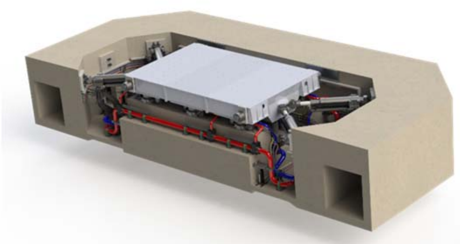
National Science Foundation

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

UC San Diego
JACOBS SCHOOL OF ENGINEERING
Structural Engineering

Joint Academia-Industry NHERI@UC San Diego Workshop



September 21-22, 2020
University of California, San Diego

General Housekeeping Items

- Workshop slides can be downloaded from Google Drive (link is provided in the agenda)
- For any problems and technical difficulties, please contact: Dr. Koorosh Lotfizadeh (E-mail: klotfiza@ucsd.edu)

Workshop Objectives

- Promote academia-industry collaborations and identify high priority research needs, which would benefit from the newly upgraded NHERI@UC San Diego Experimental Facility.
- Disseminate information on the use of the NHERI@UC San Diego Experimental Facility to conduct state-of-the-art research and experimentation in natural hazards mitigation.
- Identify and formulate grand challenge research needs to advance the science, technology and practice in earthquake disaster mitigation and prevention and to improve seismic design codes and standards.
- Provide information for preparing competitive NSF research proposals which use the NHERI@UC San Diego facility.
- Identify and develop opportunities to utilize the NHERI@UC San Diego Experimental Facility.
- Brainstorm on example uses of the facility given grand challenge discussions.

Workshop Program – Monday

Day 1 (Sept 21, 2020): Facility Capabilities and Keynote Presentations

8:00 – 8:15am	Registration, speaker check-in, and coffee
8:15 – 8:30am	Welcome, introduction, workshop schedule (Prof. Joel Conte, UC San Diego PI)
8:30 – 9:30am	NHERI@UC San Diego Facility description and capabilities (Prof. Joel Conte)
9:30 – 10:00am	Highlights of recent projects (Prof. Jose Restrepo, UC San Diego Senior Personnel and Prof. Tara Hutchinson, UC San Diego Co-PI)
10:00 – 10:15am	Coffee break
10:15 – 10:45am	Keynote Presentation # 1: Building structures (Prof. John van De Lindt, Colorado State University)
10:45 – 11:15am	Keynote Presentation # 2: Geostructures (Dr. Sissy Nikolaou, Assistant Vice President and Principal at WSP)
11:15 – 11:45am	Keynote Presentation # 3: Bridge structures (Dr. Anthony Sanchez, Principal Bridge Engineer, SYSTRA IBT)
11:45 – 12:15pm	Keynote Presentation # 4: Lifelines and Utilities (Dr. Craig Davis, C A Davis Engineering, formerly LADWP resilience program manager)
12:15 – 12:30pm	Concluding remarks (Prof. Joel Conte)
2:00 – 4:00pm	Advising on future projects (office hours); see agenda for availability and zoom links

Workshop Program – Tuesday

Day 2 (Sept 22, 2020): Breakout Sessions and Discussion

8:00 – 8:15am	Registration, speaker check-in, and coffee
8:15 – 8:30am	Virtual Walkthrough of the LHPOST6 construction site
8:30 – 9:00am	Keynote Presentation # 5: Project Preplanning and technology transfer (Mr. William Holmes, retired from Rutherford and Chekene in San Francisco, NHERI Technology Transfer Committee Chair)
9:00 – 9:15am	Introduction to breakout sessions (Prof. Joel Conte)
9:15 – 11:00am	Breakout sessions, 10 groups
11:00 – 11:15am	Coffee break
11:15 – 12:30am	Summary of breakout sessions and general discussion
12:30 – 12:45am	Concluding remarks (Prof. Joel conte)
2:00 – 4:00pm	Advising on future projects (office hours); see agenda for availability and zoom links

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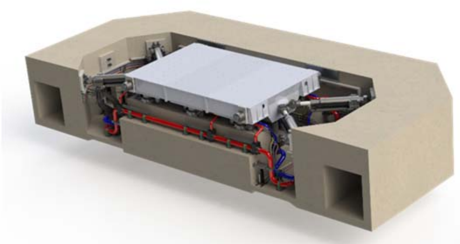
NHERI@UC San Diego: Facility Description and Capabilities

Joel Conte, Professor

University of California, San Diego



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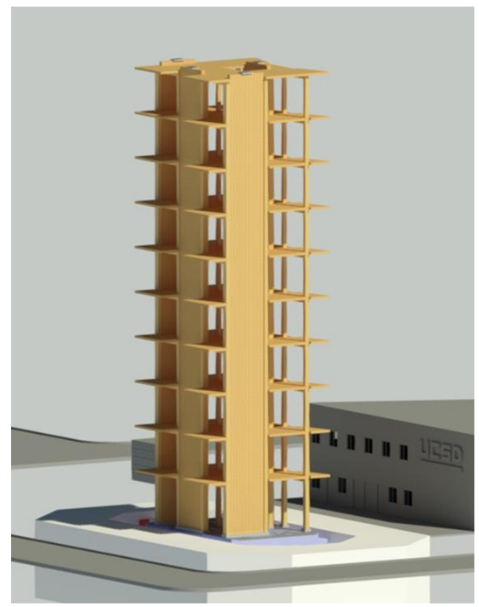
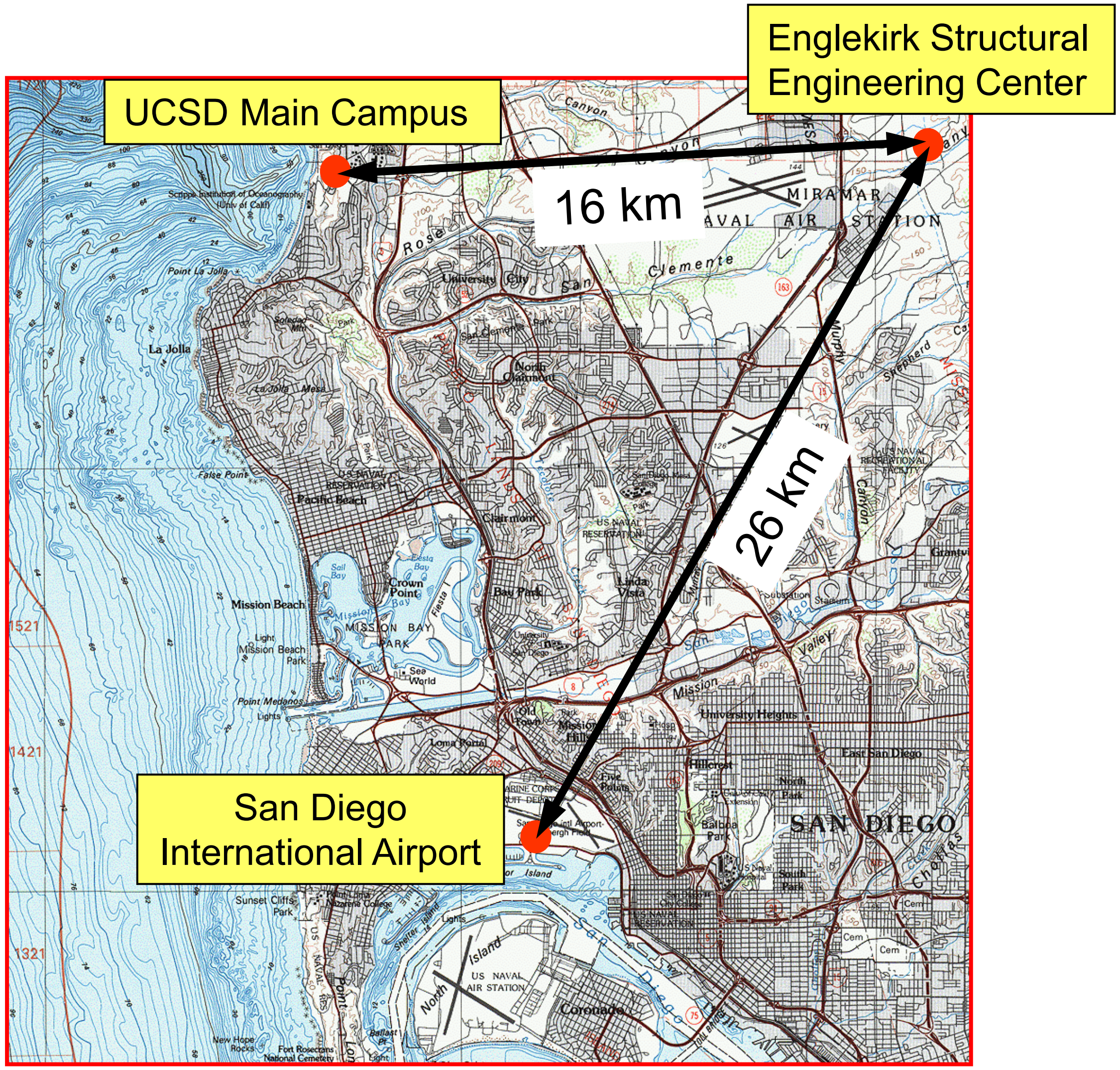


Outline

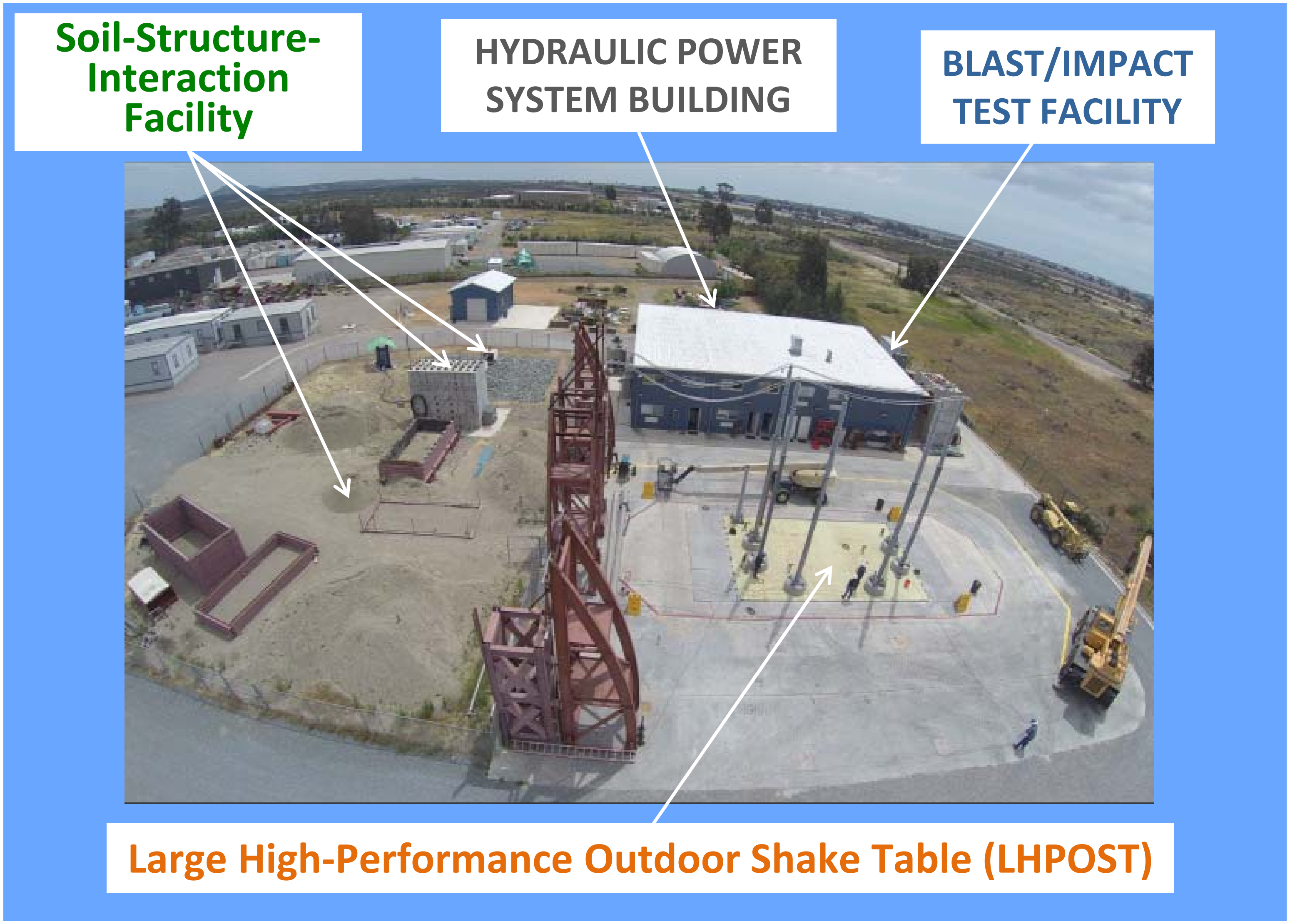
- Overview of NHERI@UC San Diego Large High-Performance Outdoor Shake Table (LHPOST) Experimental Facility
  - Description of Facility
  - Performance Characteristics
  - Capabilities and Limitations
- A Few Large-Scale Shake Table Tests Performed on the NHERI@UC San Diego Shake Table
- Current Six Degree-of-Freedom (6-DOF) Upgrade of LHPOST into LHPOST6
- New Research Opportunities Made Possible by the LHPOST6

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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Raj Nathan
President

15-12065

NHERI@ UCSan Diego

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

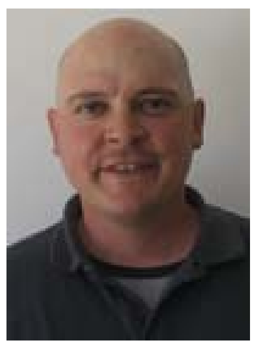
Benson Shing
Co-PI
Site Operations

Lelli Van Den Einde
Co-PI
Education and
Community Outreach

José Restrepo
Senior Personnel

Enrique Luco
Senior Personnel

Koorosh
Lotfizadeh
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@UC San Diego EF

- 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**.

