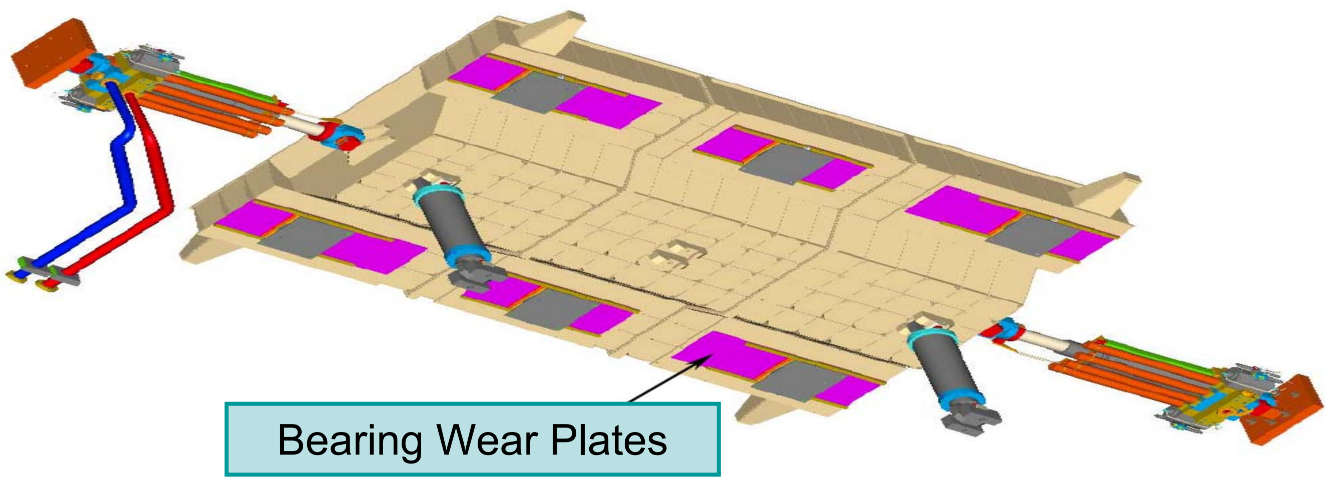
- **Simulation of near-source earthquake ground motions** which involve large acceleration, velocity and displacement pulses.
- Seismic testing of **extensively instrumented large/full-scale structural specimens** under extreme earthquake loads at near real-world conditions.
- Seismic testing of **extensively 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



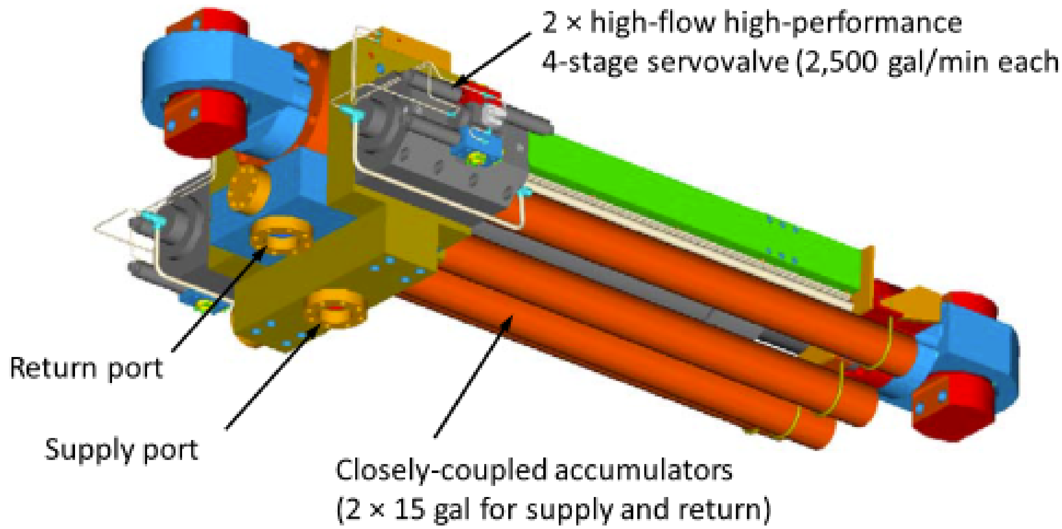


Hold-down Struts

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

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/min
Peak Retract Flow Rate	14,010 lt/min



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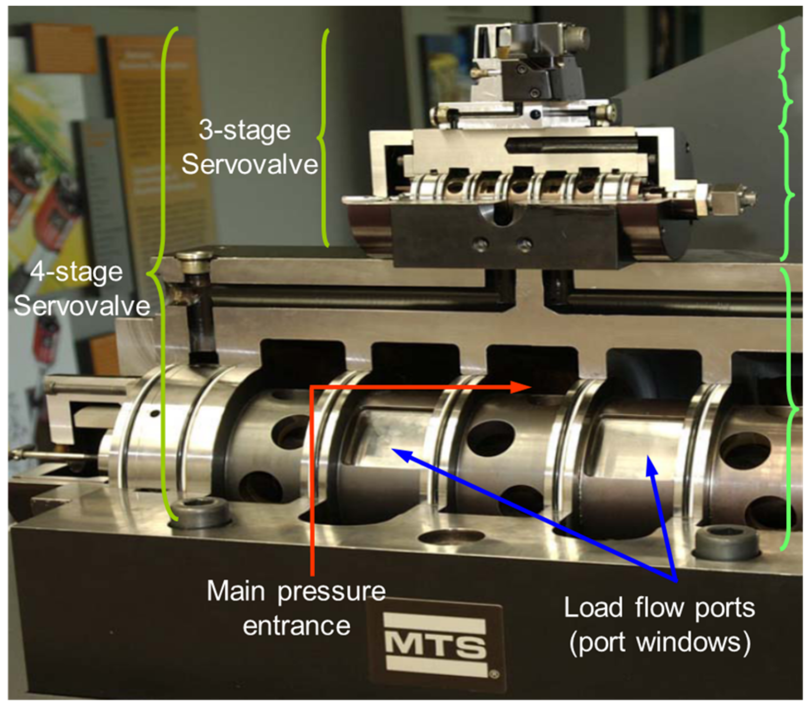
High-Flow High-Performance Servovalves

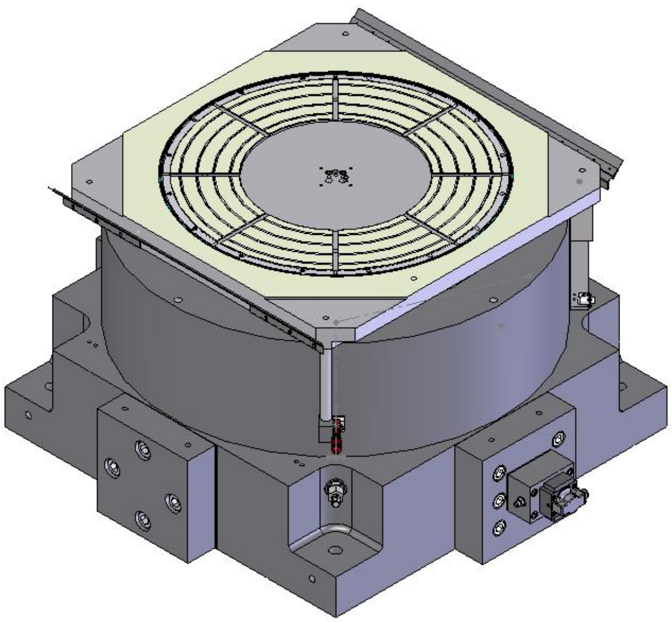
Servovalves (Qty. 2E + 2W)	
Pilot 2nd Stage Rating (Manufacturer Moog)	**19 lt/min**
Pilot 3rd Stage Rating	**630 lt/min**
4th Stage Flow Rating	**10,000 lt/min (2,5000 gpm)**
Port Area Ratios	1:0.8:0.64:0.5
Valve Sleeve Windows Area Ratio	1:0.64



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)

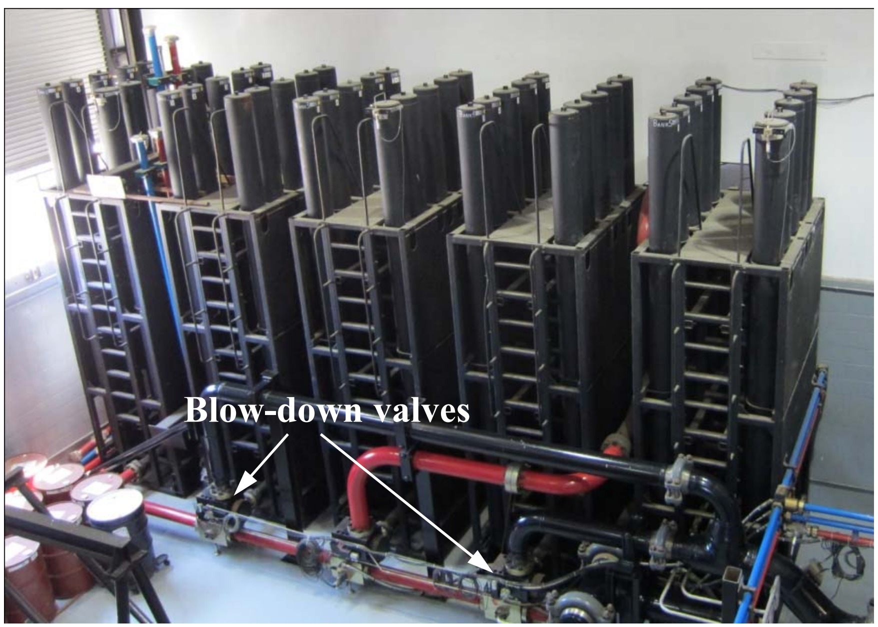


Hydraulic Power System

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

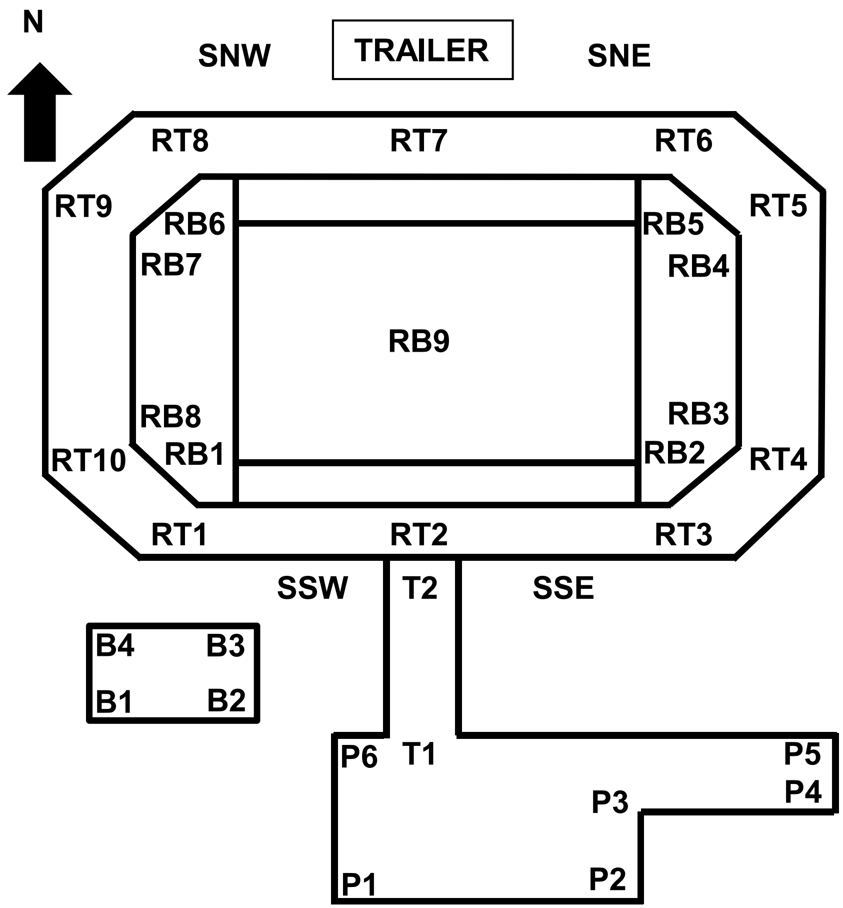


Surge tank

Bare Table Motions

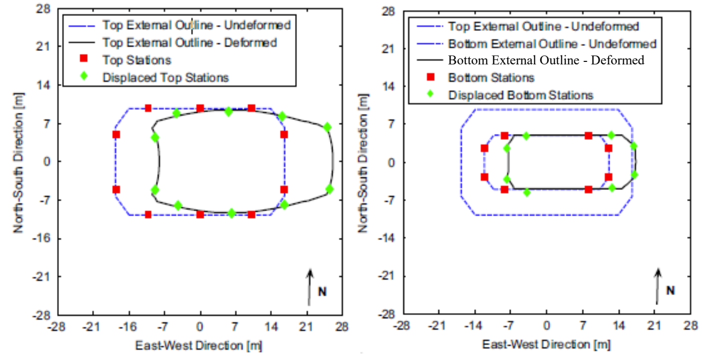
Forced Vibration Tests of the Reaction Mass at the NEES-UCSD Shake Table

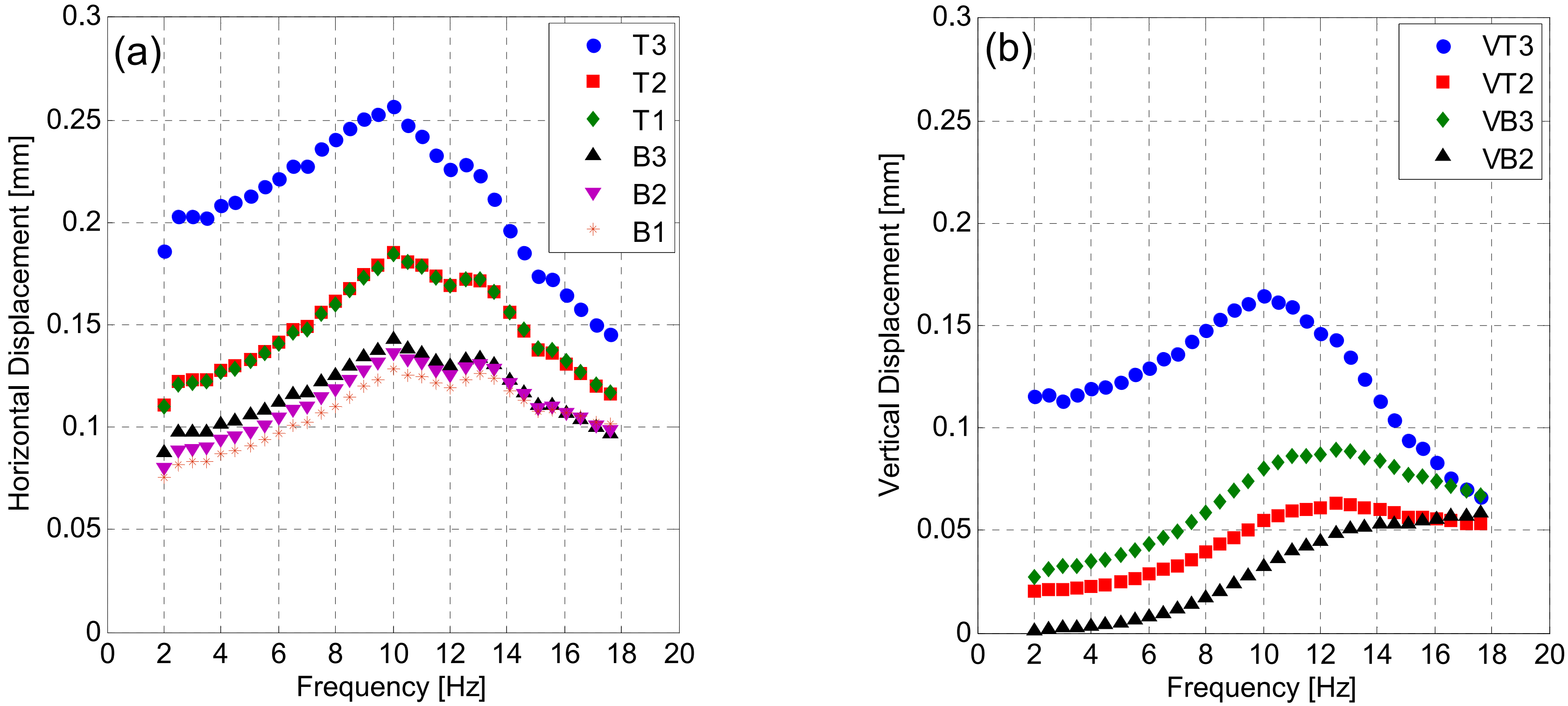
Commissioning Tests



Instrument locations on Reaction Block and adjacent foundations

Frequency Response Functions of Reaction Mass





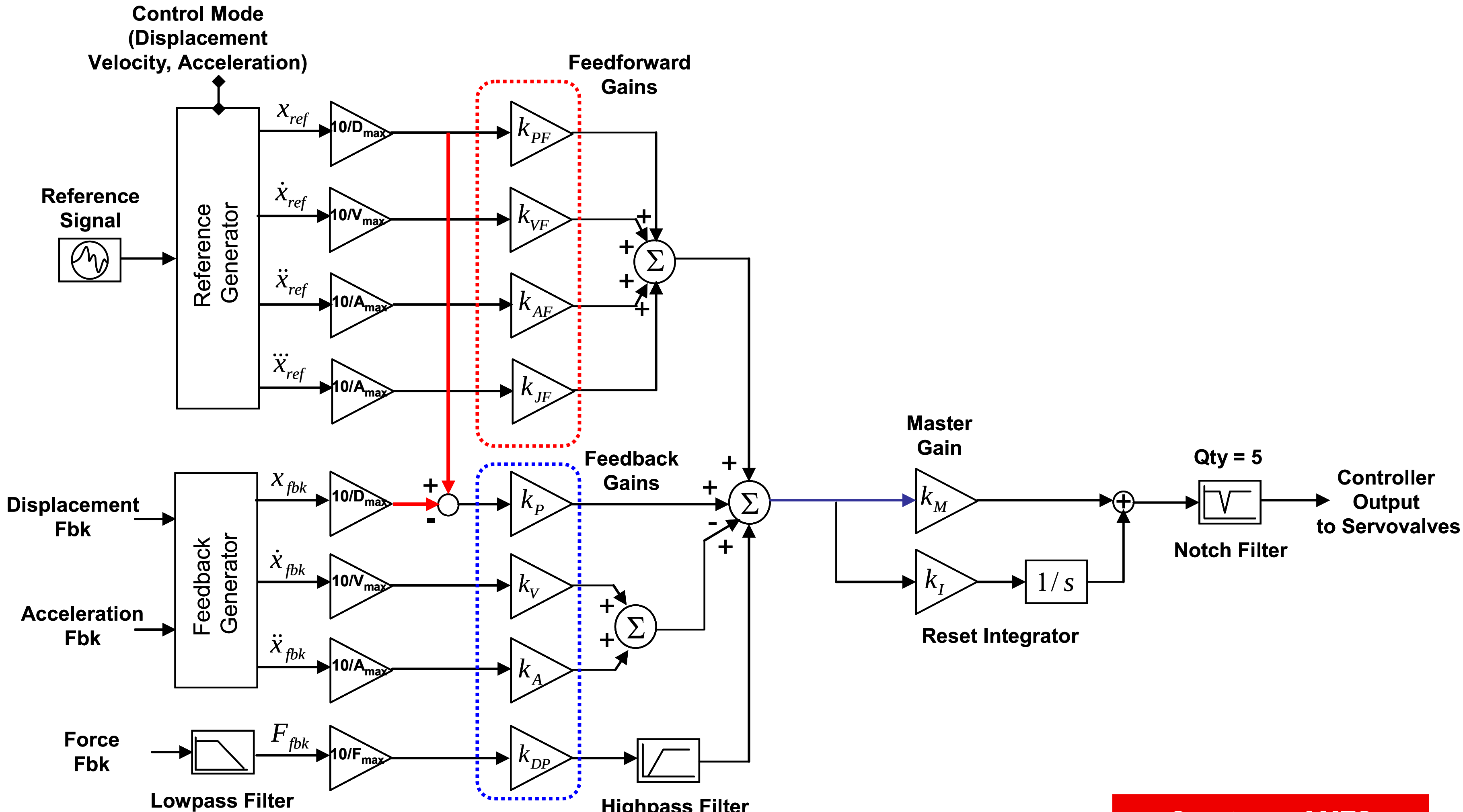
Amplitudes of the EW (a) and vertical (b) frequency response functions of the reaction block for EW excitation. The results shown are based on Test 2 and correspond to scaled displacement amplitudes for a harmonic force of constant amplitude 6.8 MN.

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 dynamic linear/nonlinear sources of signal distortions** within the system for both harmonic and broadband command signals:
  - Amplitude/phase control (APC)
  - Adaptive harmonic cancellation (AHC)
  - 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)

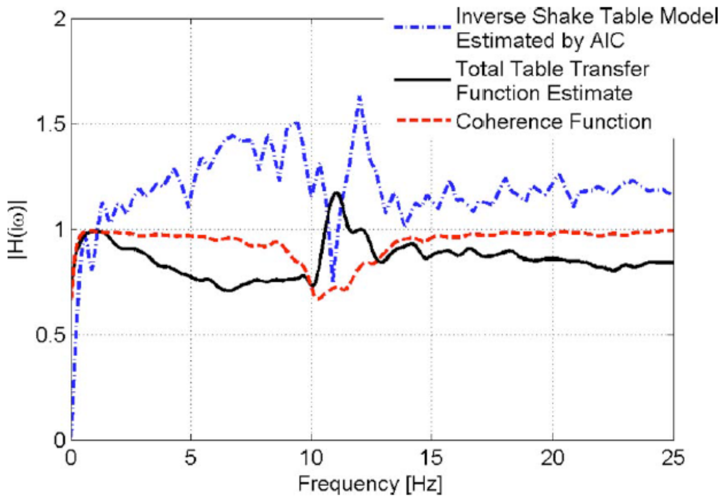


Courtesy of MTS
Systems Corporation

Tuning of LHPOST Controller (MTS 469D)

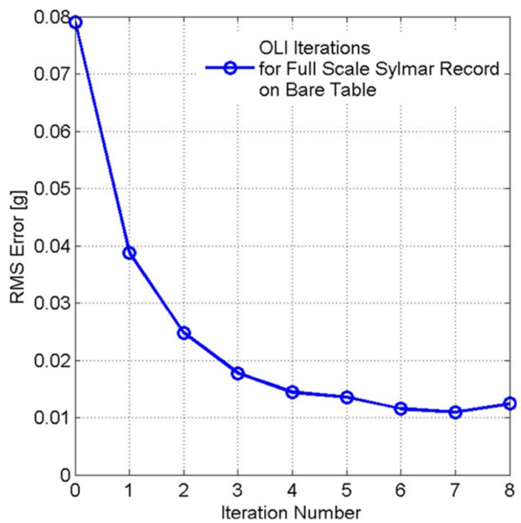
Tuning: Process of adjusting multiple control parameters (e.g., feedback and feedforward gains) and of preconditioning the input motion (through OLI) to optimize signal reproduction (tracking) capability of the shake table system.

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.