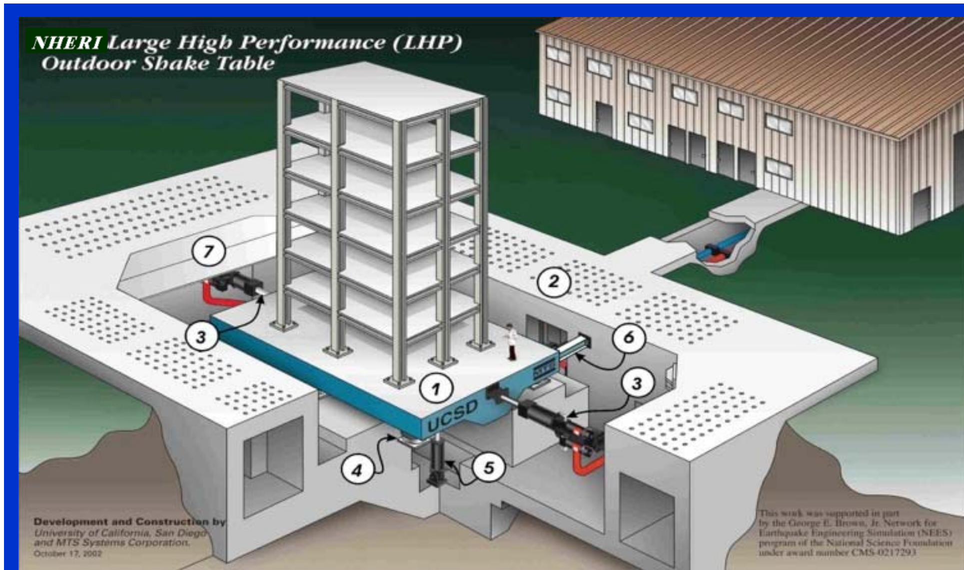
  (2) Experimental data to support the **development, calibration and validation of high-fidelity physics-based computational models** of structural/geotechnical/soil-foundation-structural systems that will **progressively shift the current reliance on physical testing to model-based simulation** for the 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 (2004 – 2019):
  - Reinforced concrete buildings and bridge column
  - Precast concrete parking structure
  - Unreinforced and reinforced masonry building structures
  - Metal and light-steel building structures
  - Woodframe/timber dwellings and buildings
  - Wind turbine
  - Soil retaining walls
  - Underground structures (deep and shallow)

Large High-Performance Outdoor Shake Table (LHPOST)

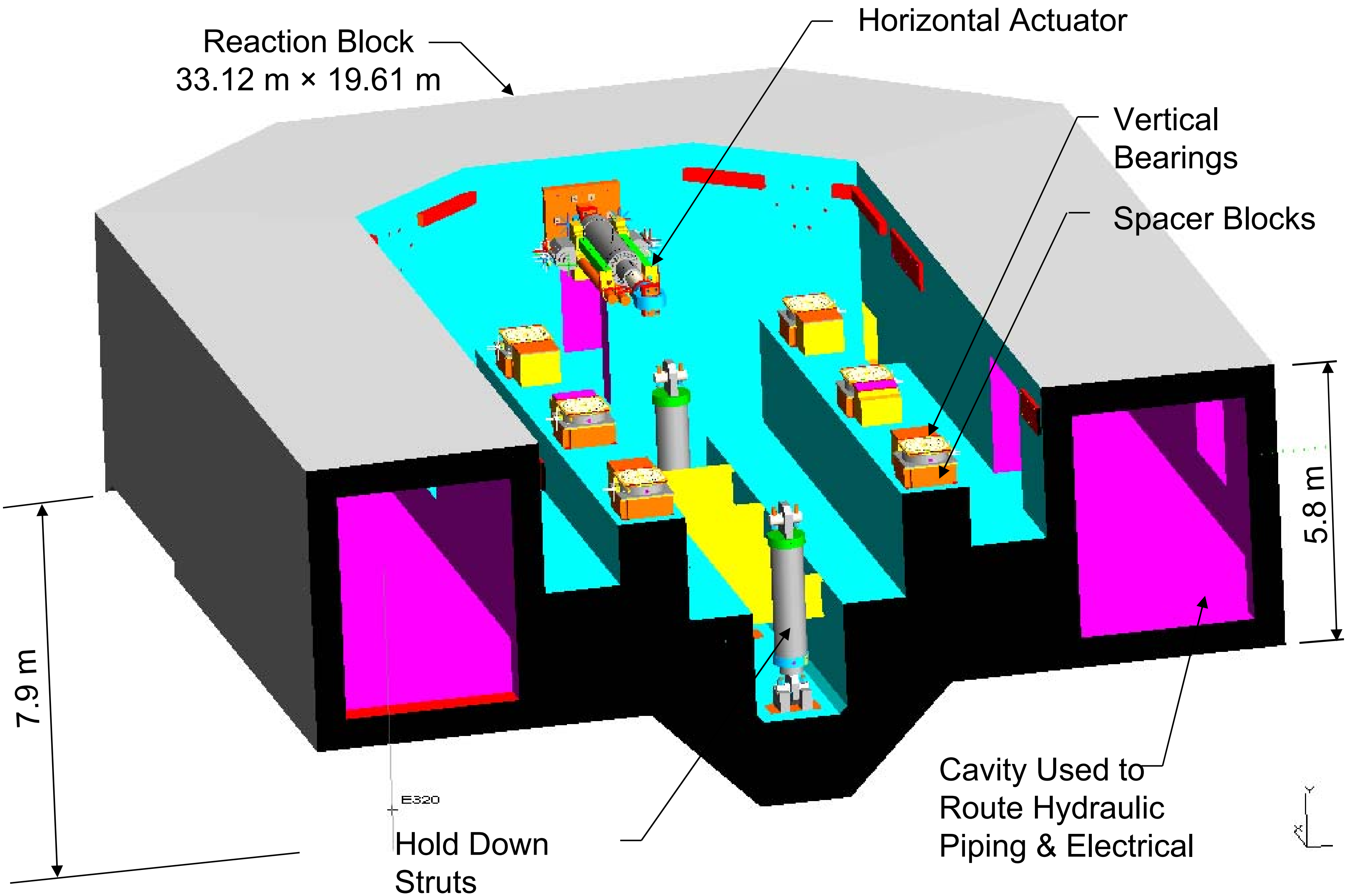


Performance Characteristics in Current 1-DOF Configuration	
Designed as a 6-DOF shake table, but built as a 1-DOF system to accommodate funding available	
Stroke	**± 0.75m**
Platen Size	40 ft × 25 ft (12.2 m × 7.6 m)
Peak Velocity	**1.8 m/sec**
Peak Acceleration	4.7g (bare table condition); 1.2g (4.0MN/400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

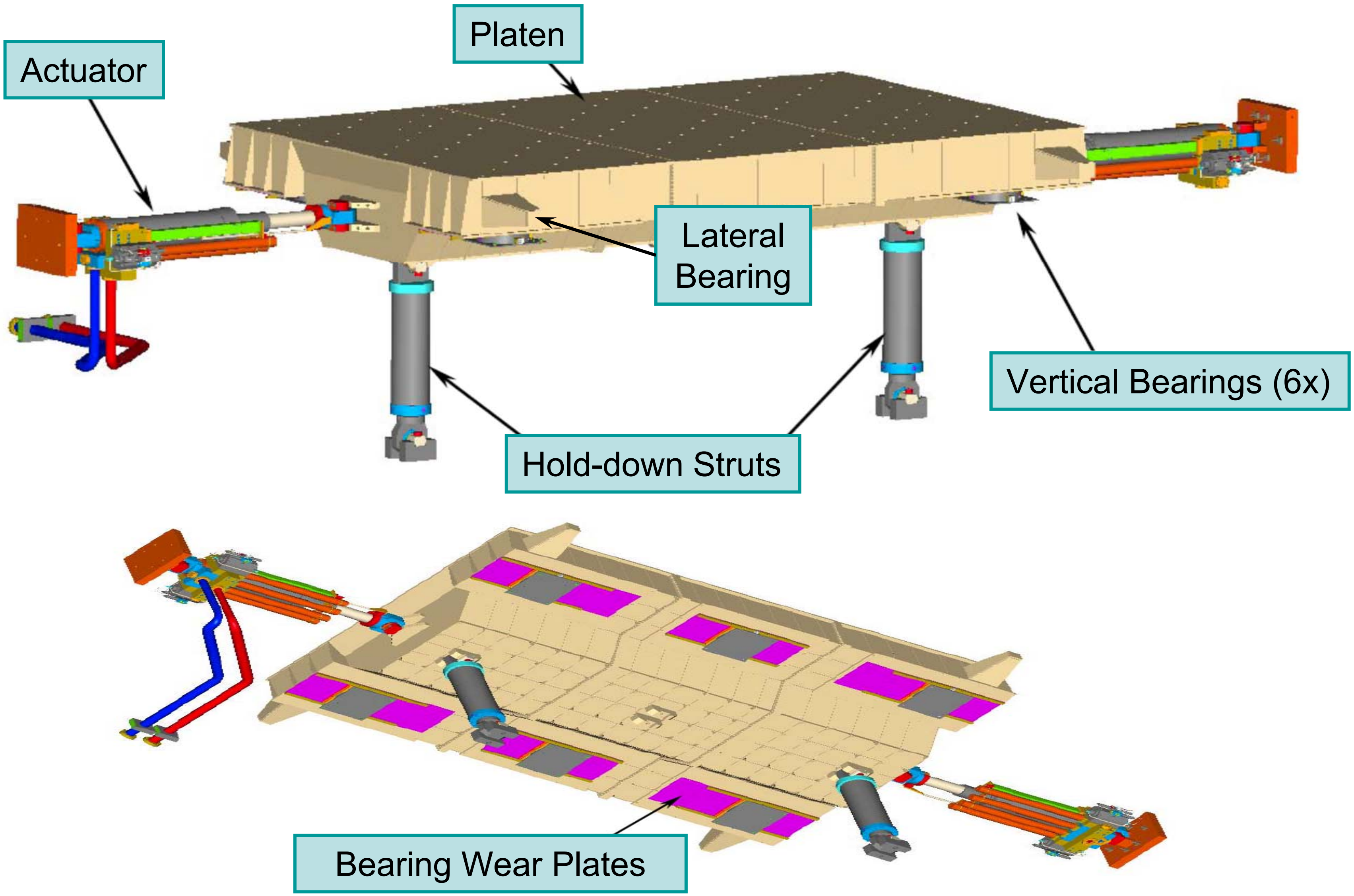
Capabilities/Provisions of the NHERI@UC San Diego EF

- **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

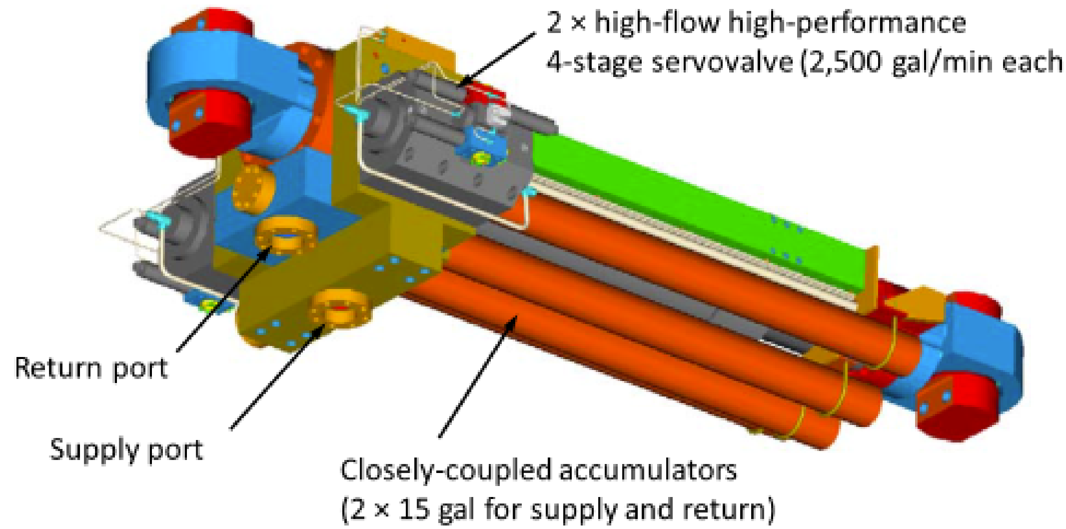


Hold-down Struts

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

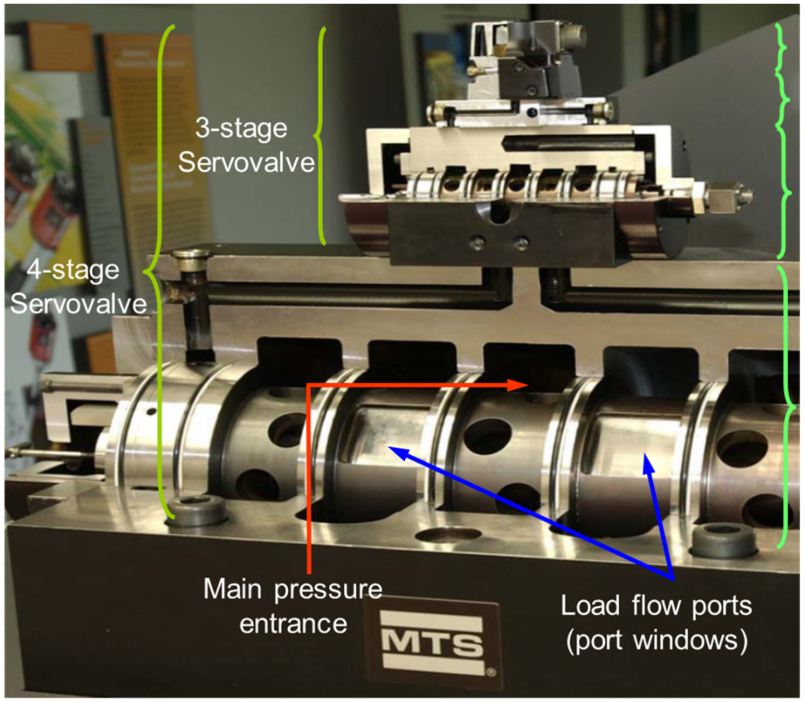
Horizontal Actuators

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



High-Flow High-Performance Servovalves

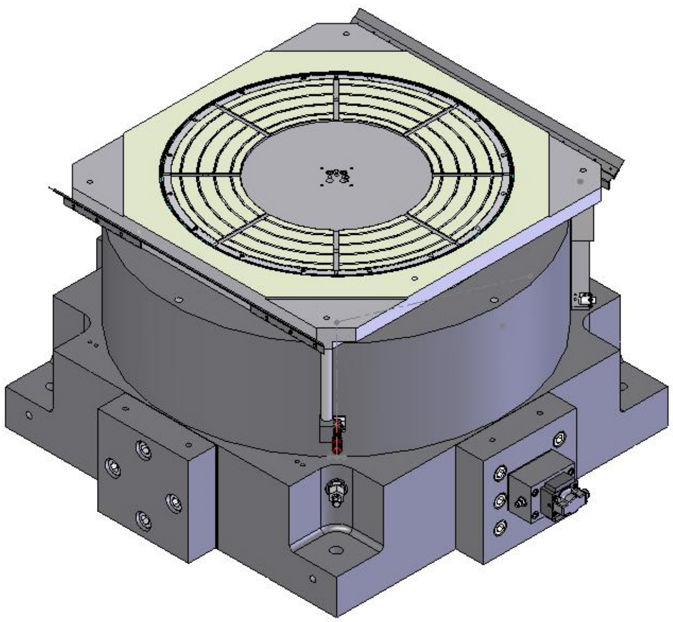
Servovalves (Qty. 2E + 2W)	
Pilot 2nd Stage Rating (Manufacturer Moog)	**19 lt/min**
Pilot 3rd Stage Rating	**630 lt/min**
4th Stage Flow Rating	**10,000 lt/min (2,500 gpm)**
Port Area Ratios	1:0.8:0.64:0.5
Valve Sleeve Windows Area Ratio	1:0.64



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)

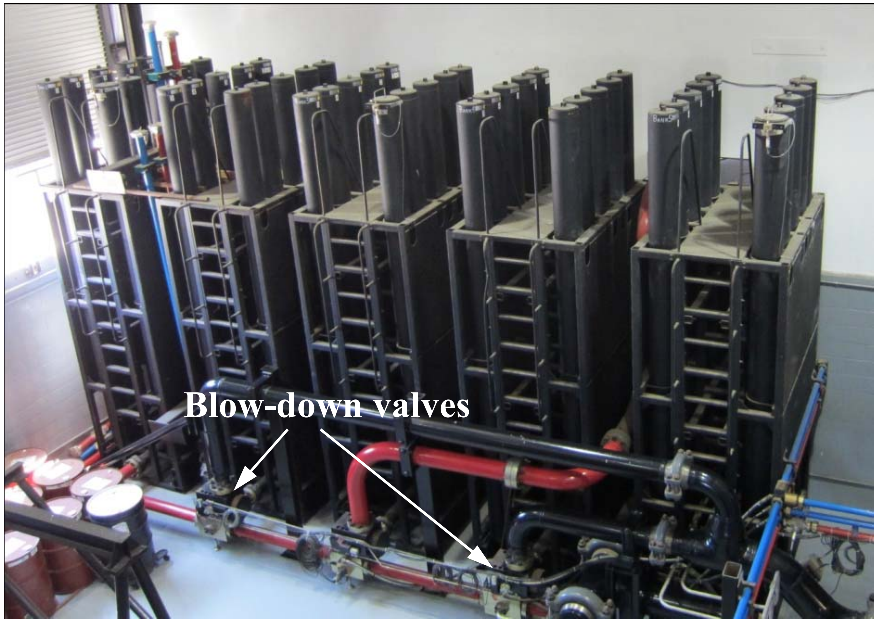


Hydraulic Power System

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

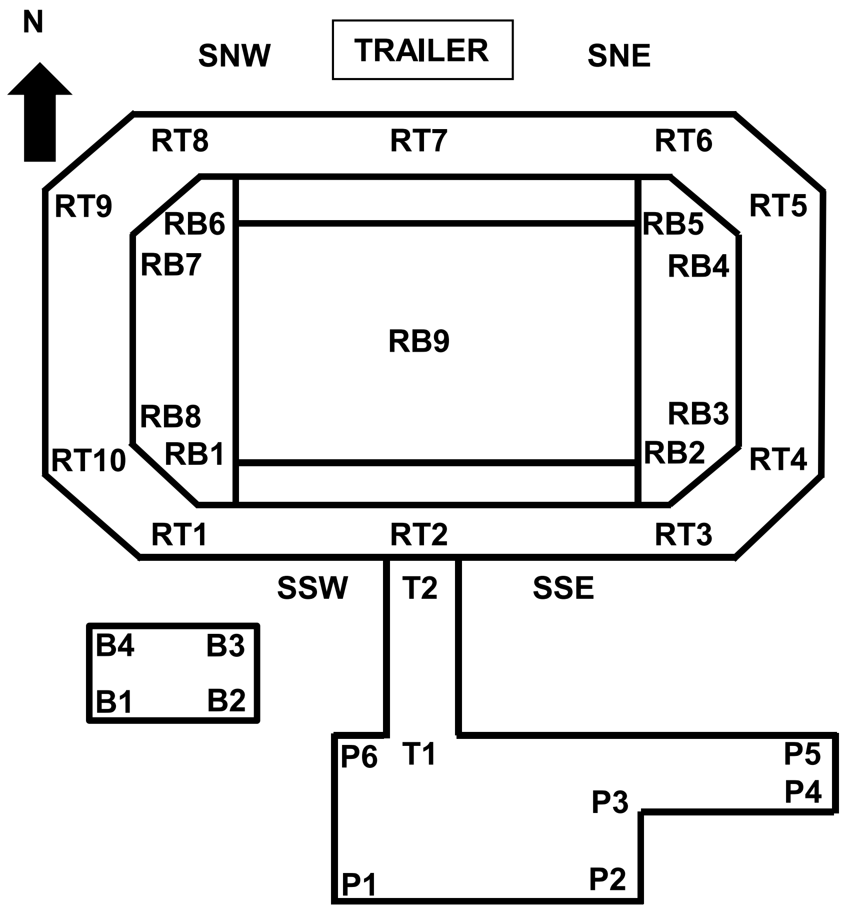


Surge tank

Bare Table Motions

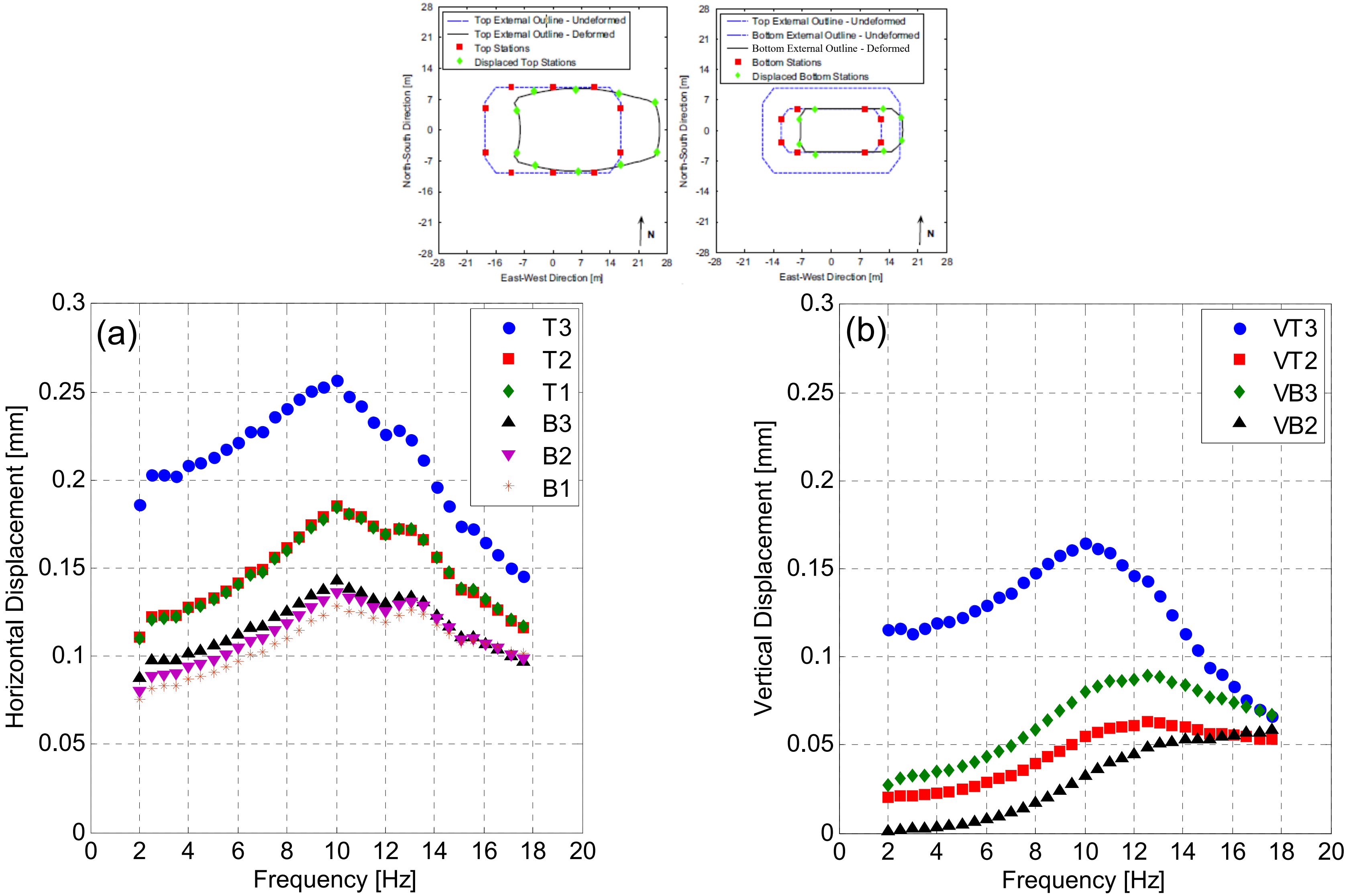
Forced Vibration Tests of the Reaction Mass at the NEES@UC San Diego Shake Table

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.

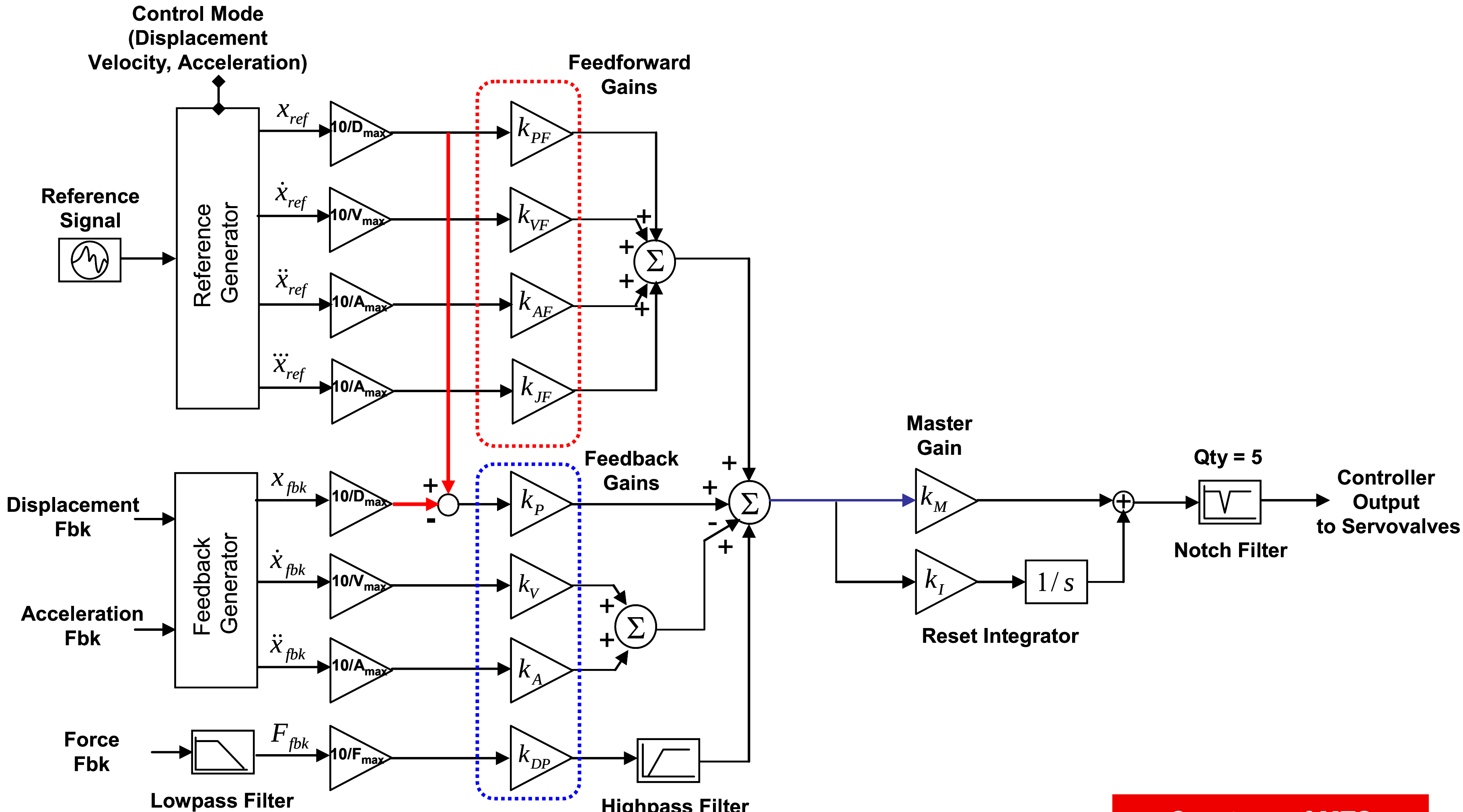
- TVC is a linear **state variable controller**. The three **state variables controlled by TVC** are:
  - Displacement
  - Velocity
  - Acceleration

  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)

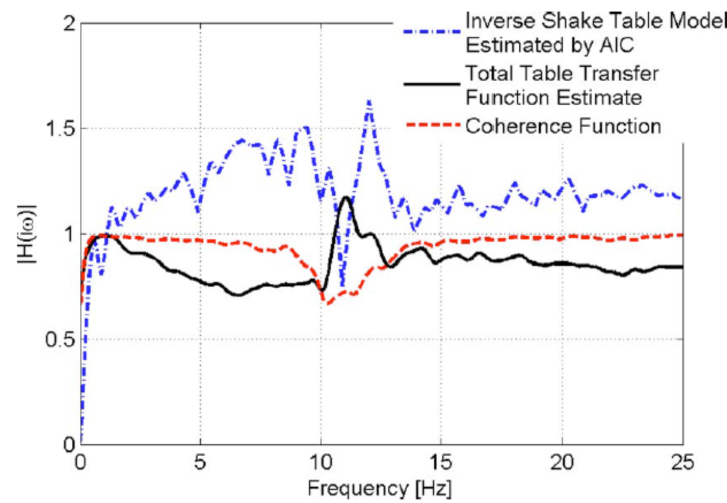


Courtesy of MTS Systems Corporation

Tuning of LHPOST Controller (MTS 469D)

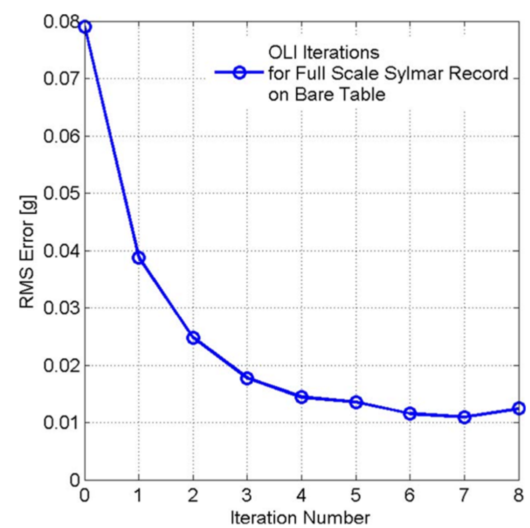
Tuning: Process of adjusting multiple control parameters (e.g., feedback and feedforward gains) and of preconditioning the input motion (through OLI) to optimize signal reproduction (tracking) capability of the shake table system.

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.

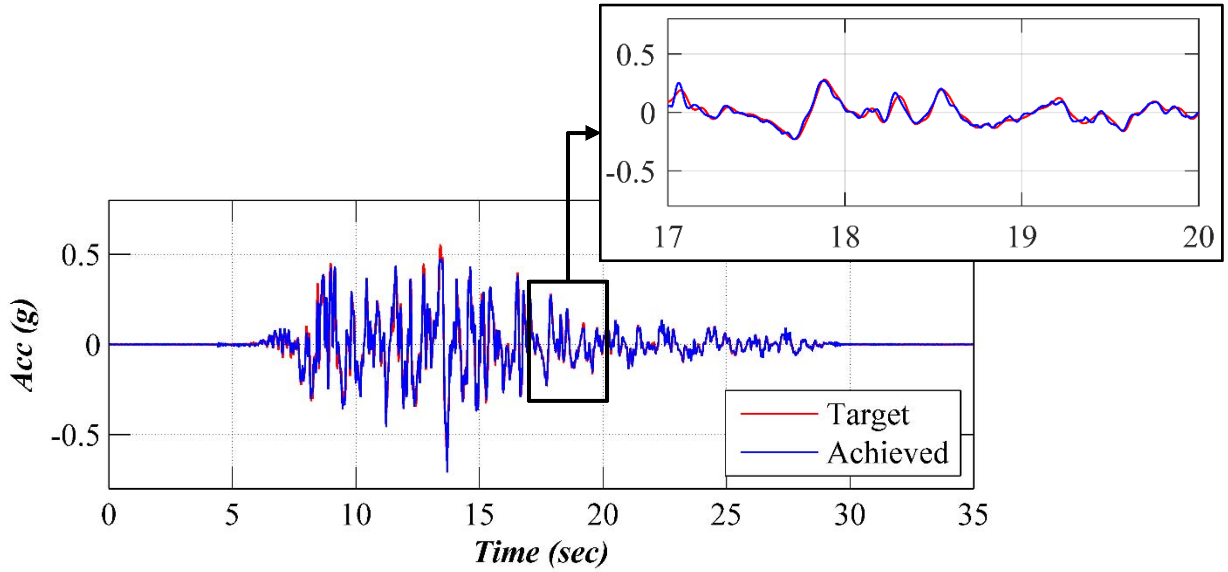


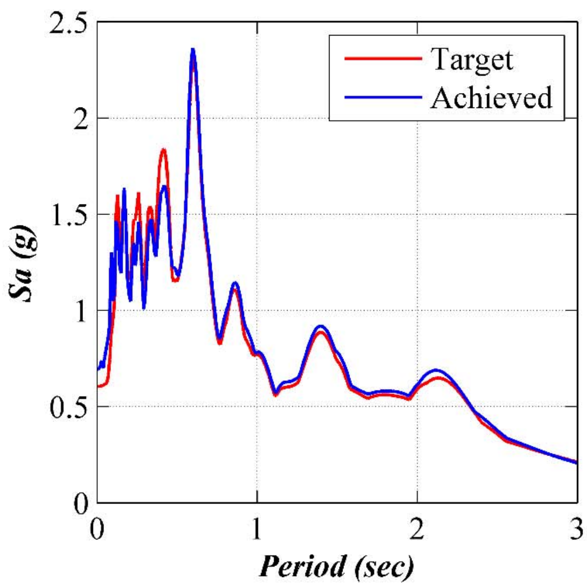
Step 2: Estimation of the inverse model of the plant using the adaptive inverse controller (AIC) technique.

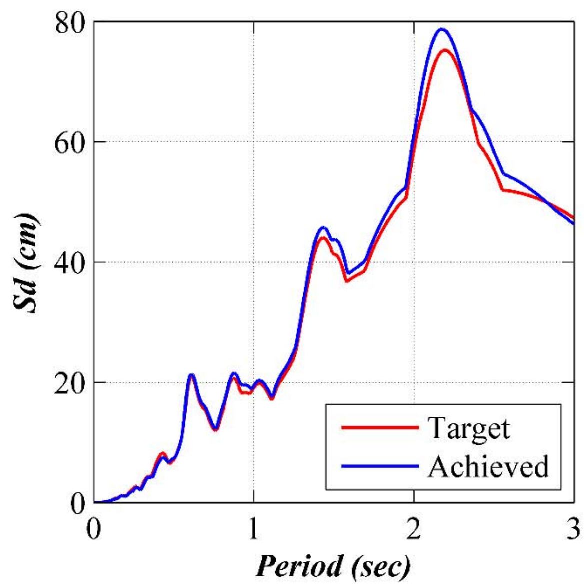
Step 3: Application of iterative time history matching technique called online iteration (OLI). The command input to the shake table controller (drive file) is repeatedly modified to optimize the match between the actual table motion and the desired/target motion (or reference signal).