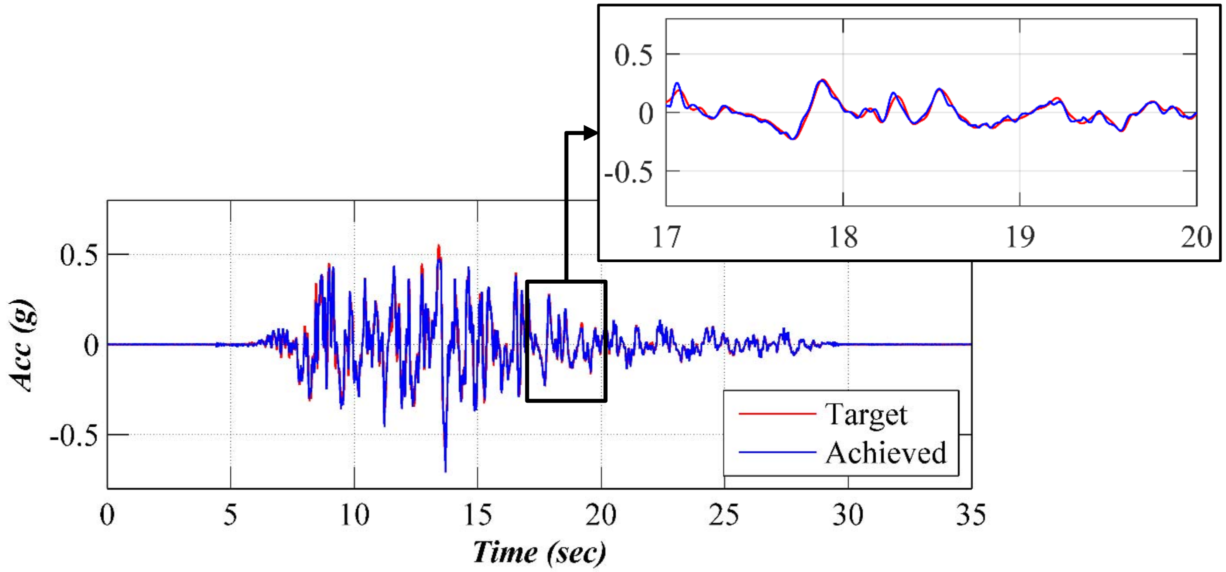


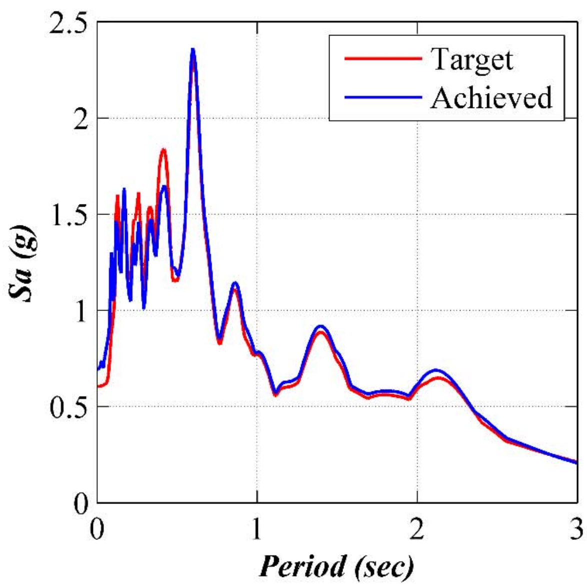
Step 2: Estimation of the inverse model of the plant using the adaptive inverse controller (AIC) technique.

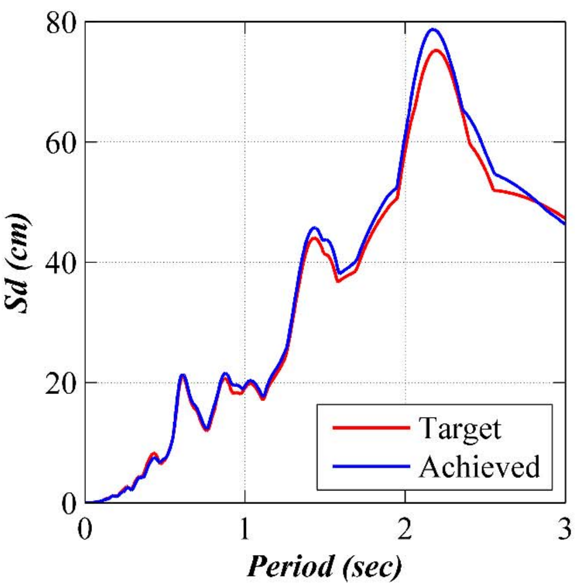
Step 3: Application of iterative time history matching technique called online iteration (OLI). The command input to the shake table controller (drive file) is repeatedly modified to optimize the match between the actual table motion and the desired/target motion (or reference signal).



Tracking Performance of NHERI@UCSD Shake Table



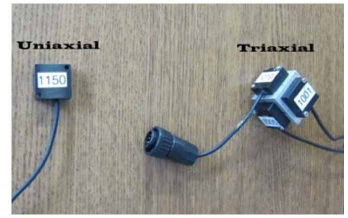




1994 Northridge Earthquake
Canoga Park (comp. 196)
Amplitude scaling: 1.55

Instrumentation for LHPOST

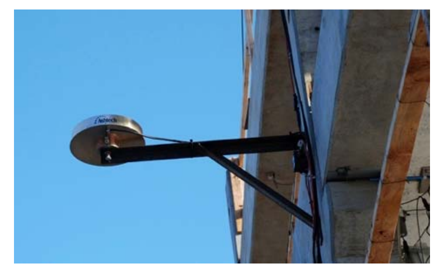
- **Data Acquisition**
  - **12 DAQ nodes with 64 channels each** sampling up to **500 sps** with A/D conversion at 16 bits



- 205 MEMS-based **Accelerometers**
- 142 Linear **Displacement Transducers**
- 119 **String Potentiometer** Displacement Transducers

- Strain Gages purchased per project as needed
- 4 **Load Jacks**

- 31 **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 4K, 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**
  - NHERI@UCSD is on social media (youtube, facebook, twitter)
- **Calibration Equipment** for Data Acquisition Systems and Sensors

Selected Set of Specimens tested on the LHPOST









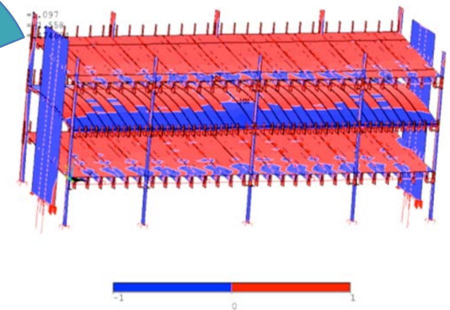




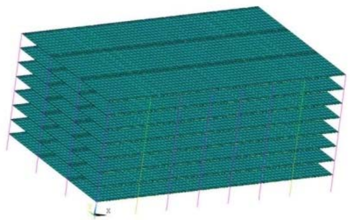
Integrated Experimental-Analytical Approach

Experimental Research
- Materials
- Structural components
- Structural systems

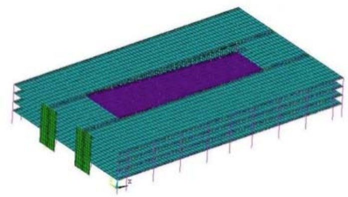
Computational Simulation
- Model development
- Model calibration
- Model validation



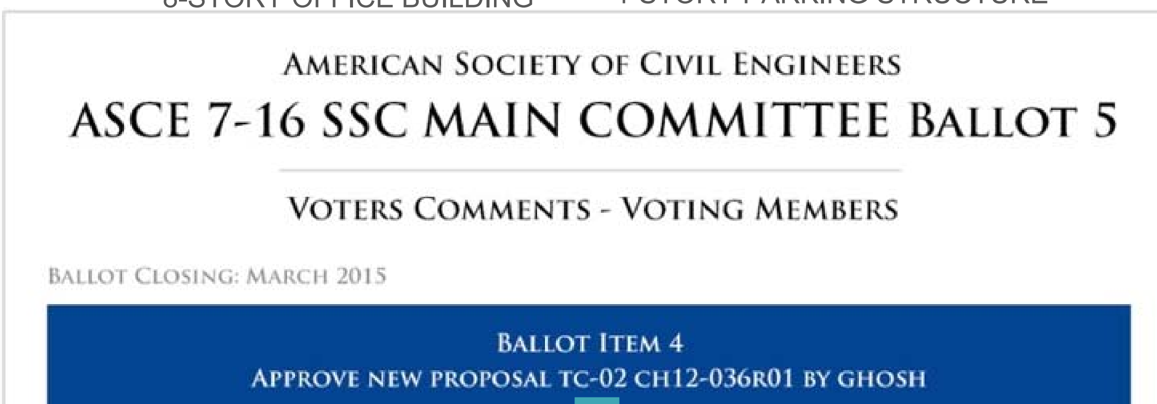
Design Provisions and Assessment Methods
- Development
- Verification through numerical simulation



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

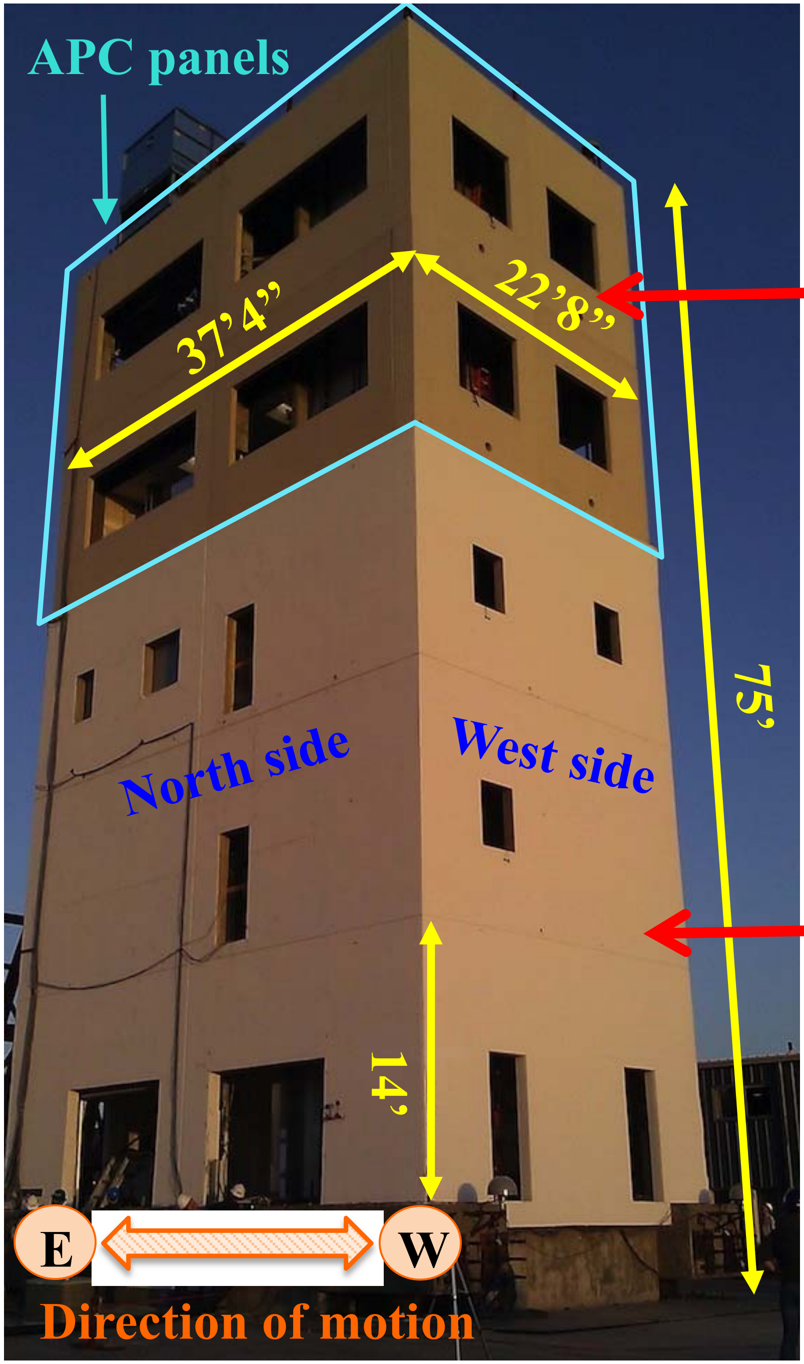
PI – Prof. Robert B. Fleischman, University of Arizona


NEES

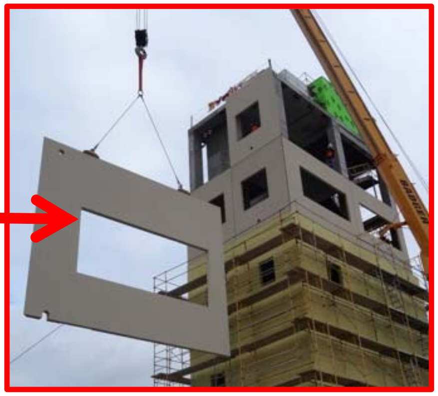
Full-scale Structural and Non-structural Building System Performance During Earthquakes

PI – Prof. Tara Hutchinson, UC San Diego

Exterior Facades

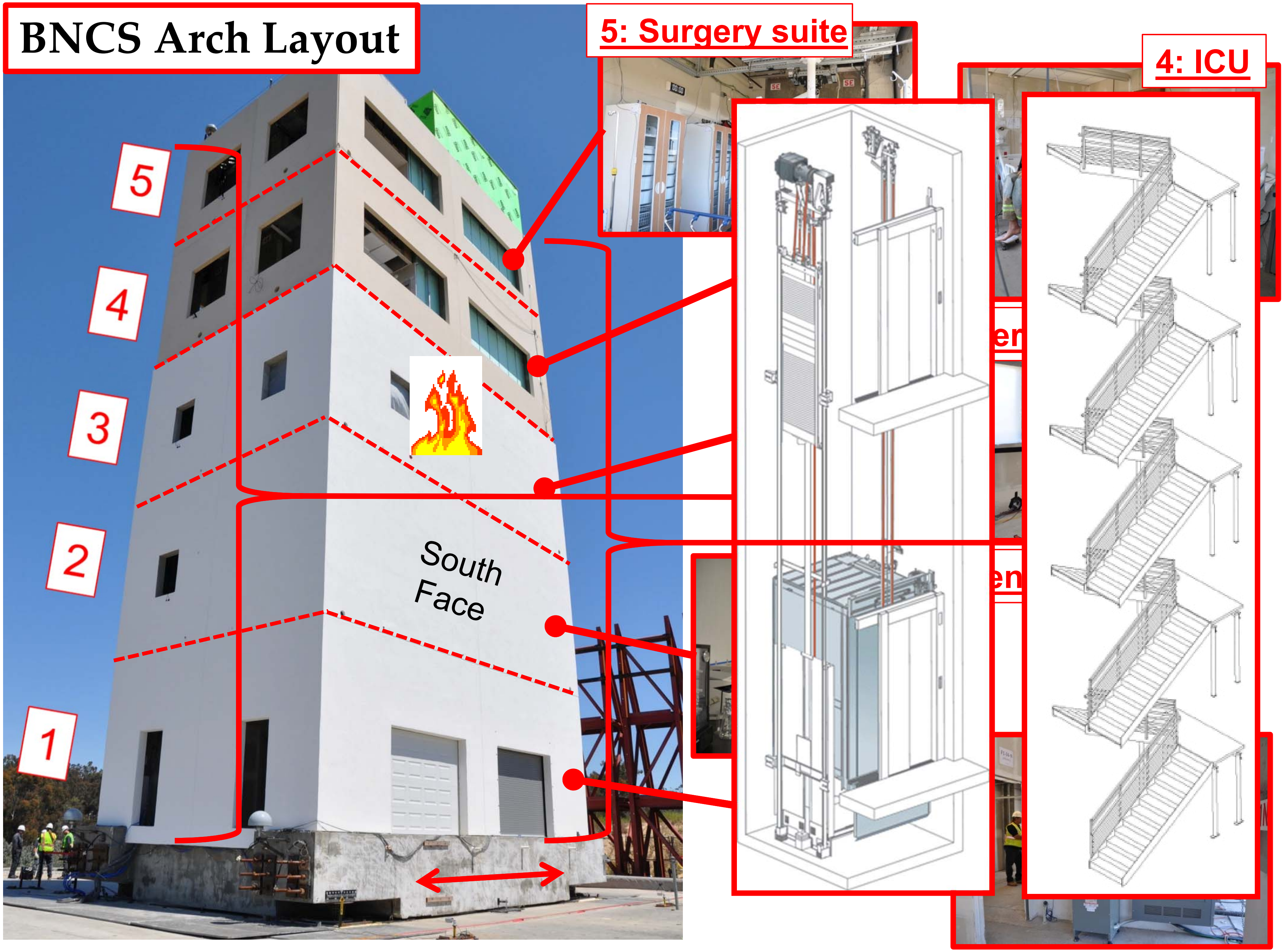


Architectural Precast Concrete Cladding



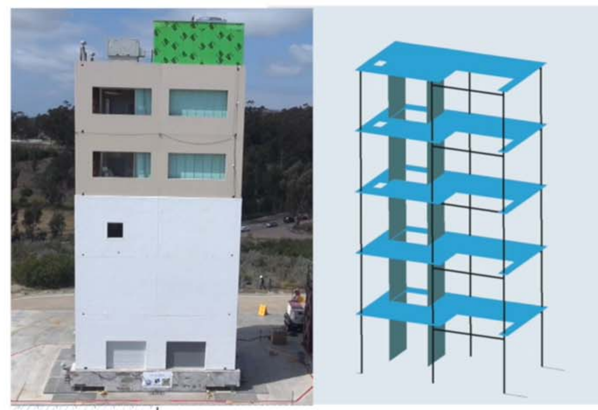
Balloon-framed metal stud+EIFS

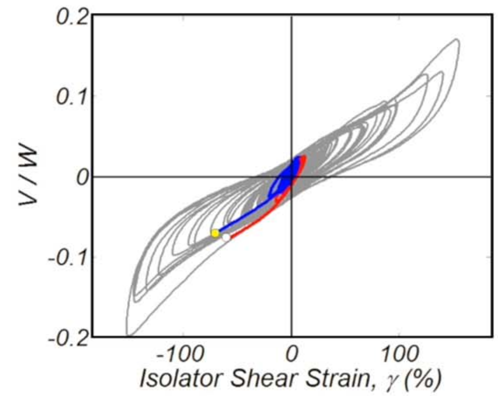
NW View

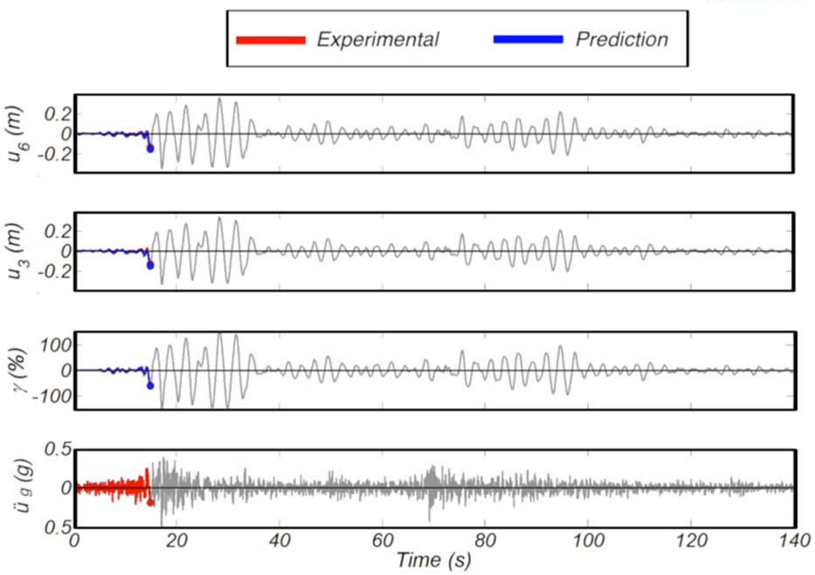


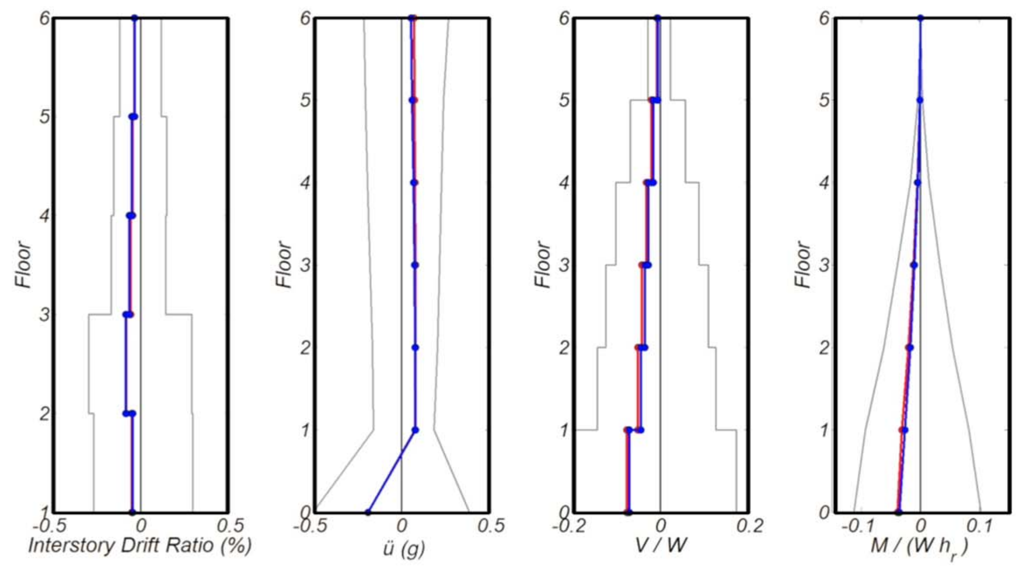
BNCS Arch Layout
5: Surgery suite
4: ICU
5
4
3
2
1
South Face

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

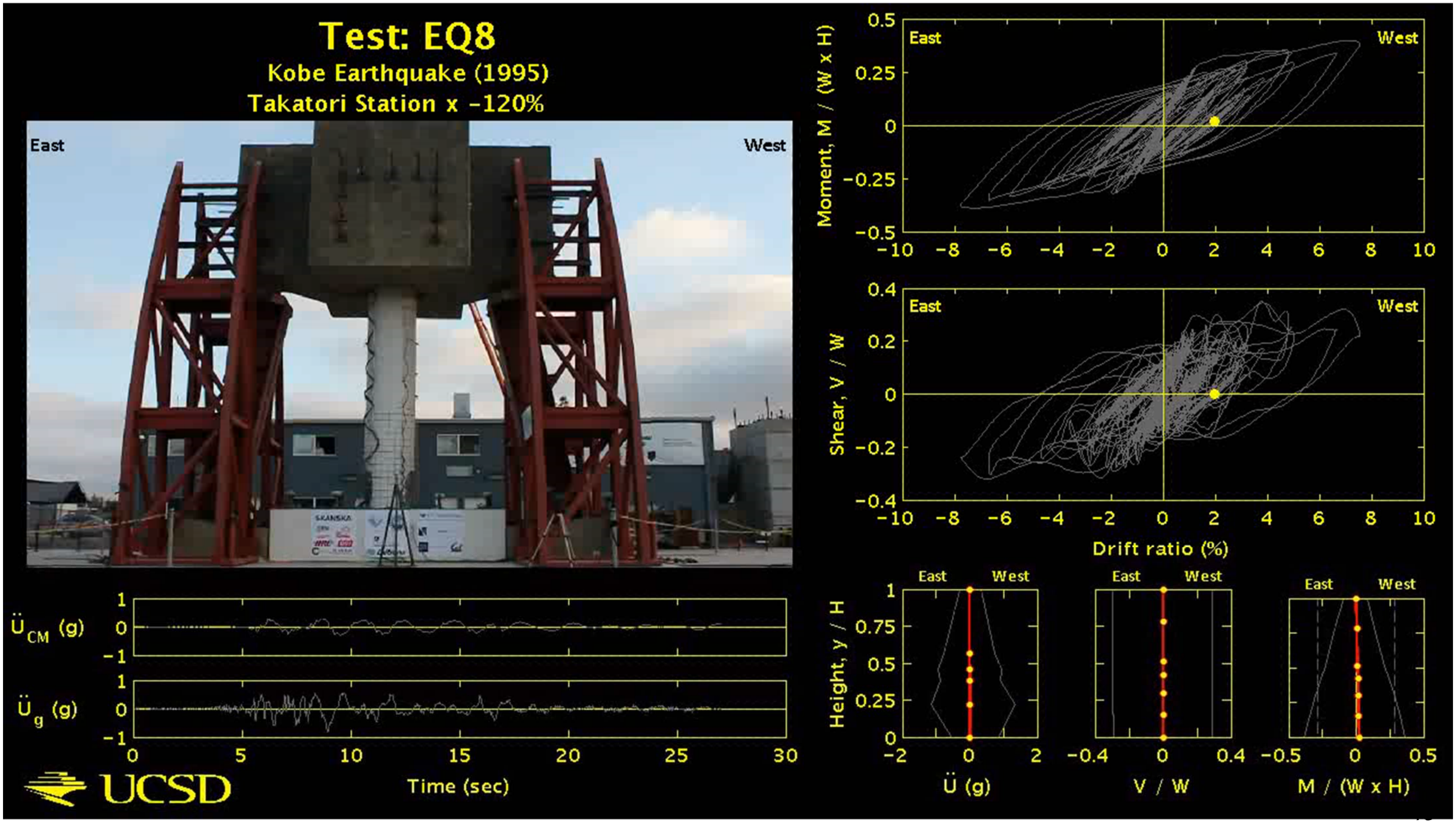
- Full-scale testing allowed to **validate the new evaluation techniques and higher performance levels** that were key to the success of the **San Francisco's mandatory soft story retrofit program** (6000 buildings in San Francisco undergoing the rigors of that program)