Tracking Performance of NHERI@UC San Diego Shake Table







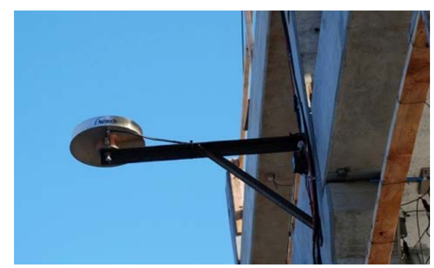
1994 Northridge Earthquake
Canoga Park (comp. 196)
Amplitude scaling: 1.55

Instrumentation for LHPOST

- **Data Acquisition**
  - **12 DAQ nodes with 64 channels each** sampling up to **25.6 kS/sec** per channel with **24-bit A/D resolution**

- 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@UC San Diego is on social media (youtube, facebook, twitter)
- **Calibration Equipment** for Data Acquisition Systems and Sensors

Selected Set of Specimens tested on the LHPOST











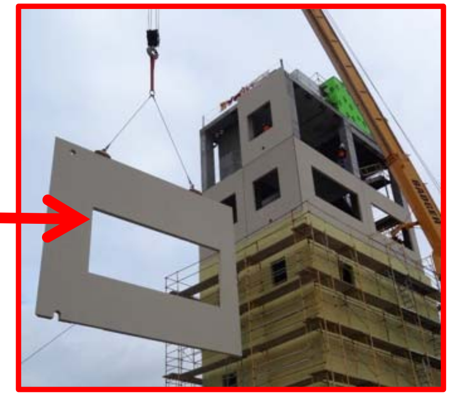


Full-scale Structural and Non-structural Building System Performance During Earthquakes

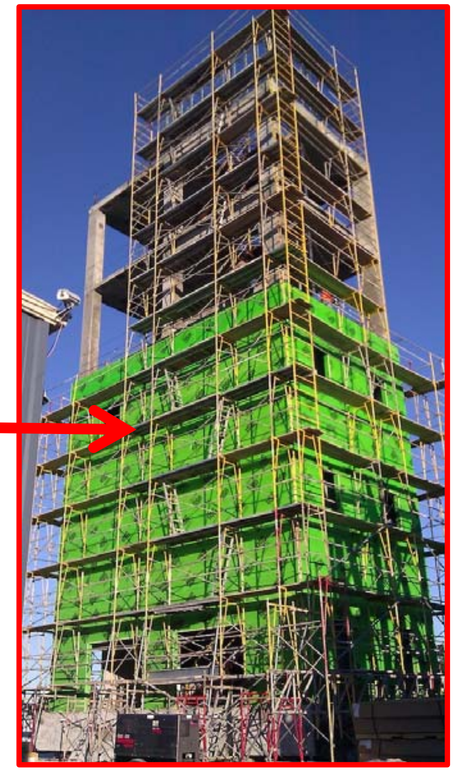
PI – Prof. Tara Hutchinson, UC San Diego

Exterior Facades

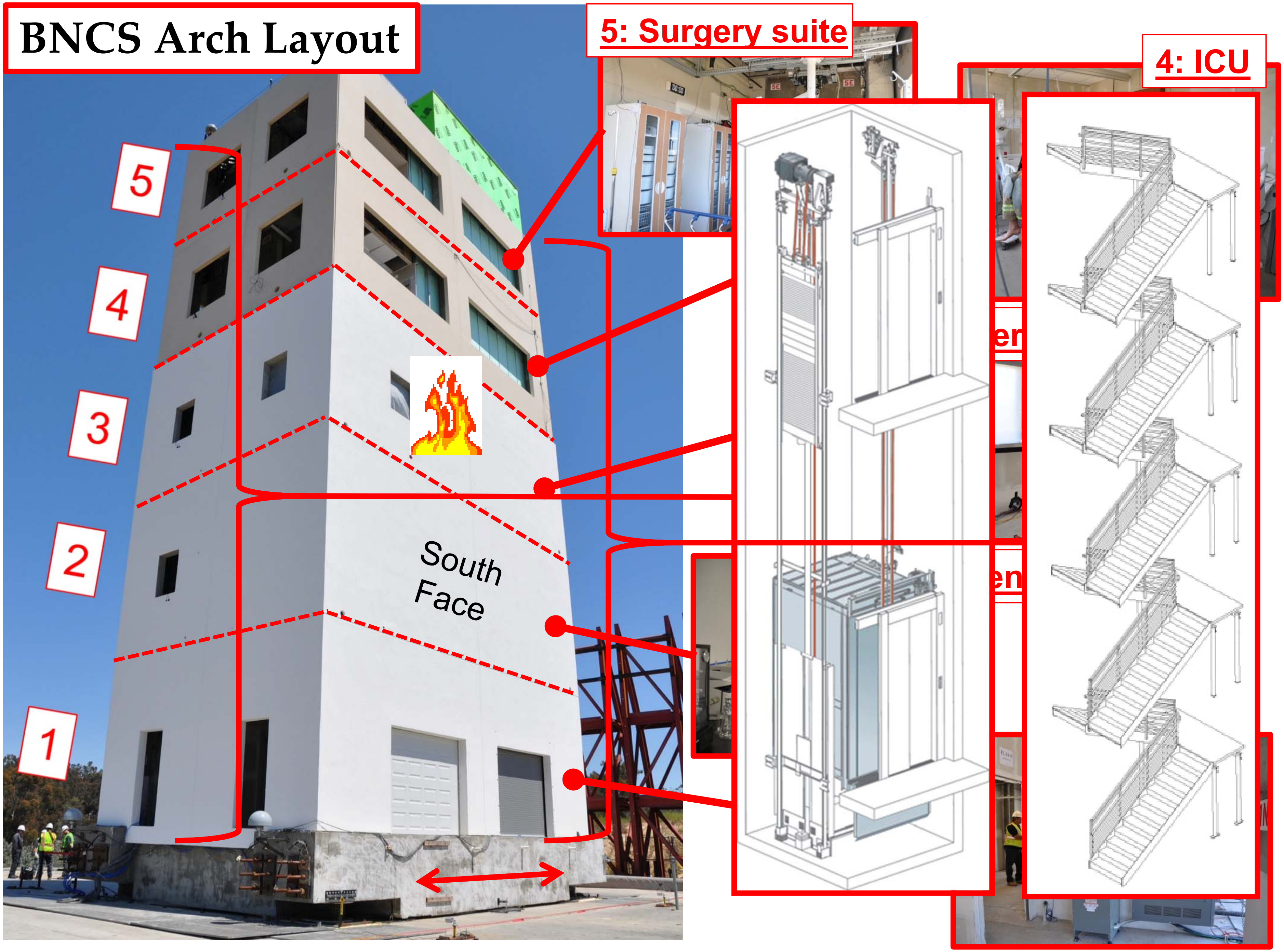
Architectural Precast Concrete Cladding



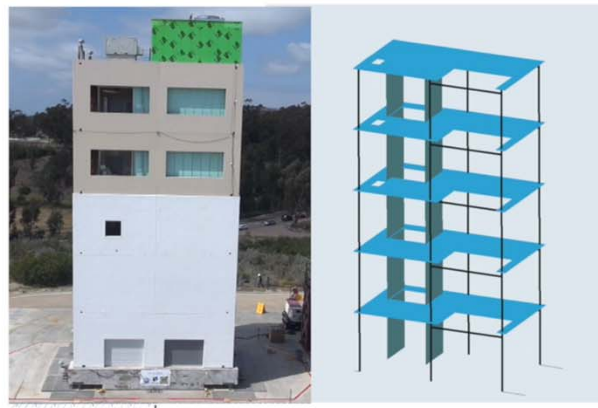
Balloon-framed metal stud+EIFS

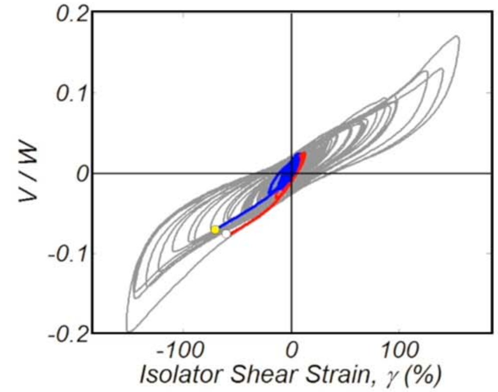


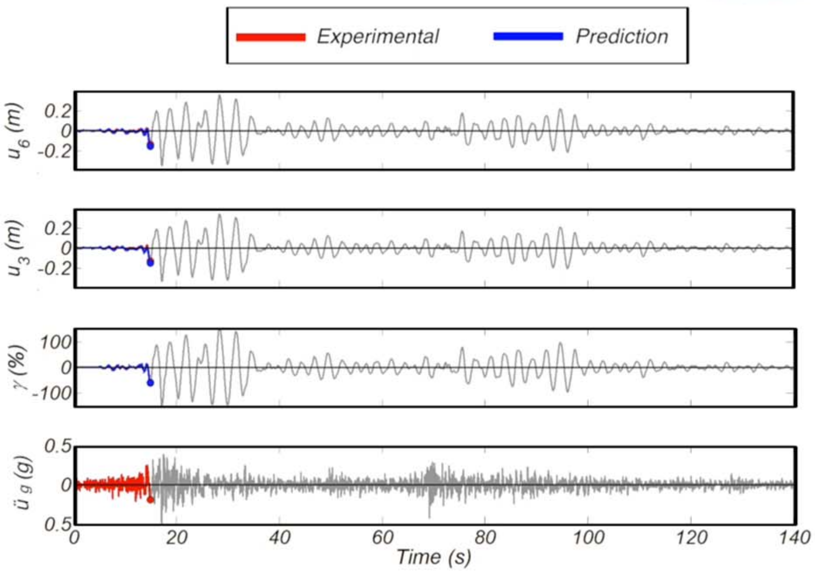
NW View

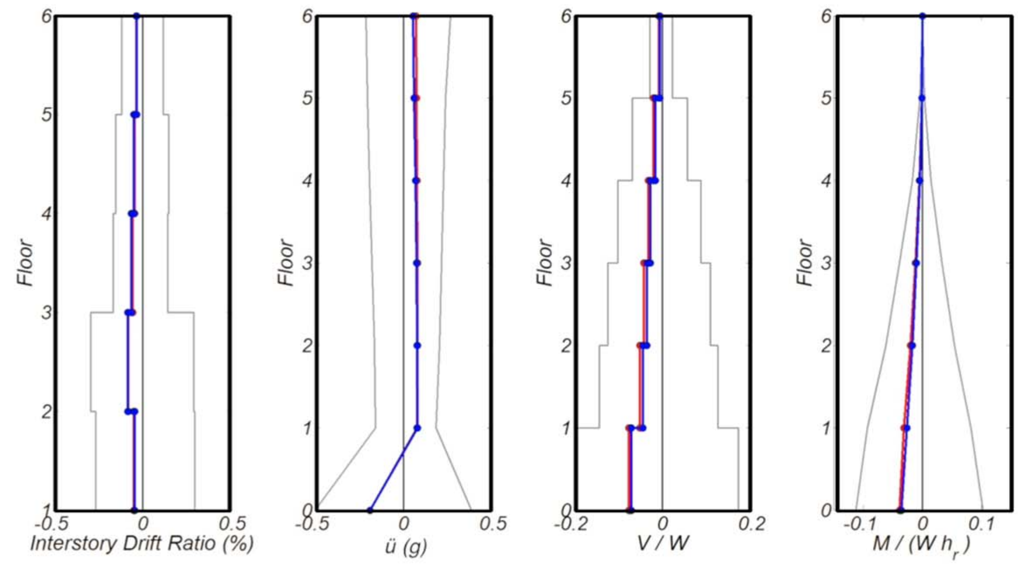

BNCS Arch Layout
5: Surgery suite
4: ICU
5
4
3
2
1
South Face

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









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

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

Experimental Program to Investigate Soil-Pile Interaction in Soil Strata

PI – Prof. Ahmed Elgamal, UC San Diego

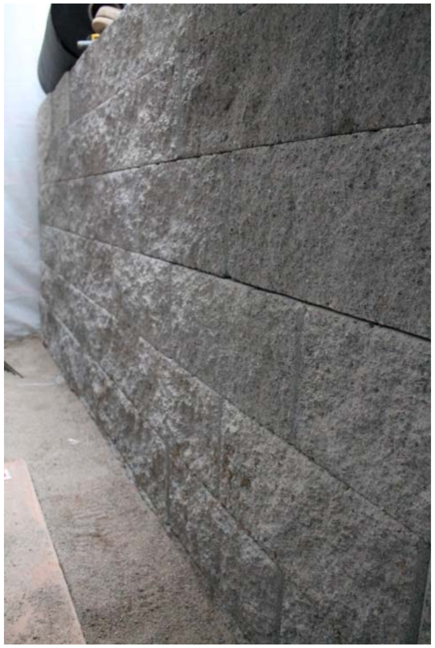
Liquefaction-Induced Lateral Spread Displacements and Soil-Pile Interaction in Multi-Layer Soil Strata

PI – Prof. Ahmed Elgamal, UC San Diego

Seismic Performance Tests of Full-Scale Retaining Walls

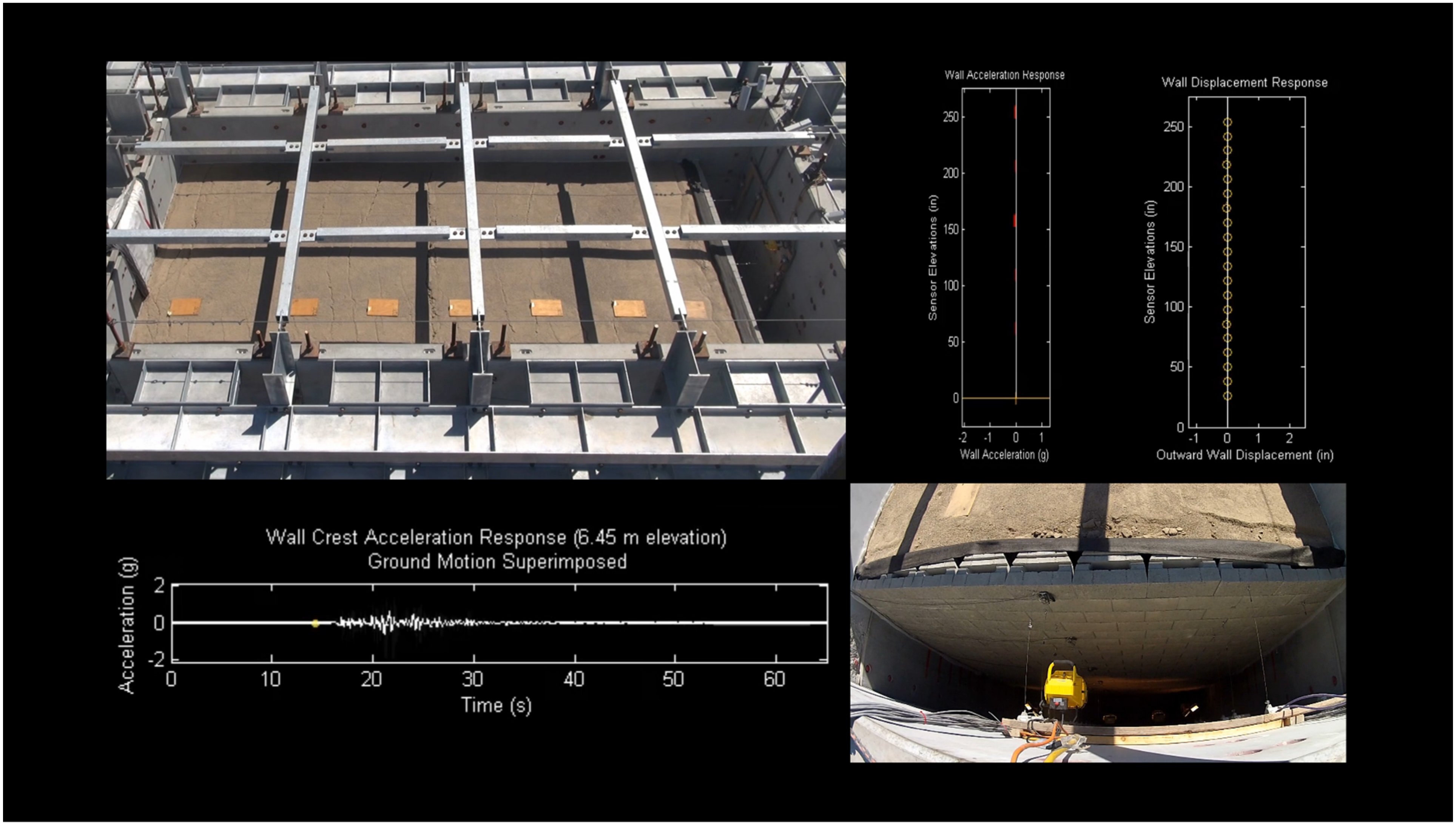
PI – Prof. Patrick Fox UCSD

22 ft. Above Table Elevation



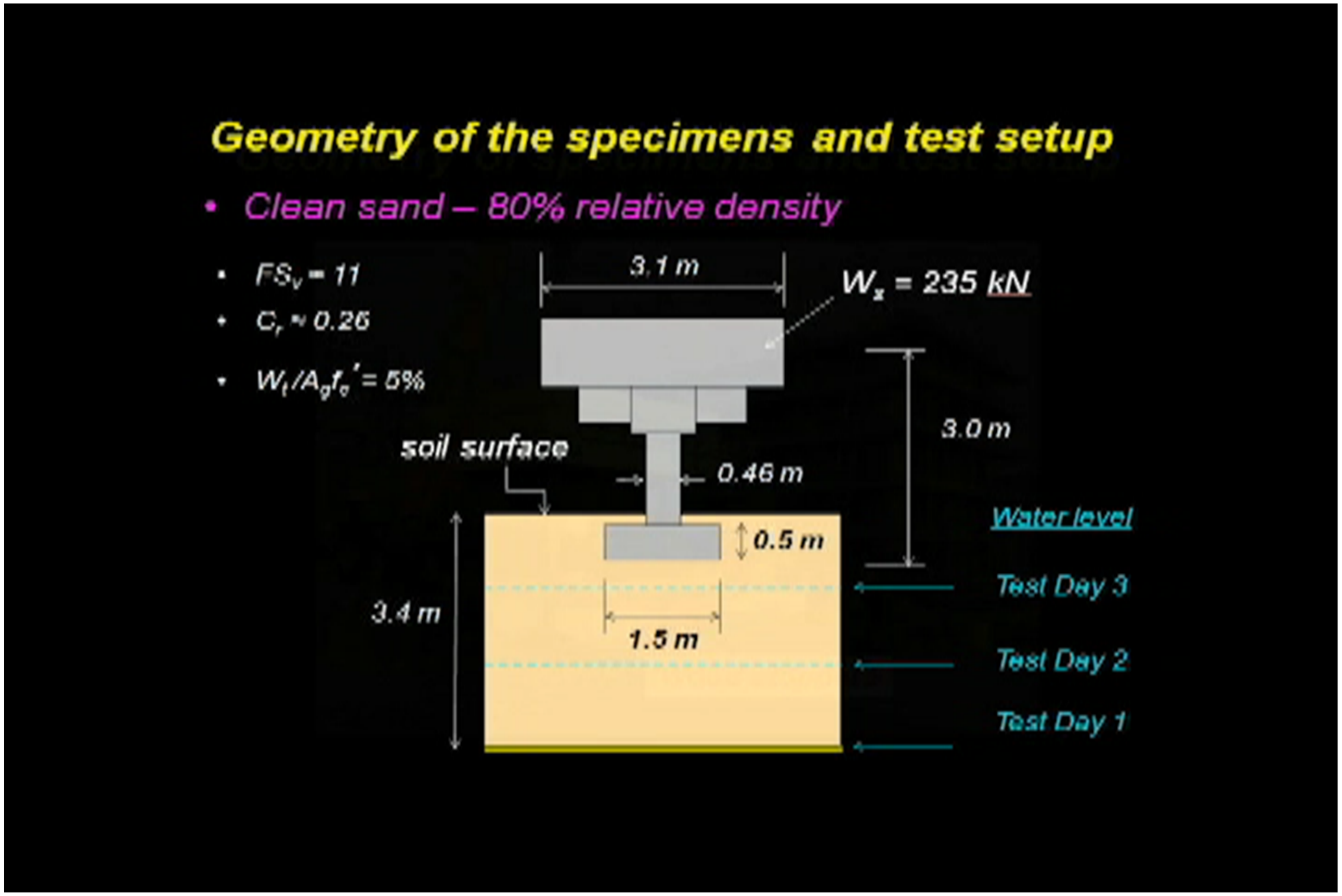
Earthquake Performance of Full-Scale Reinforced Soil Walls

PI – Prof. Patrick Fox UCSD



Soil-Foundation-Structure Interaction Test

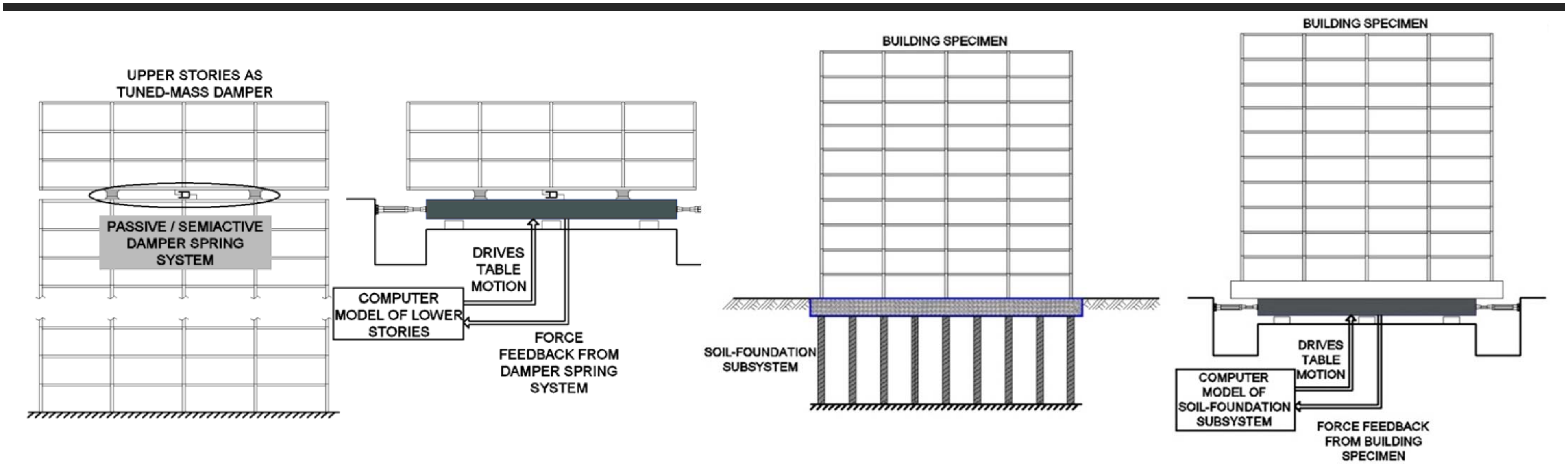
PI – Prof. Marios Panagiotou, UC Berkeley



Staging Facility

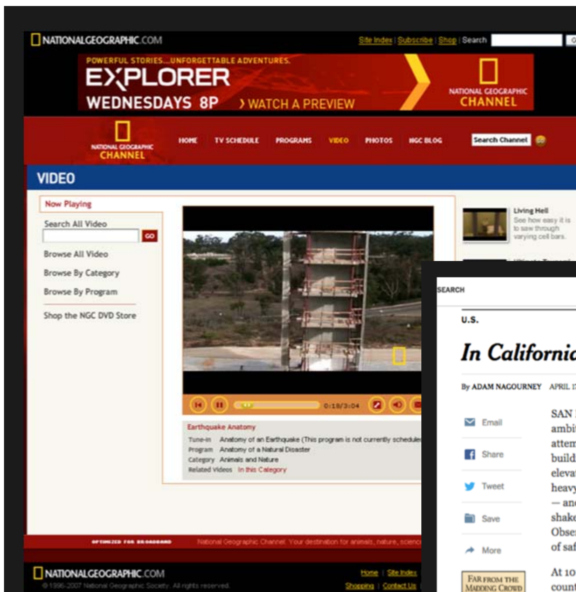
Hybrid Shake Table Testing

- **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-tonf (110 kips) dynamic actuator
  - Portable hydraulic power system



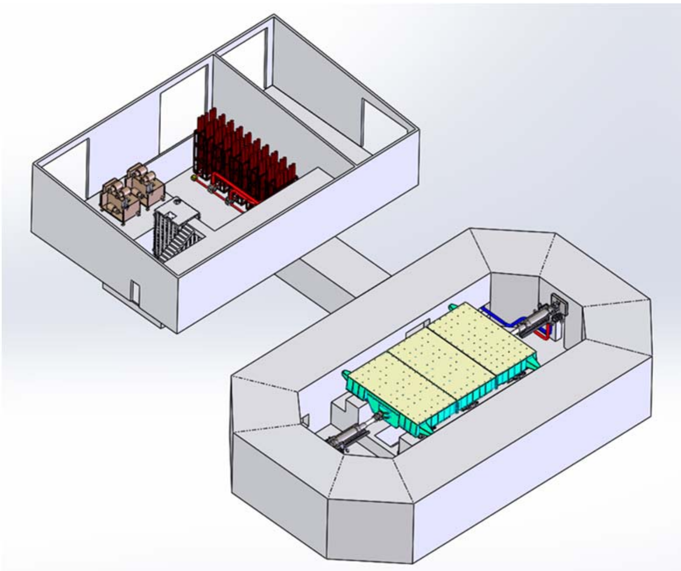
Broad Public Dissemination

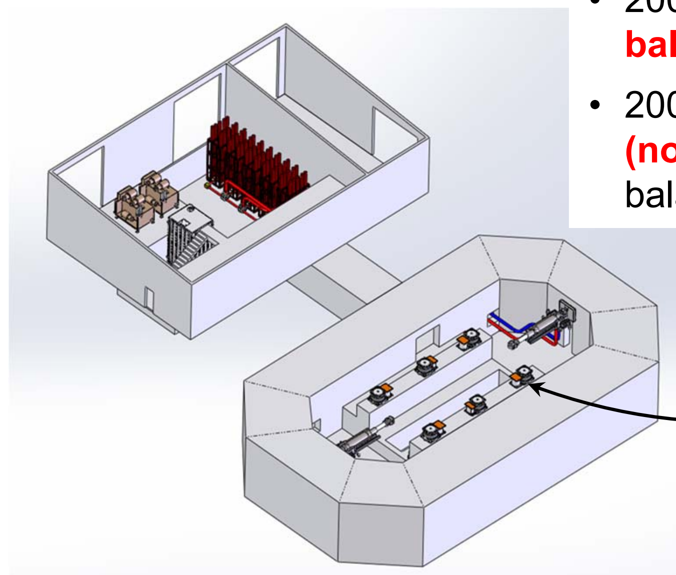
- Jacobs School of Engineering Communications and Media Relations
- International, National, Regional, and Local Exposure



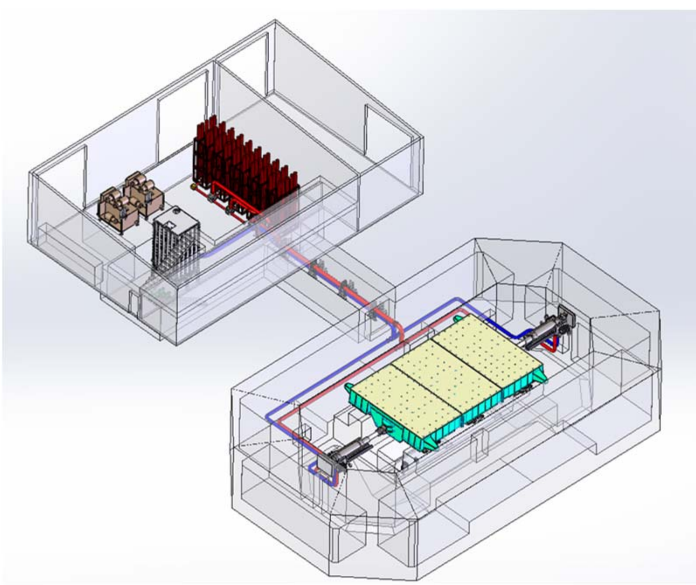
Six Degree-of-Freedom (6-DOF) Upgrade of LHPOST