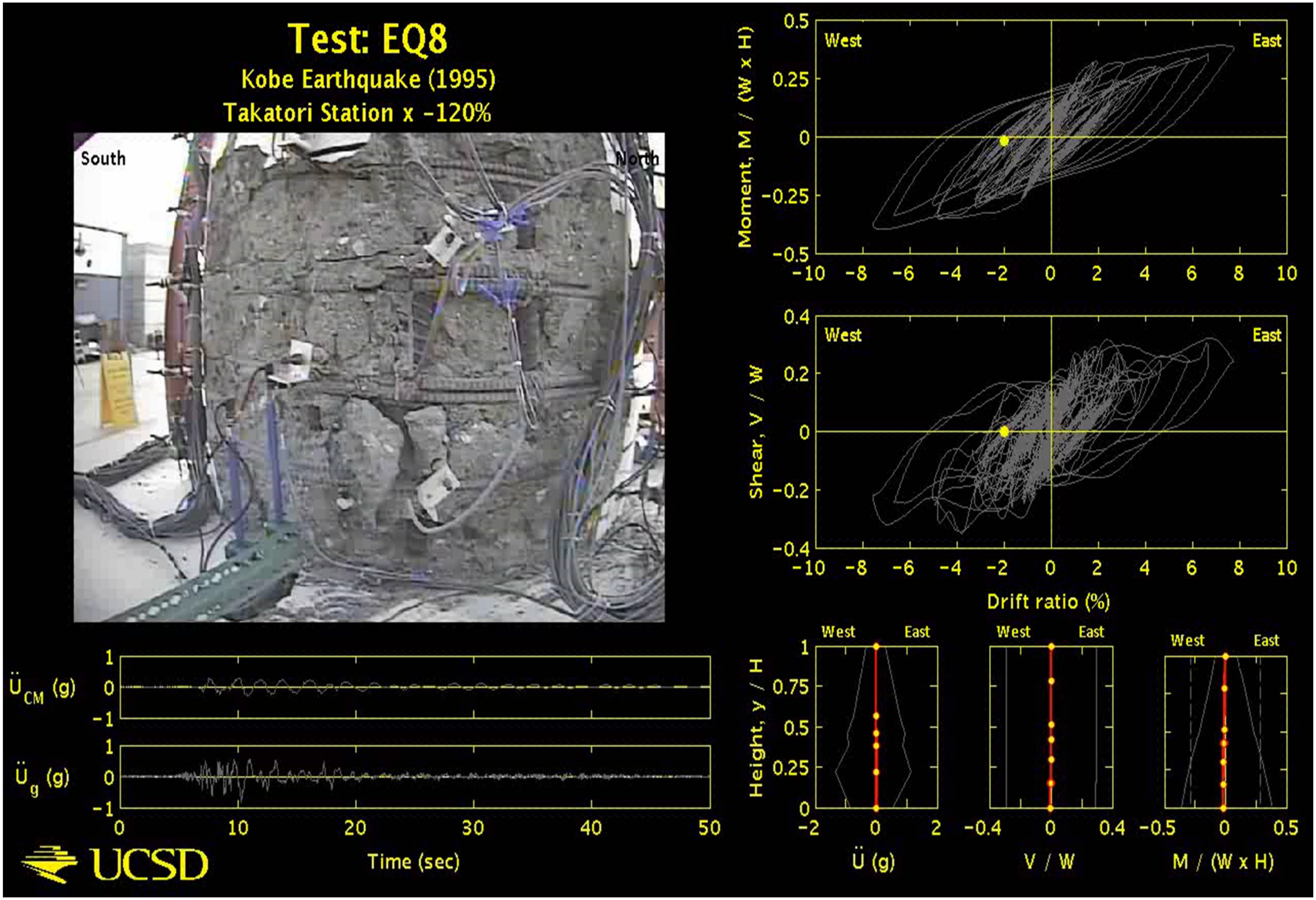
Seismic Risk Reduction for Soft-Story Woodframe Buildings

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 (%)
Height, y / H
Ü (g)
V / W
M / (W x H)
$\ddot{U}_{CM}$ (g)
$\ddot{U}_g$ (g)
Time (sec)
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

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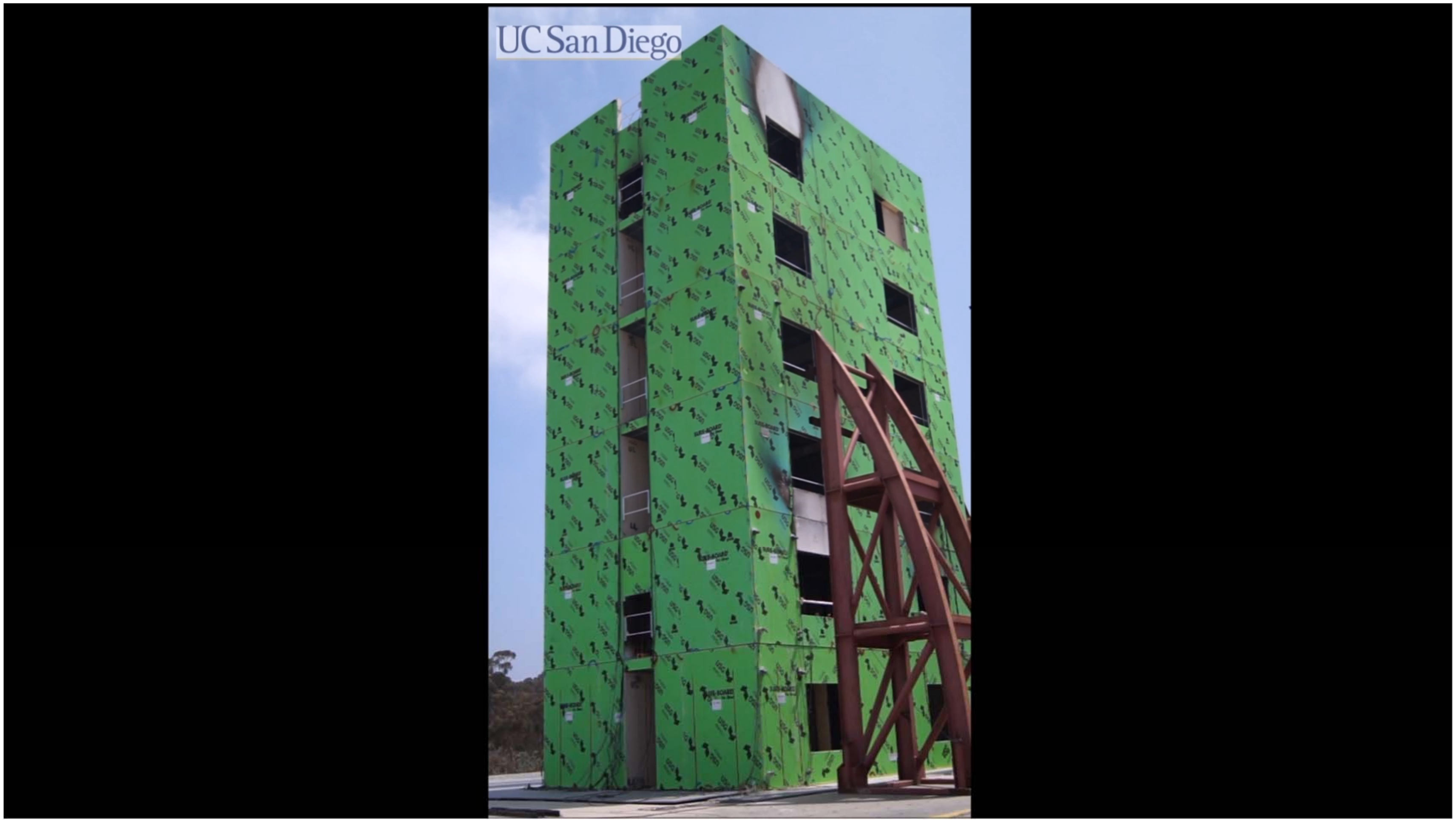
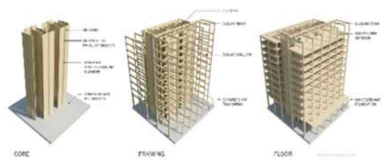


Collaborative Research: A Resilience-based Seismic Design Methodology for Tall Wood Buildings

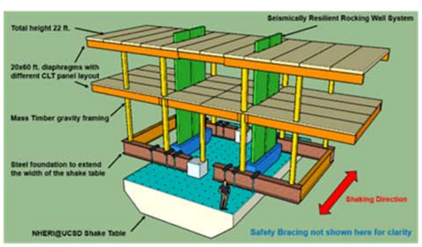
NHERI TallWood

Nheritallwood.mines.edu spei@mines.edu

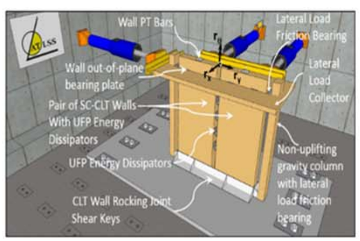


Define Tall Wood Archetypes

Investigative testing at system level

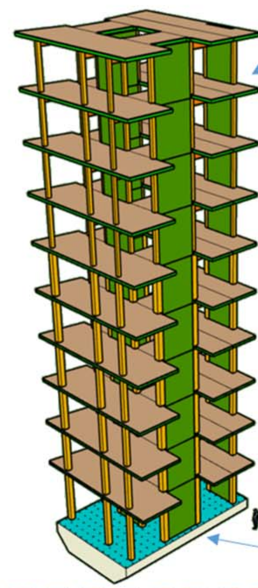


Two-story test at NHERI@UCSD 2017 Summer

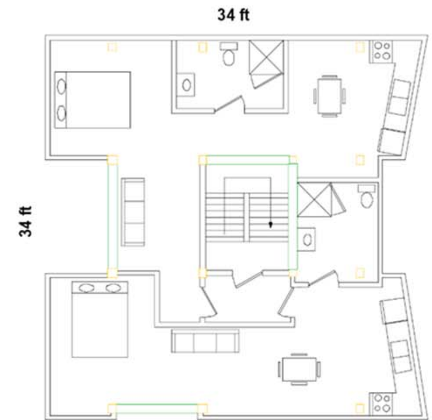


Assembly test at NHERI@Lehigh 2019

Full-scale 10-story validation Test (2021)



Mixed-Use building w/ CLT rocking wall lateral system



UCSD Shake Table

Seismic R & D

(2018~2020)

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

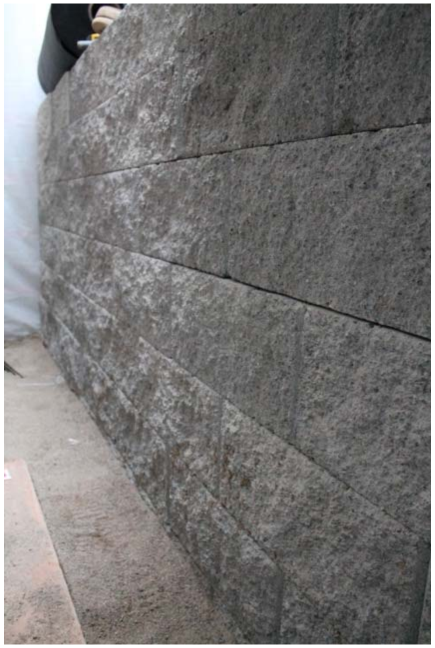
Liquefaction-Induced Lateral Spread Displacements and Soil-Pile Interaction in Multi-Layer Soil Strata

PI – Prof. Ahmed Elgamal, UC San Diego

Seismic Performance Tests of Full-Scale Retaining Walls

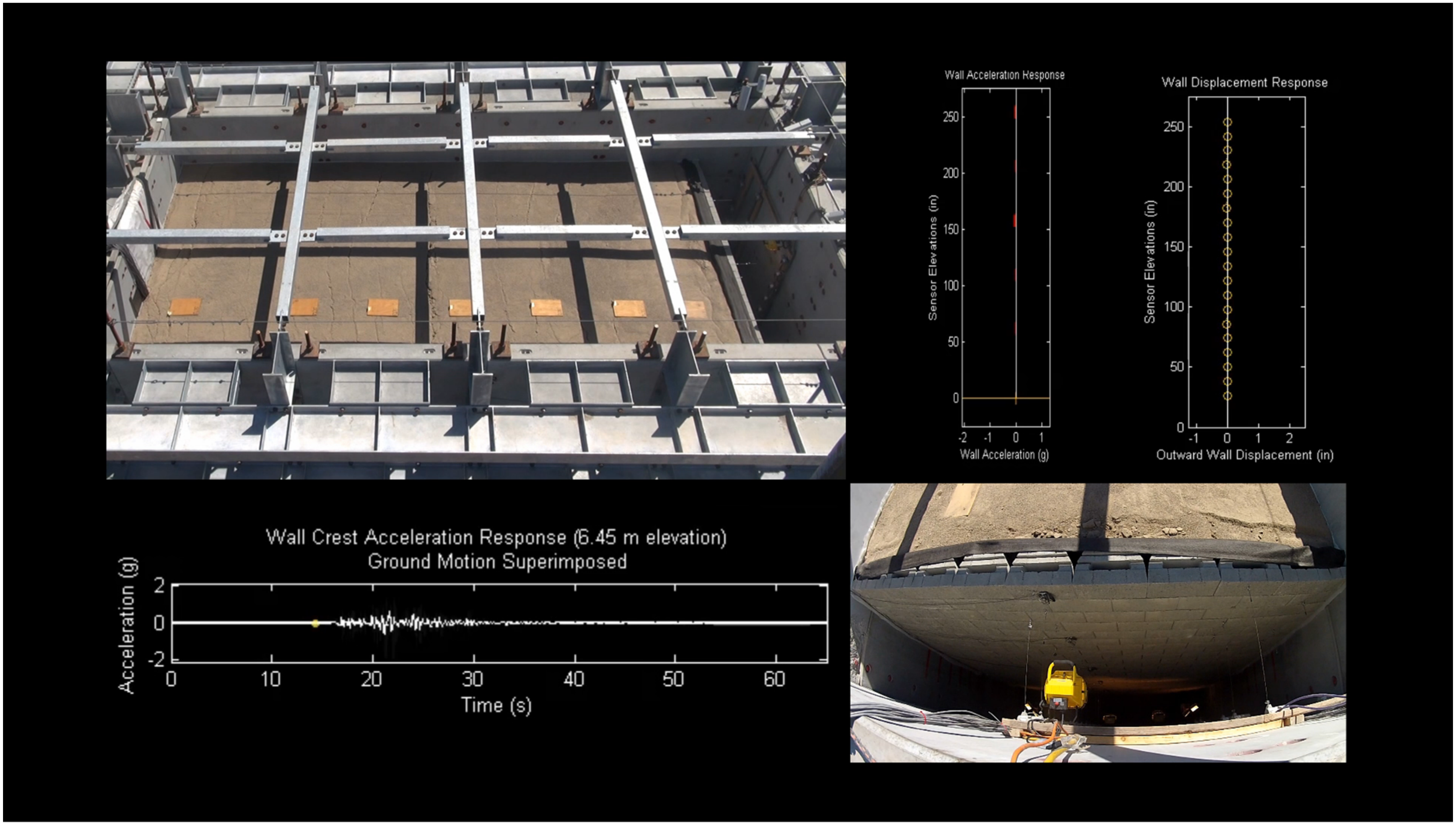
PI – Prof. Patrick Fox UCSD

22 ft. Above Table Elevation



Earthquake Performance of Full-Scale Reinforced Soil Walls

PI – Prof. Patrick Fox UCSD



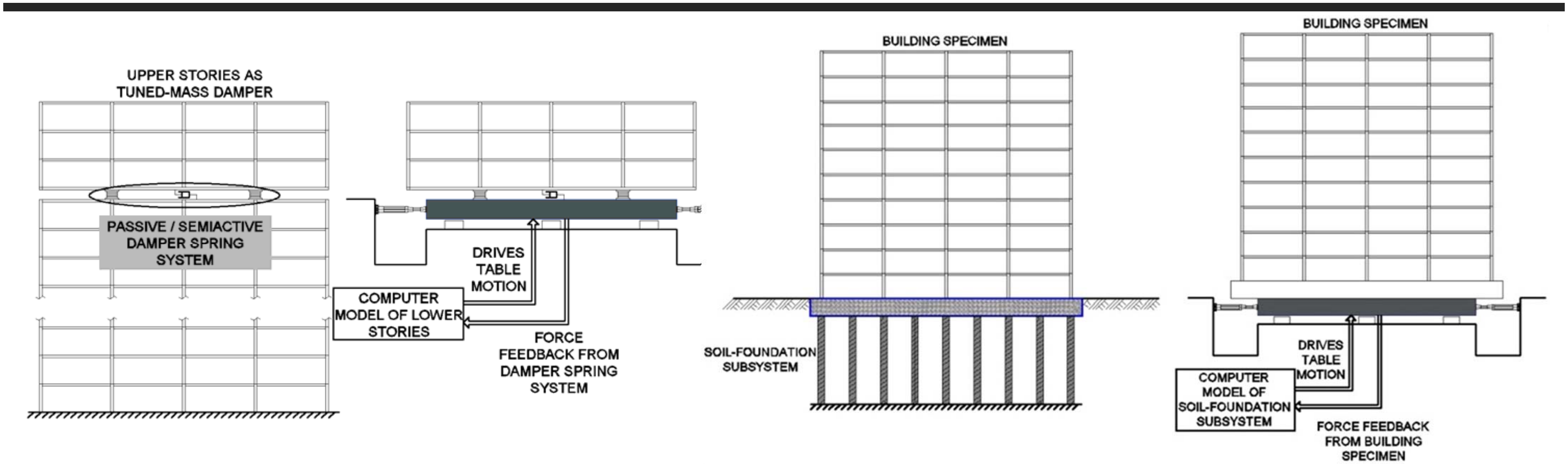
Soil-Foundation-Structure Interaction Test

PI – Prof. Marios Panagiotou, UC Berkeley

Staging Facility

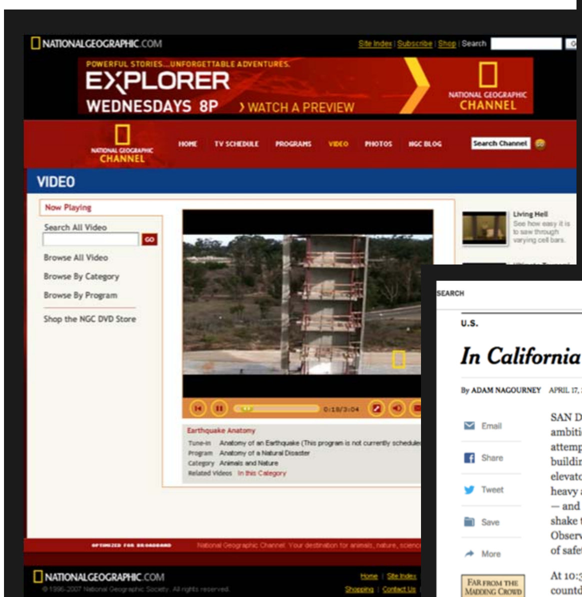
Hybrid Shake Table Testing

- **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



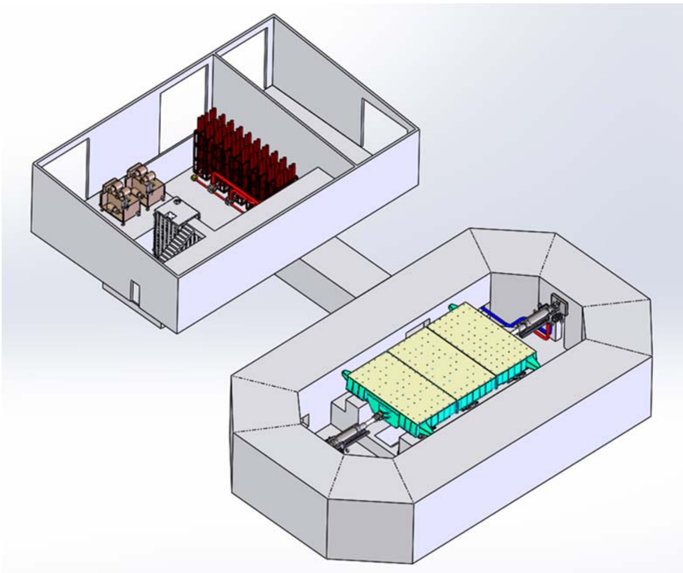
Broad Public Dissemination

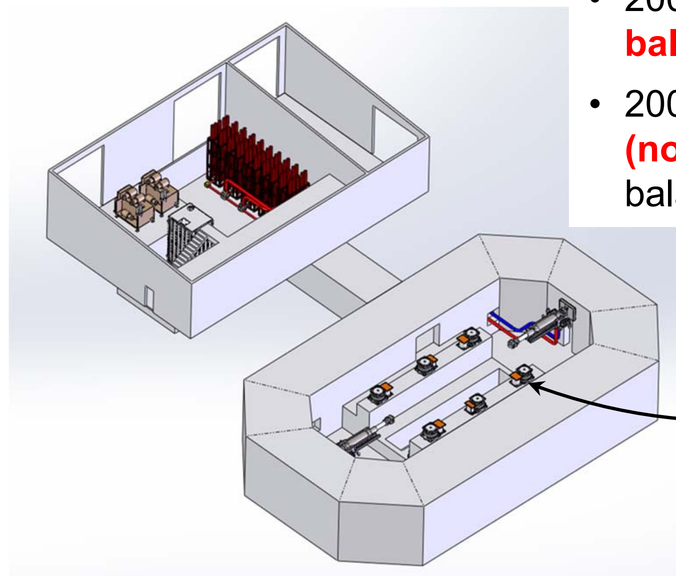
- Jacobs School of Engineering Communications and Media Relations
- International, National, Regional, and Local Exposure