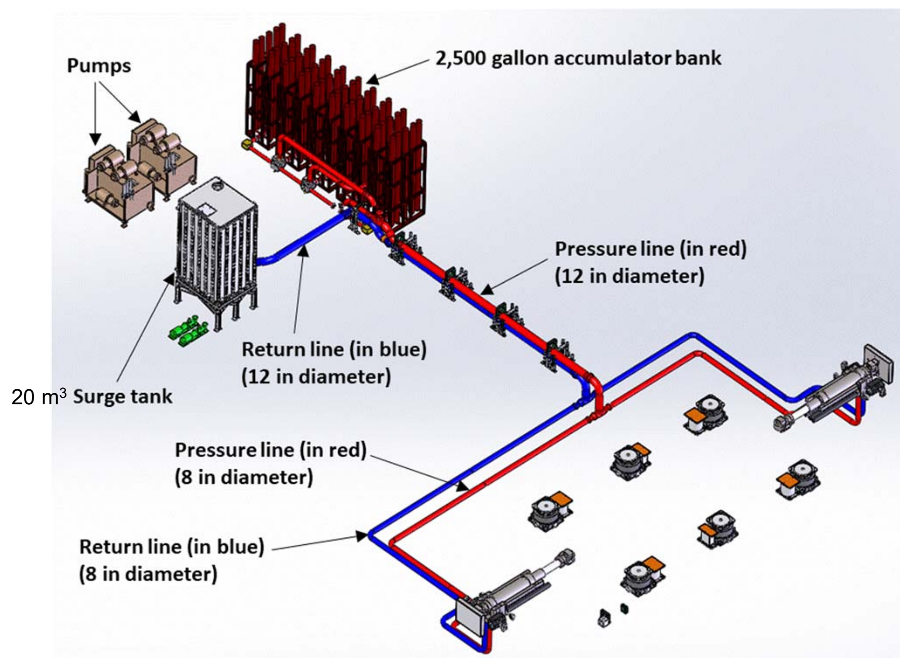
Hydraulic Power System for 1-DOF LHPOST



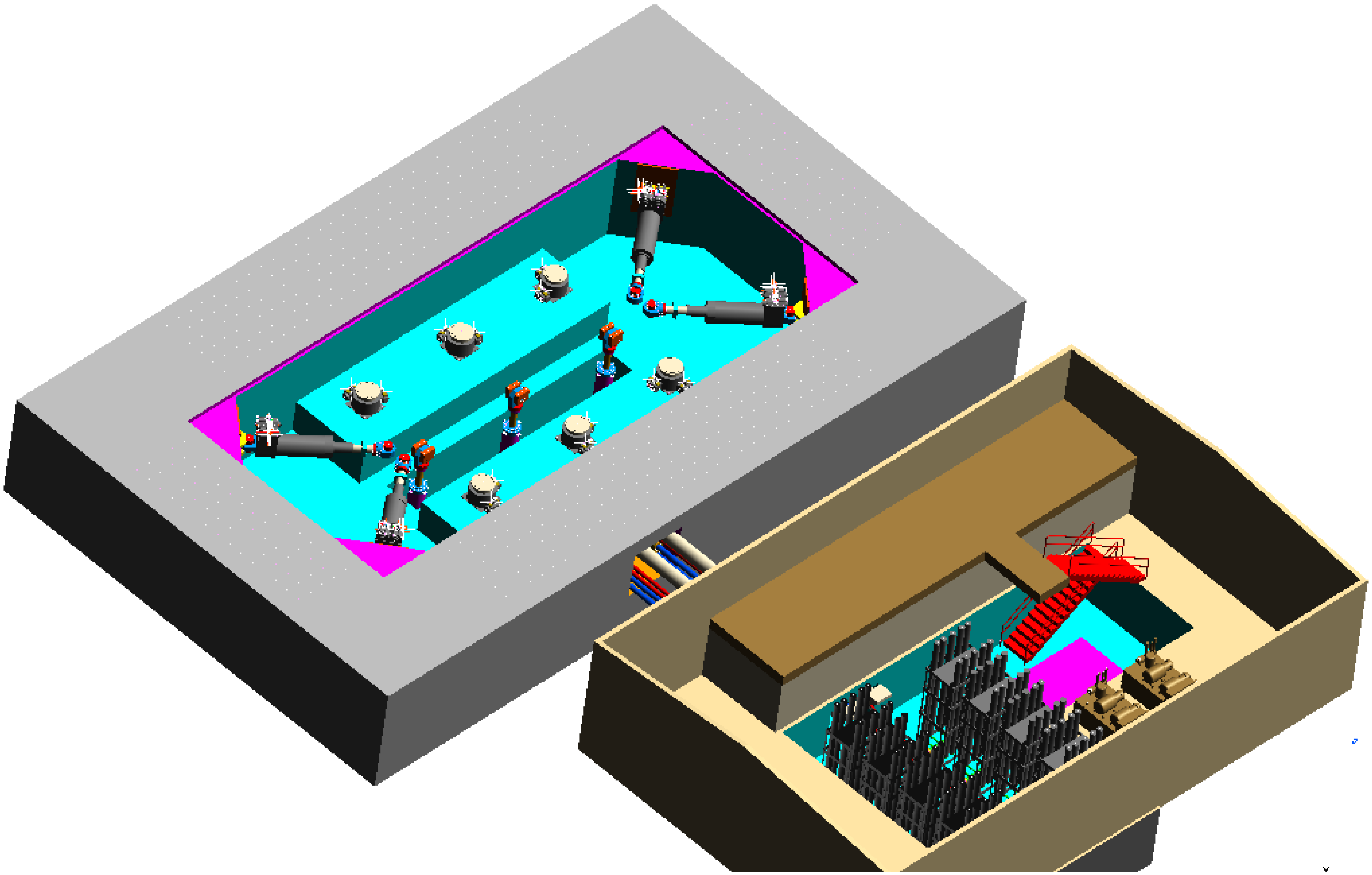


- 2004-2009: **Pressure balanced bearings**
- 2009-current: **Actuators (non-ported)** with Pressure balanced bearing

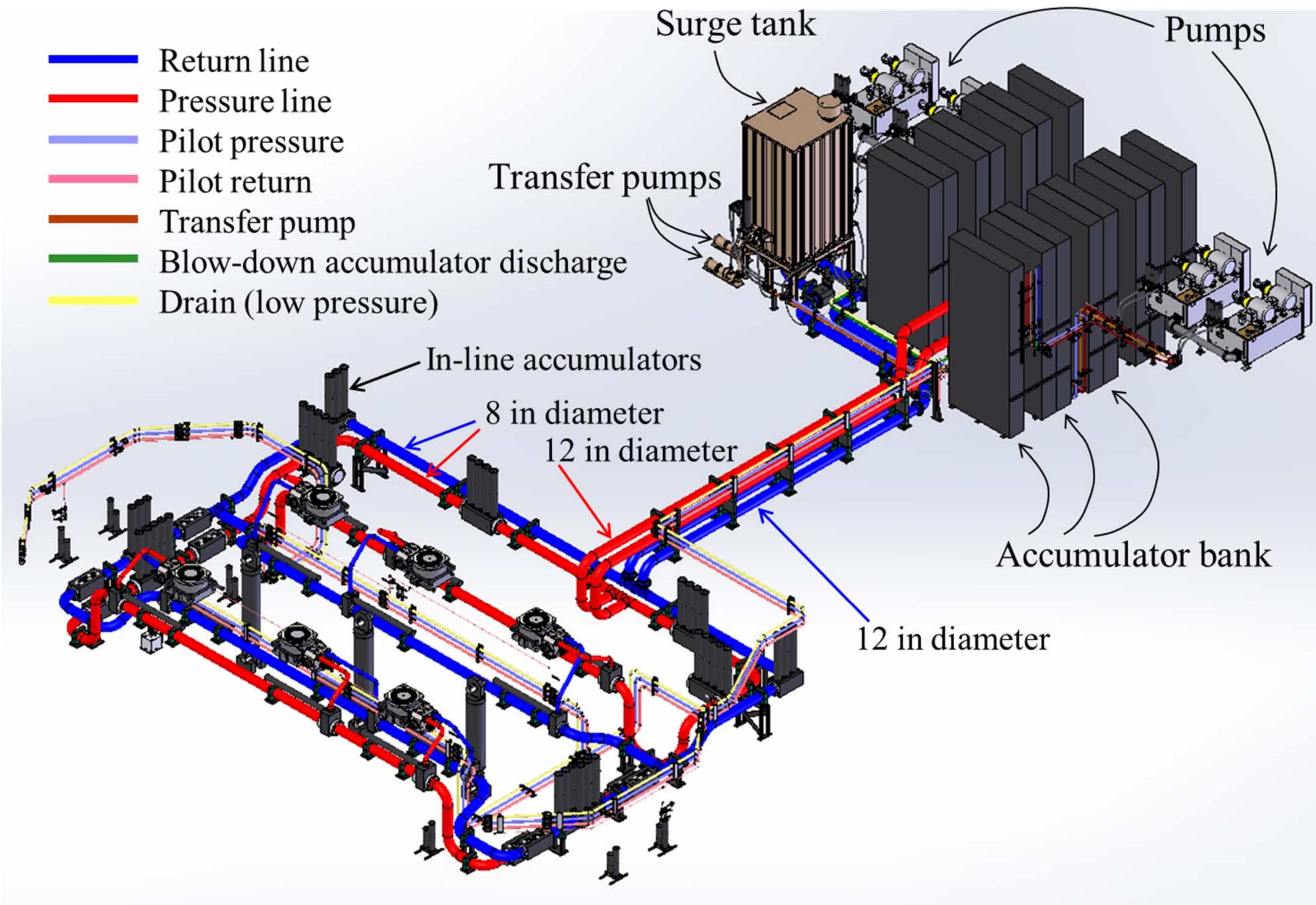




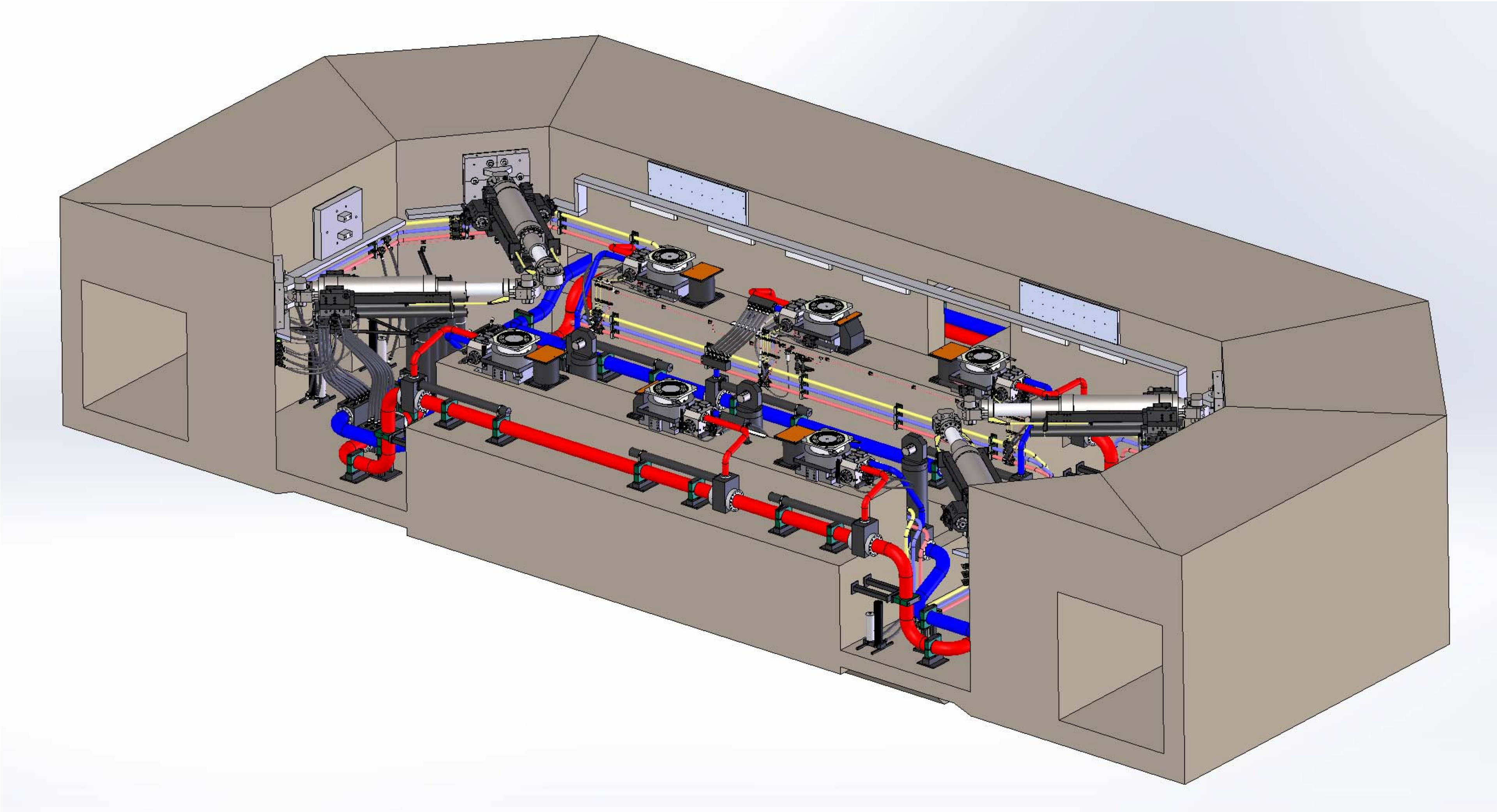
Upgrade to 6-DOF Configuration



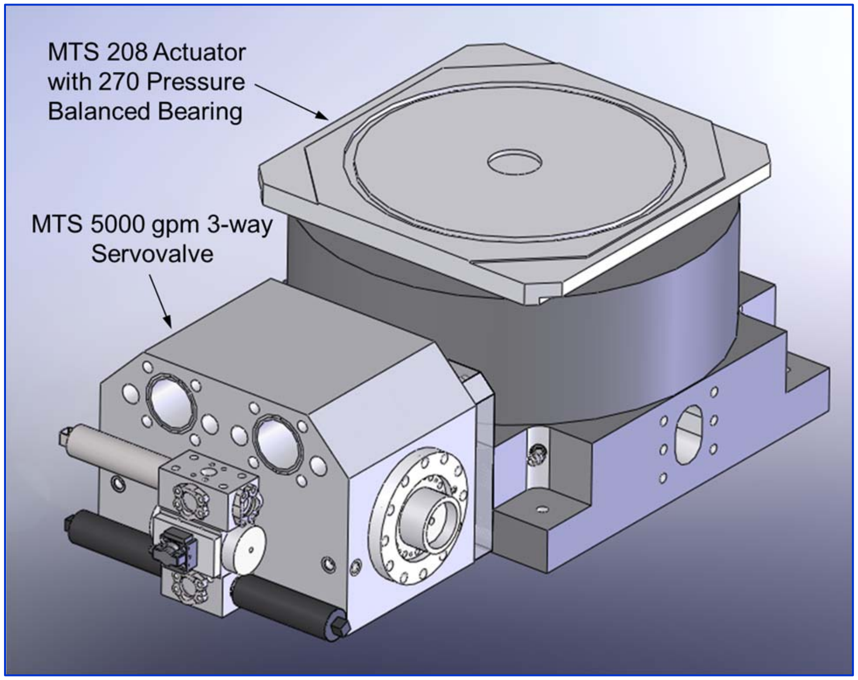
Upgrade to 6-DOF Configuration

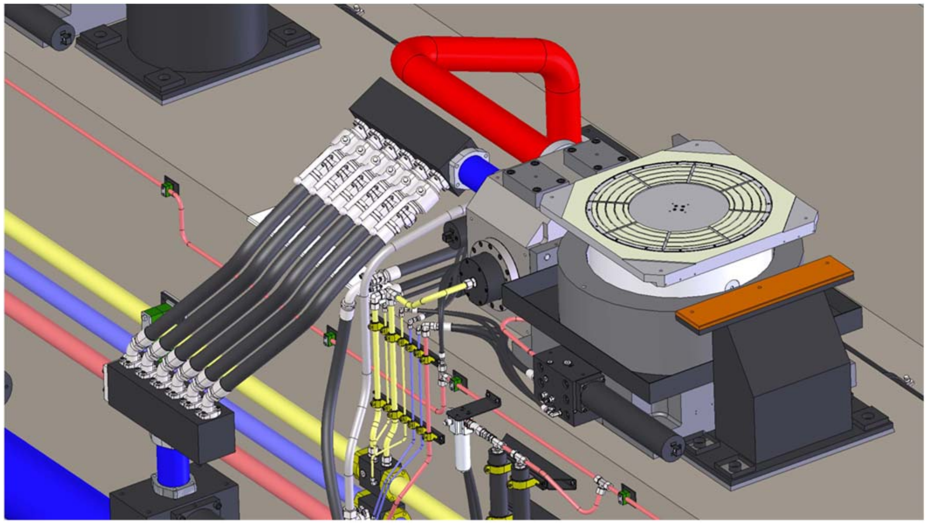


Upgrade to 6-DOF Configuration

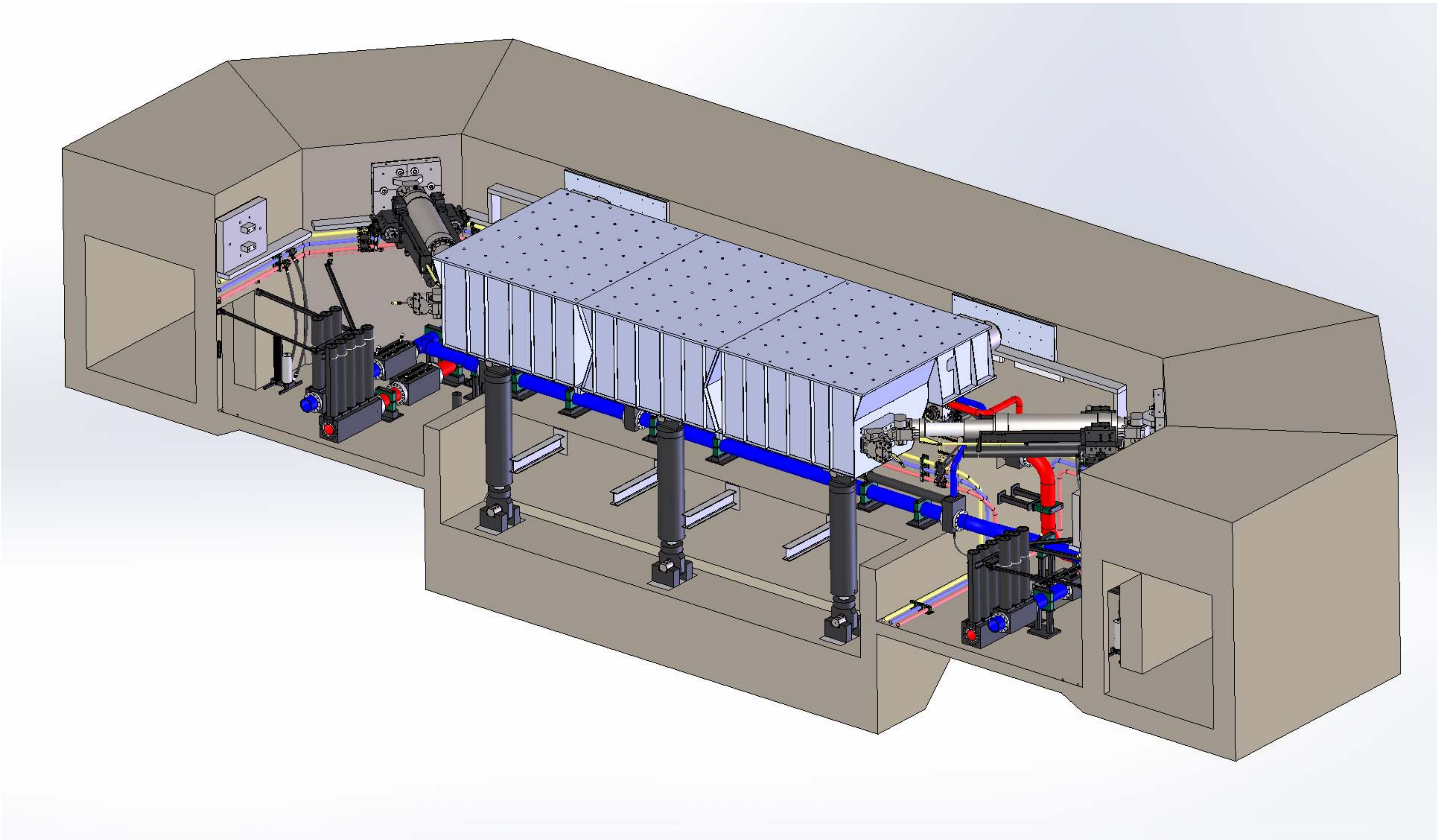


High-Flow Servovalves for Vertical Actuators

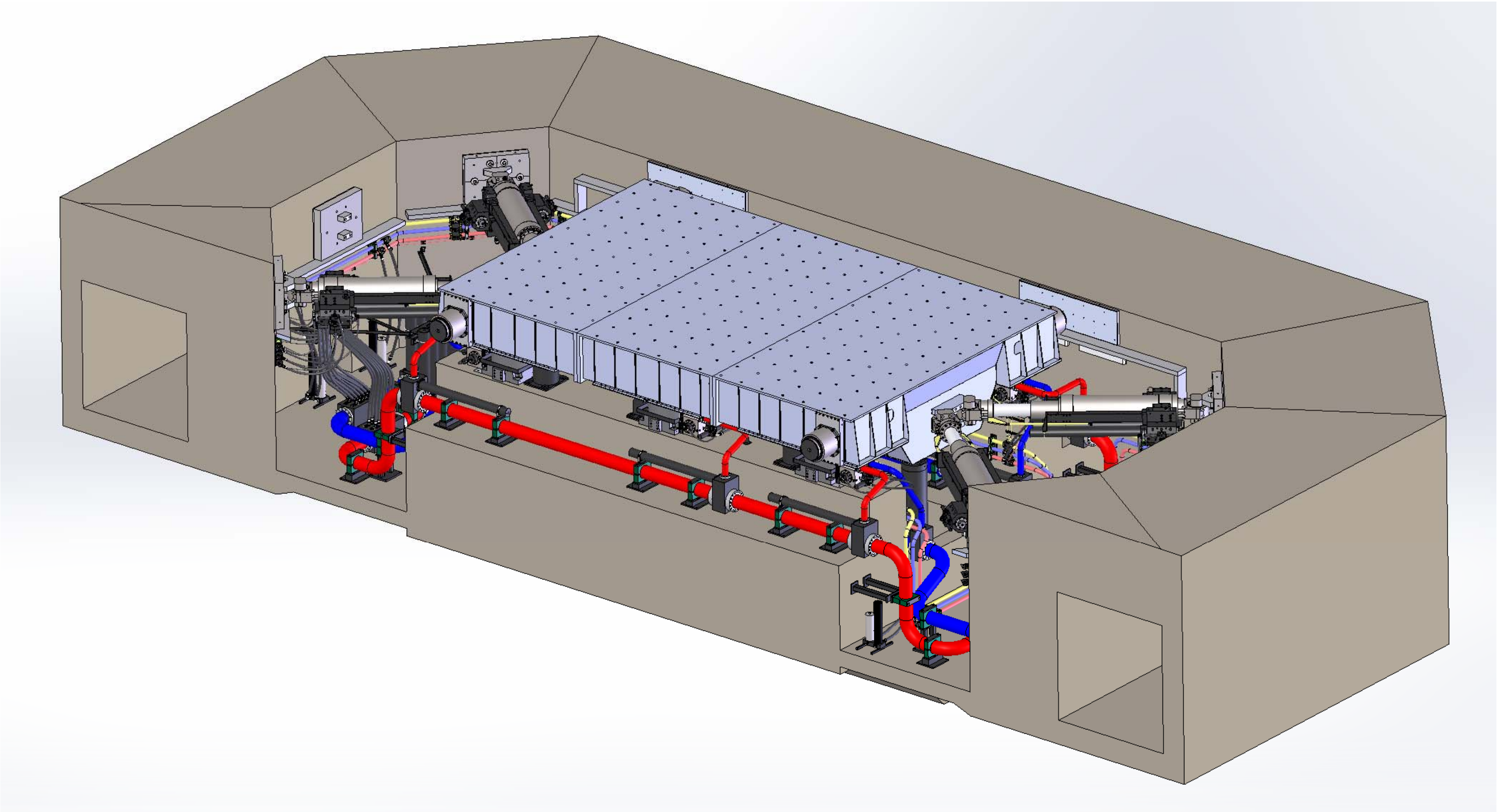




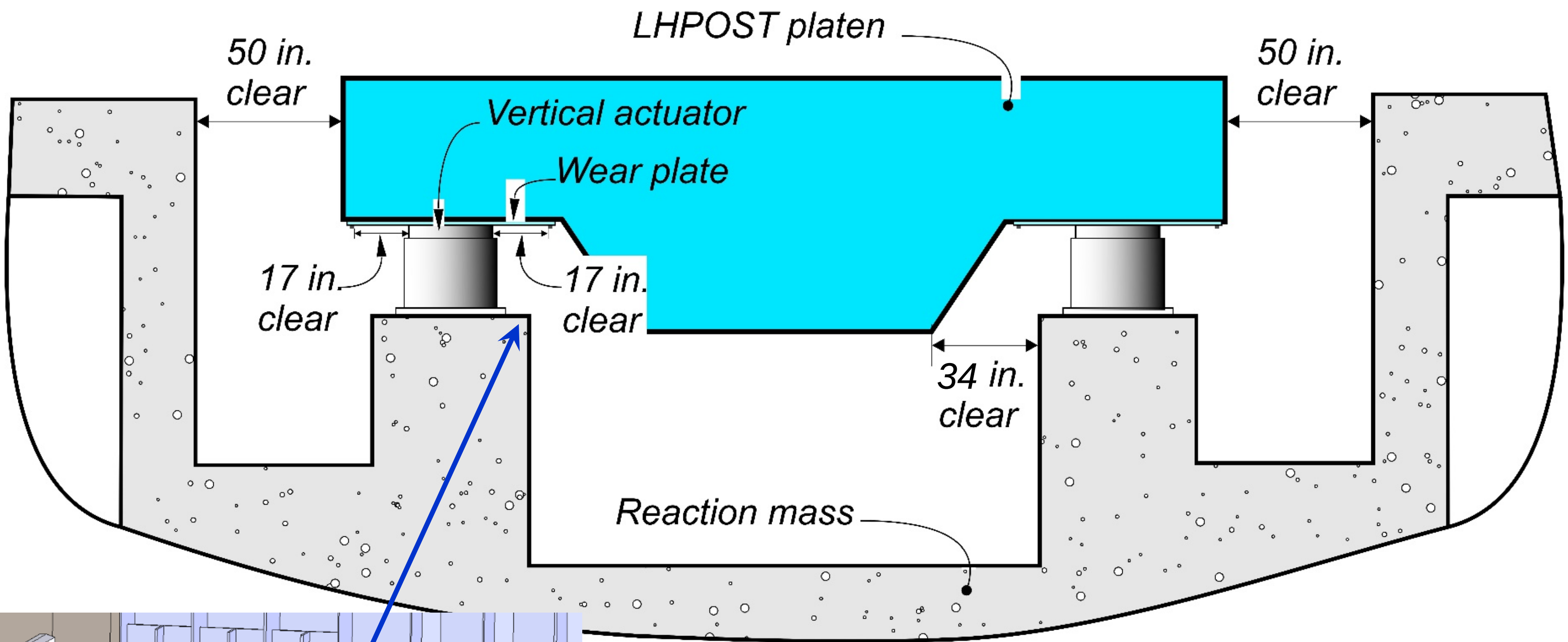
Upgrade to 6-DOF Configuration

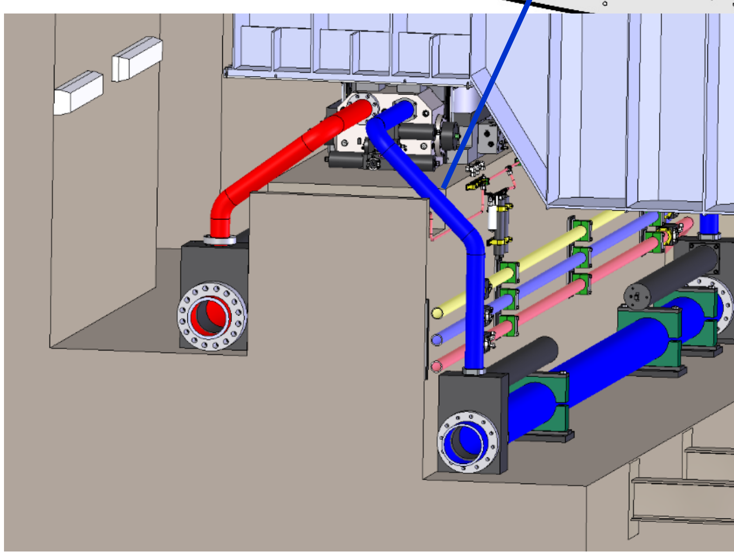


Upgrade to 6-DOF Configuration



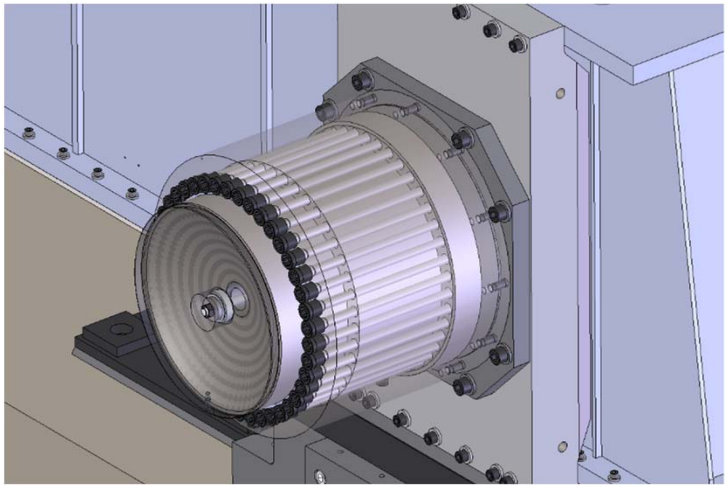
Displacement Limit in the Transverse (N-S) Direction

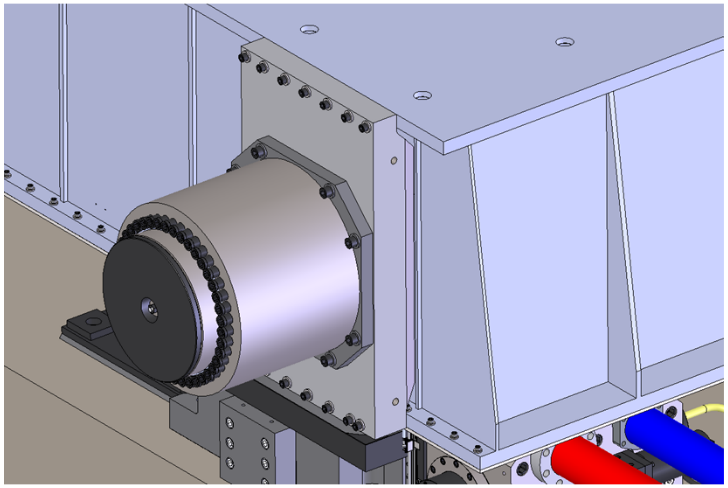


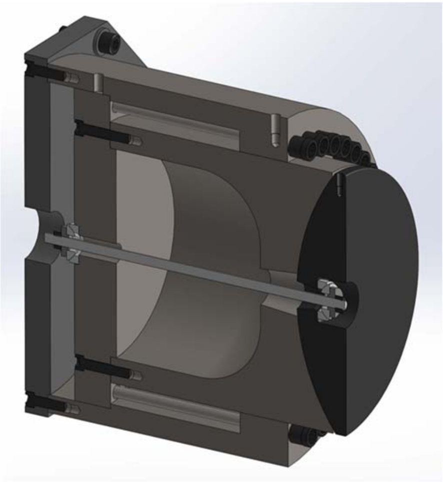


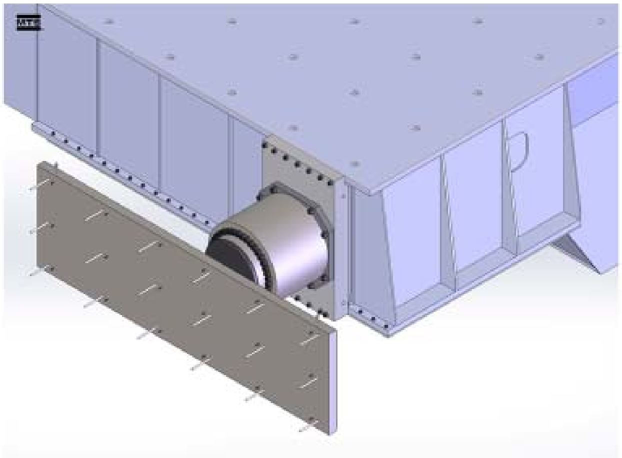
- Three lines of defense against potential impact:
  - Software limit detectors
  - Physical limit switches
  - Collision/crash protection devices

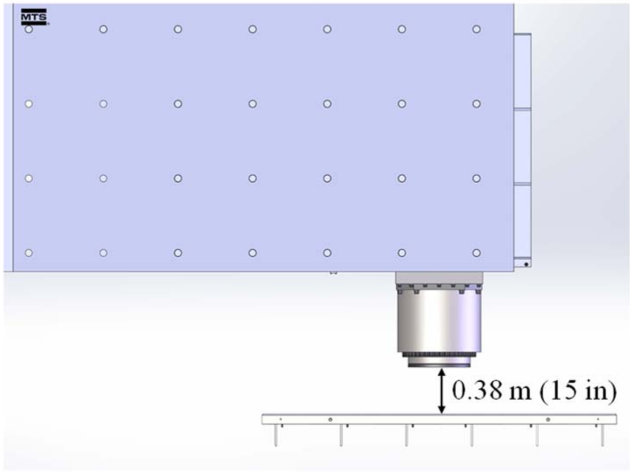
Crash Protection System











Uni-axial Performance Characteristics of LHPOST6

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*	2.2 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)