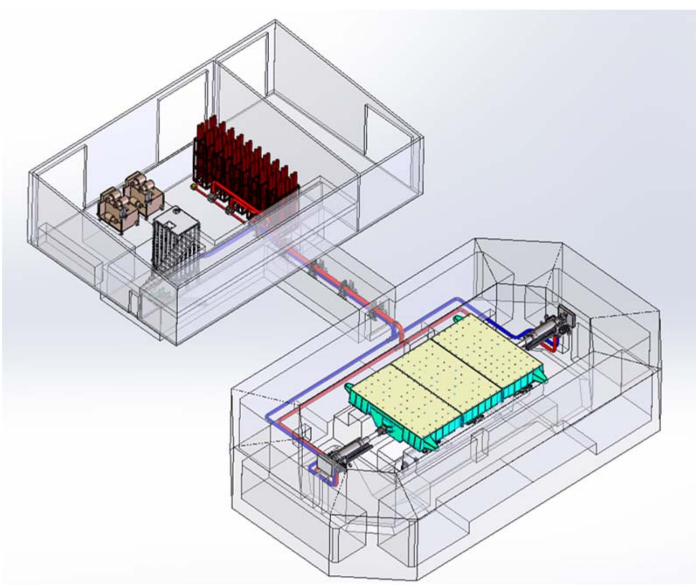
Six Degree-of-Freedom (6-DOF) Upgrade of LHPOST

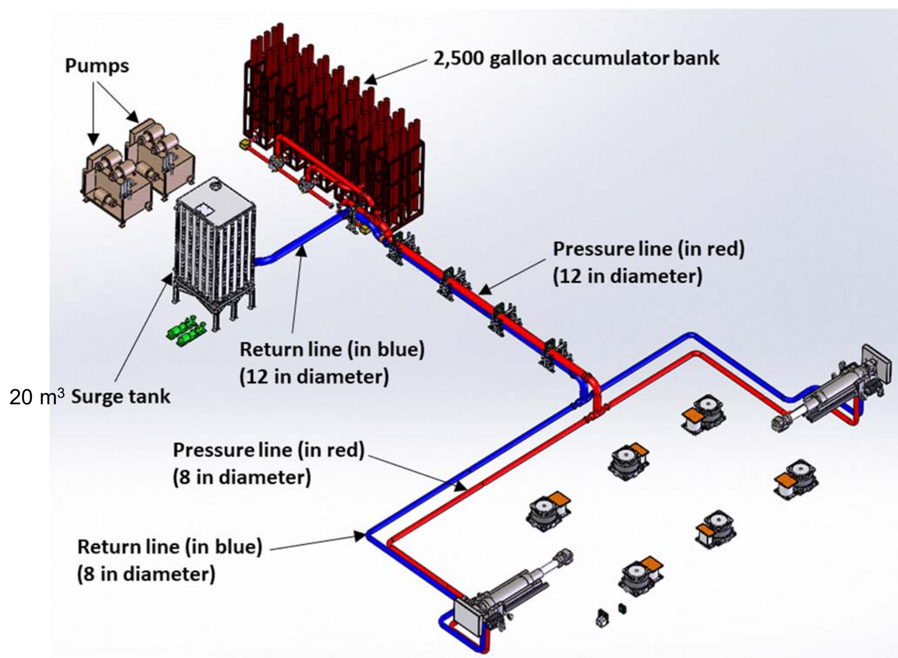
Hydraulic Power System for 1-DOF LHPOST



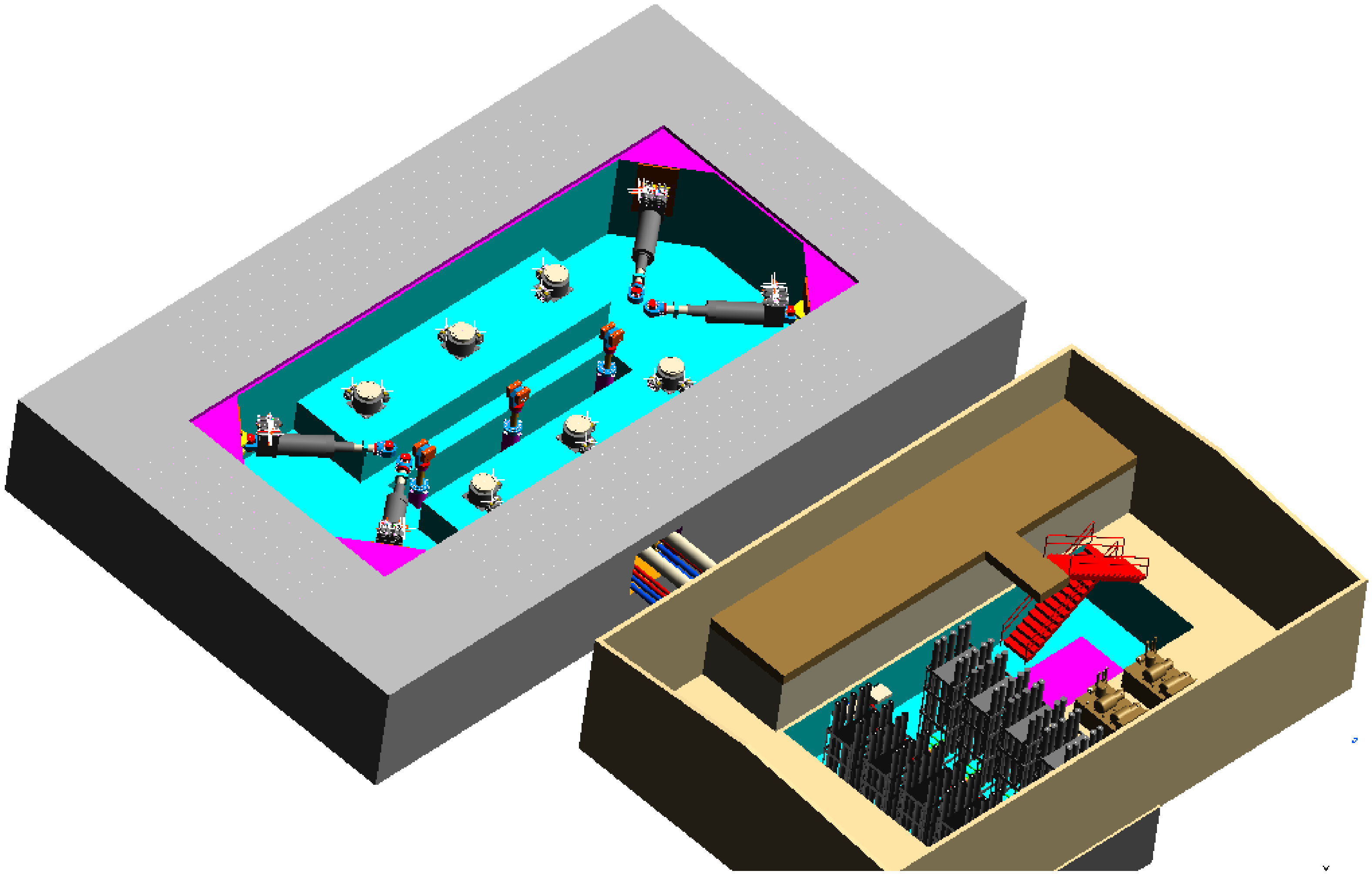


- 2004-2009 **Pressure balanced bearings**
- 2009-current **Actuators (non-ported)** with Pressure balanced bearing

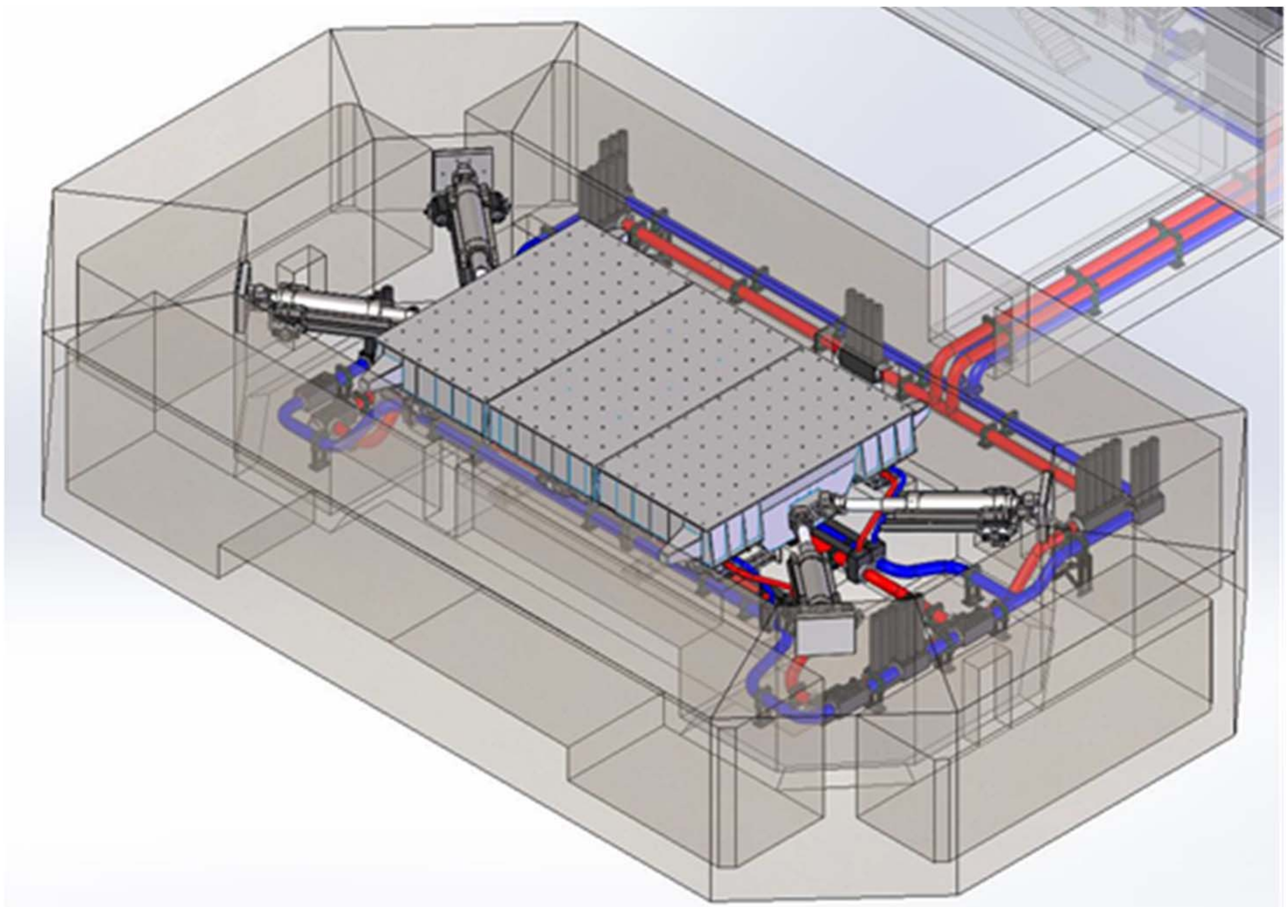




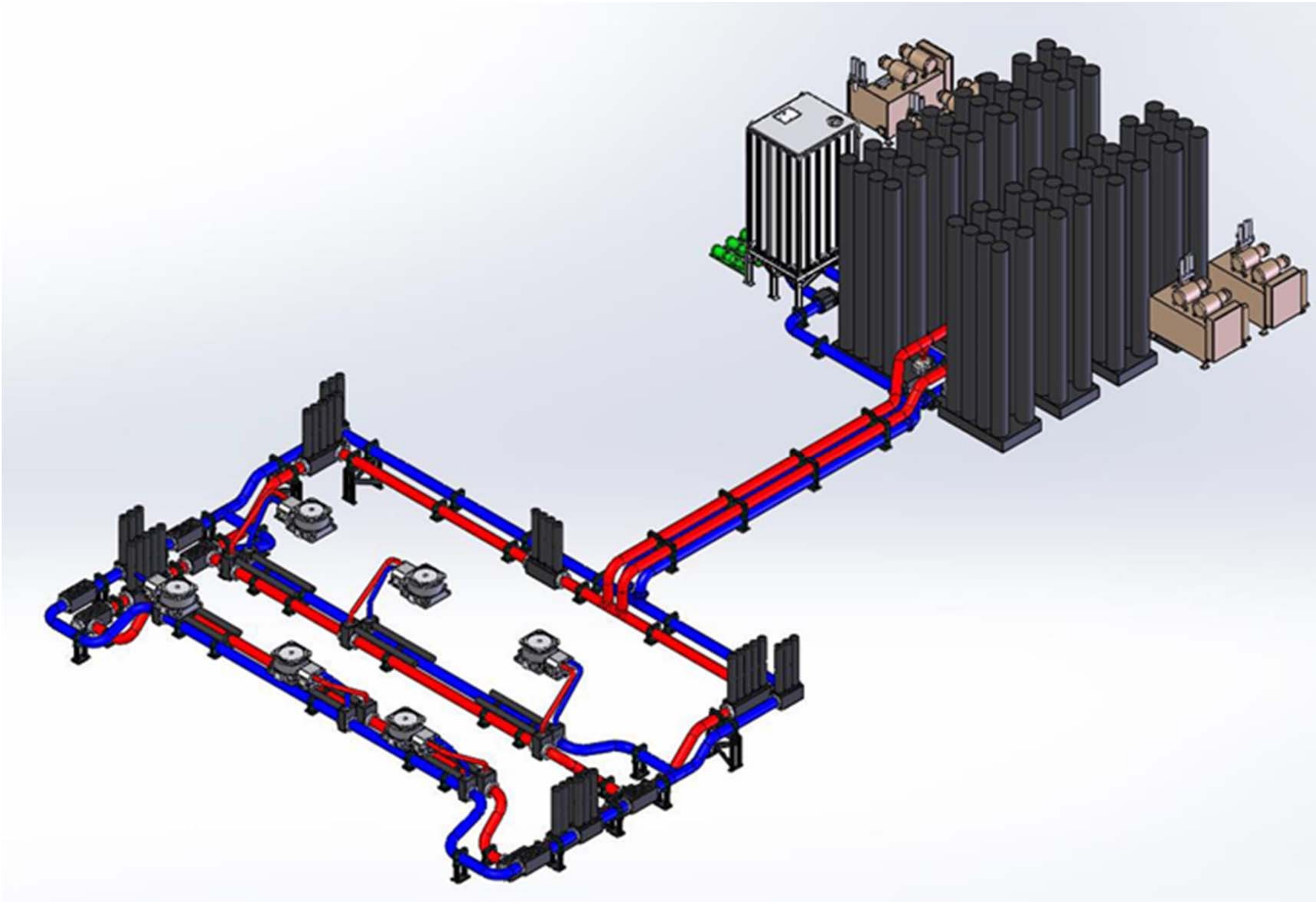
Upgrade to 6-DOF Configuration



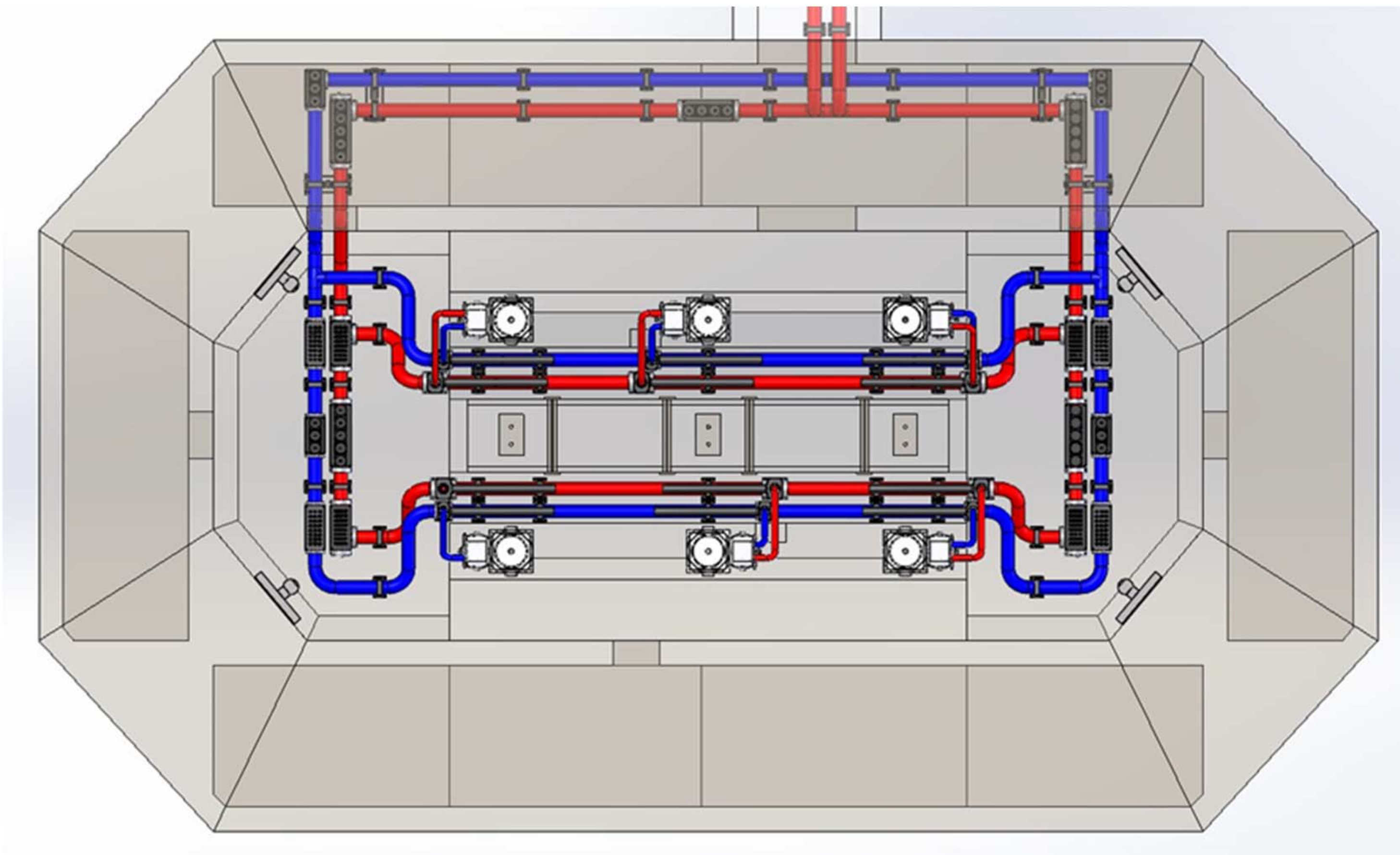
Upgrade to 6-DOF Configuration



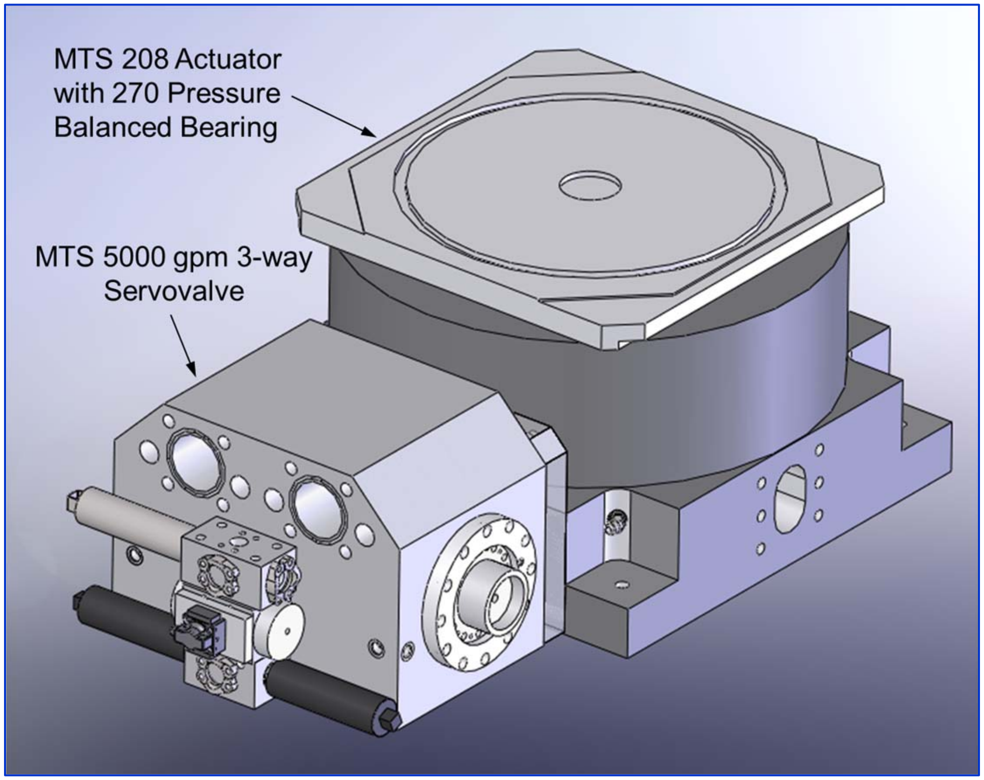
Upgrade to 6-DOF Configuration

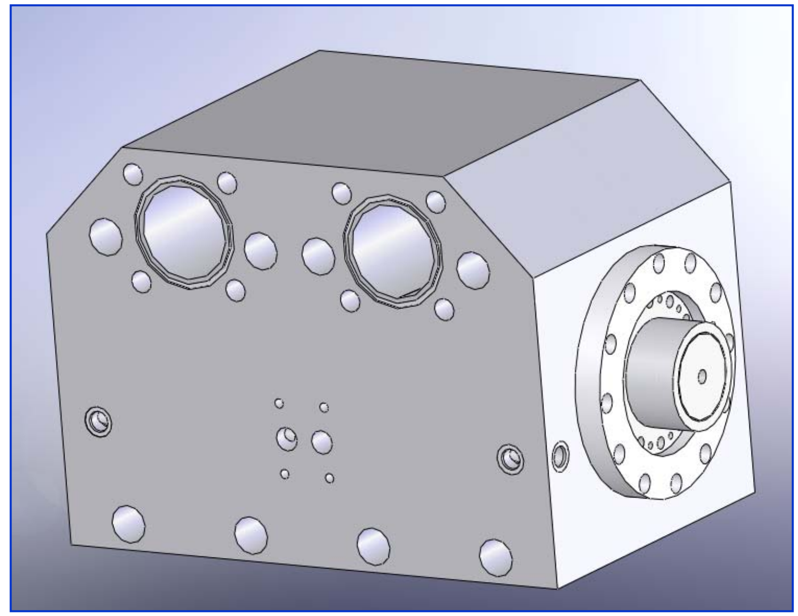


Upgrade to 6-DOF Configuration



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

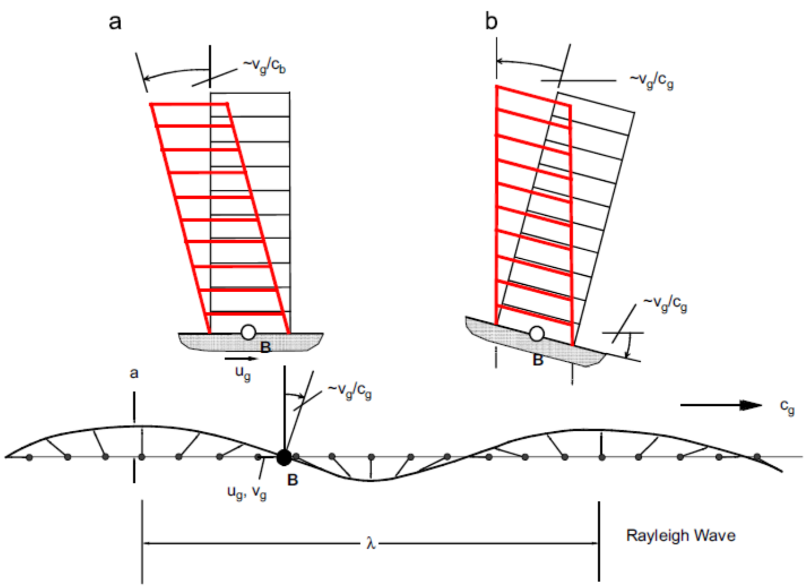
Table loaded with rigid payload of 1,100 kips (5 MN)

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.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