Target vs. Achieved (predicted using shake table model) Tri-Axial Ground Motions

1999 M7.6 Chi-Chi, Taiwan, TCU065 Station, **Ground Acceleration Components**

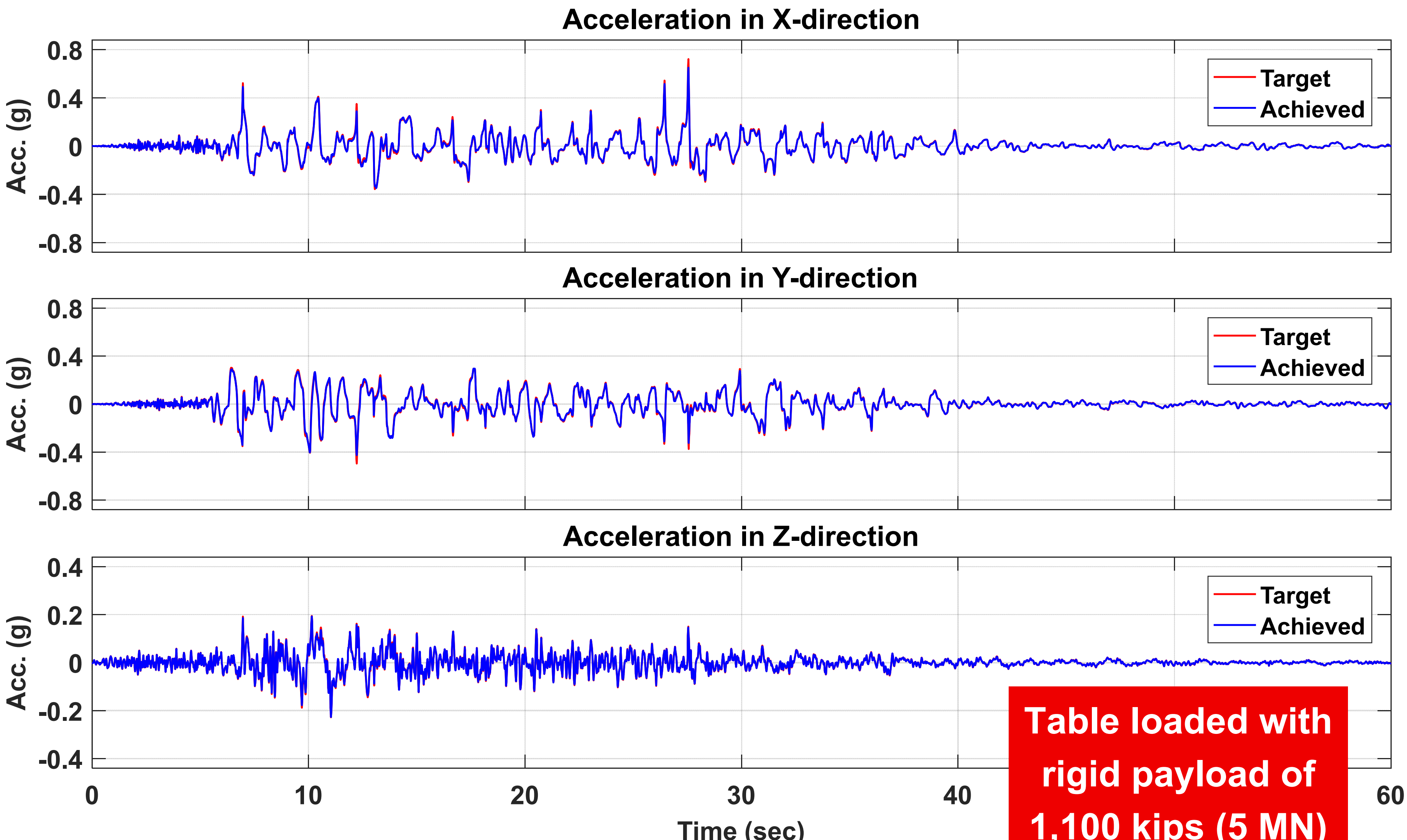


Table loaded with rigid payload of 1,100 kips (5 MN)

Target vs. Achieved (predicted using Shake Table Model) Tri-Axial Ground Motions

1999 M7.6 Chi-Chi, Taiwan, TCU065 Station, **Ground Velocity Components**

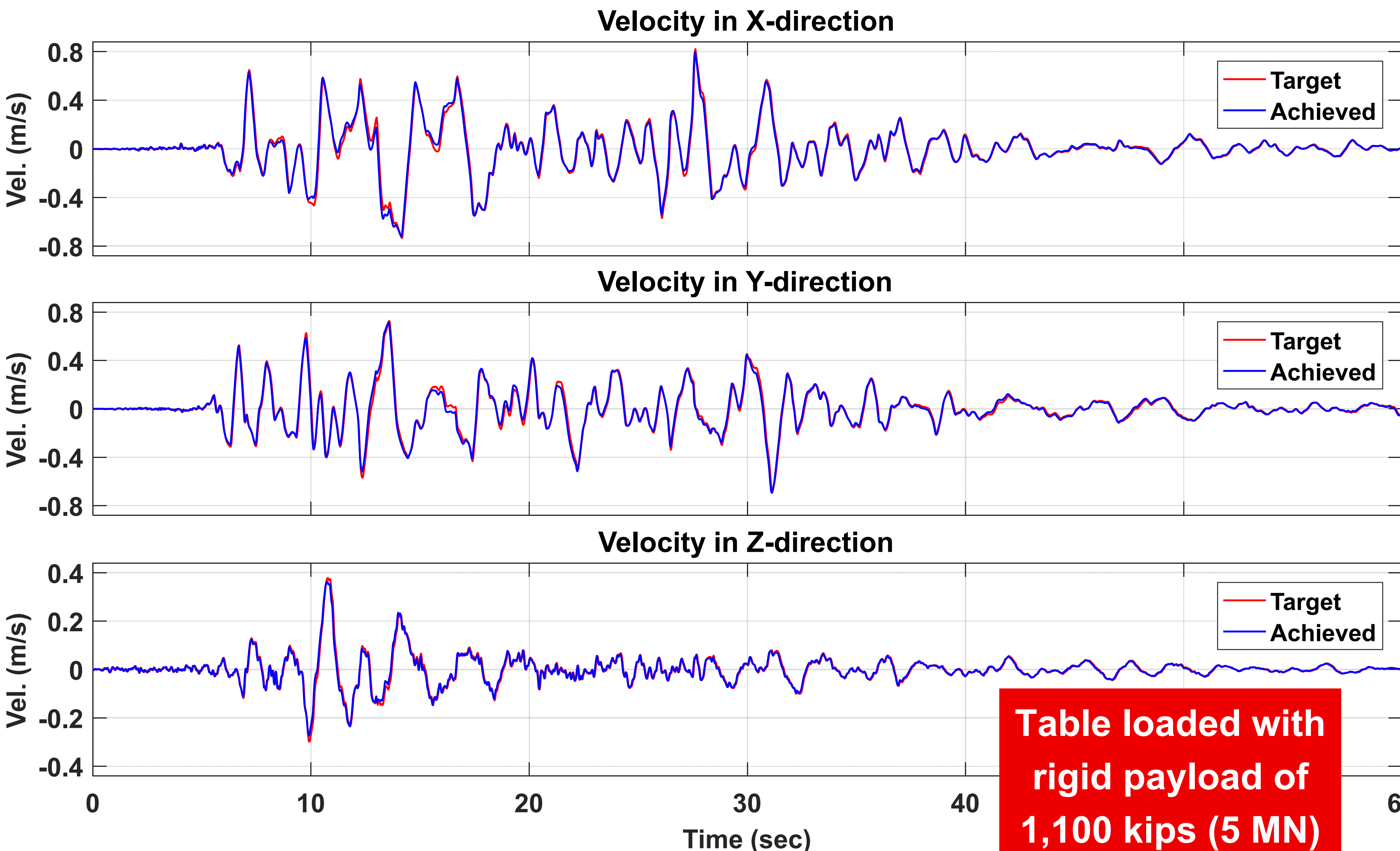
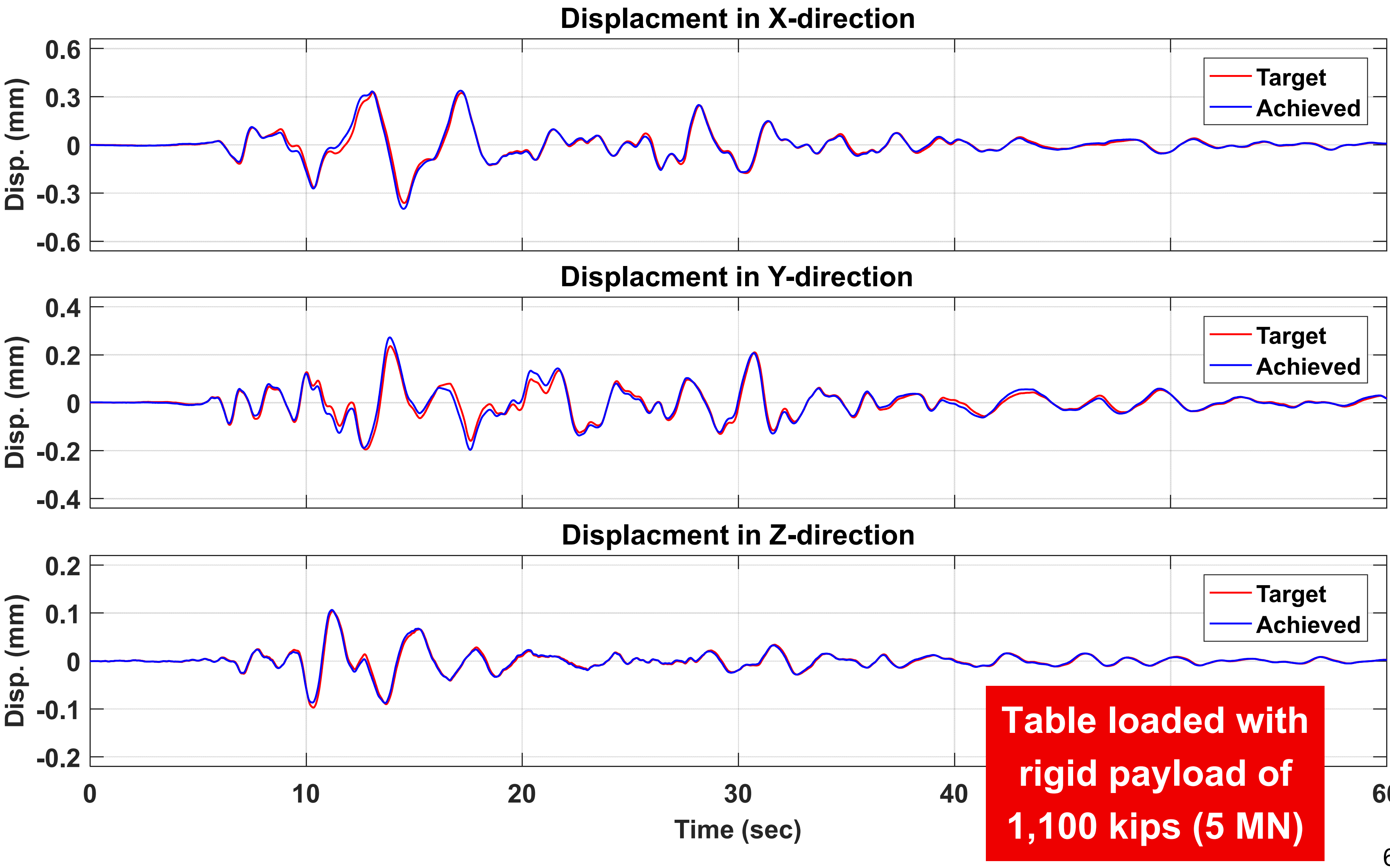


Table loaded with rigid payload of 1,100 kips (5 MN)

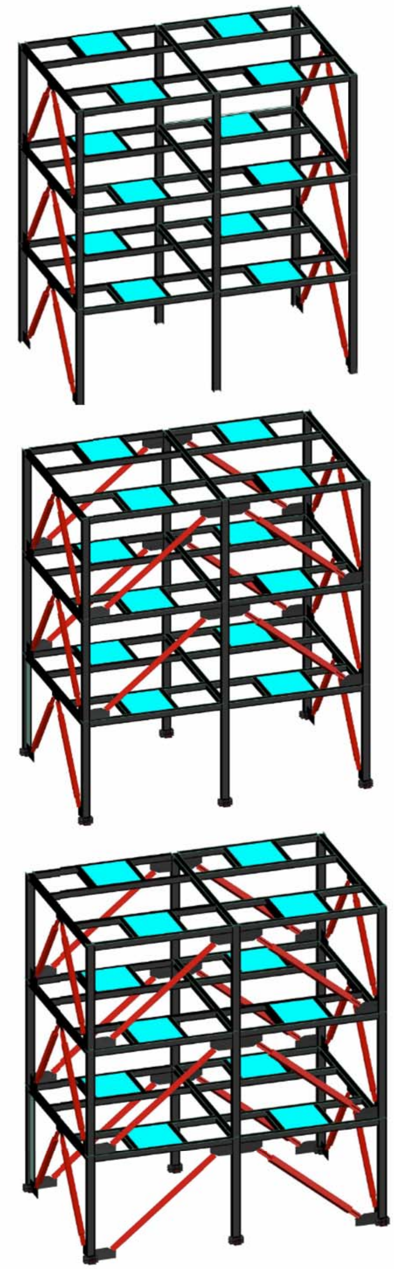
Target vs. Achieved (predicted using Shake Table Model) Tri-Axial Ground Motions

1999 M7.6 Chi-Chi, Taiwan, TCU065 Station, **Ground Displacement Components**



Modular Testbed Building

L = 32 ft
W = 20 ft
H = 36 ft



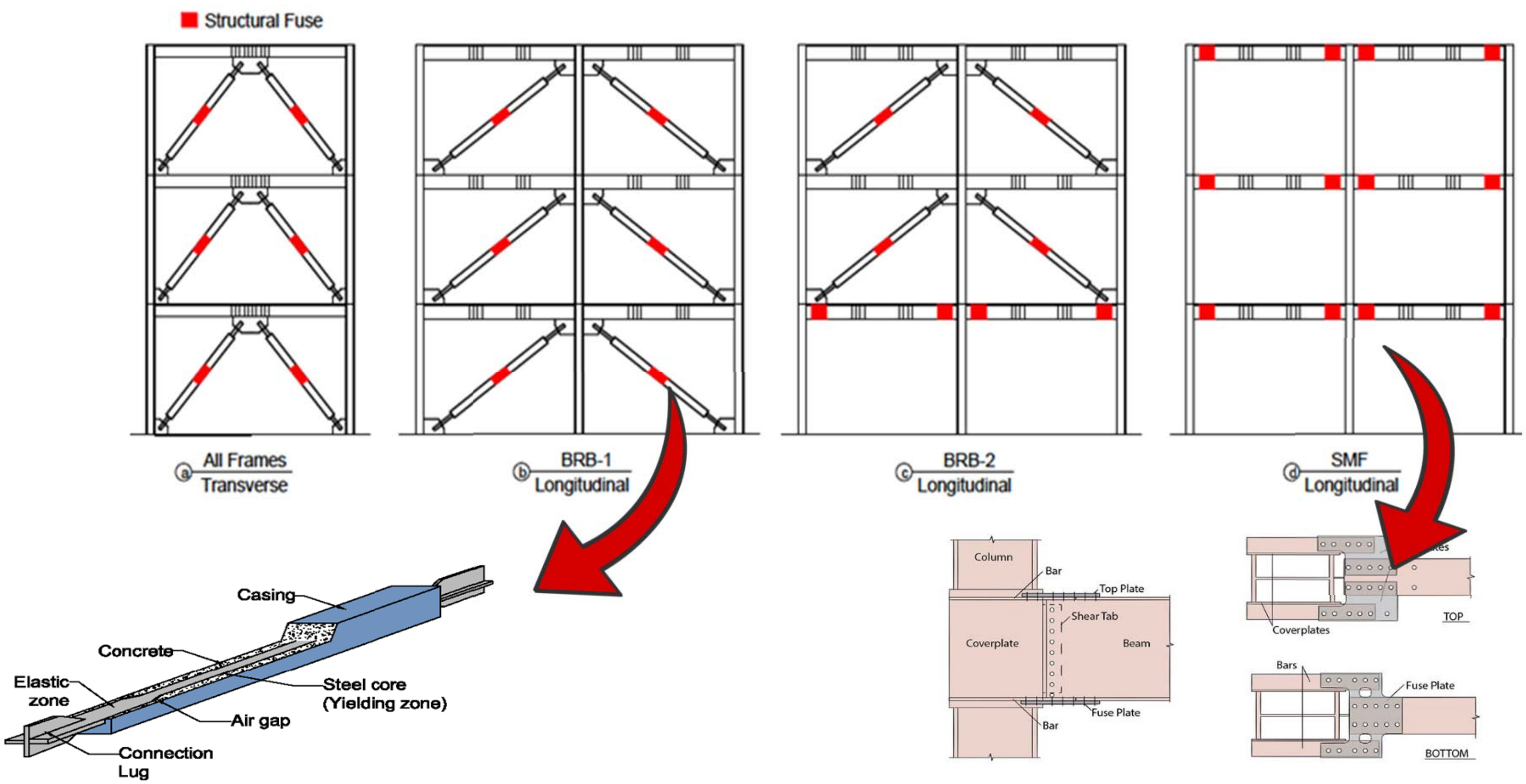
- Community-available building for NHERI users
  - Presently in design phase; materials procured
  - First structure to be tested on newly upgraded MDOF LHPOST
- ***Evolution:***
  - Multi-university collaboration (University of Utah & UCSD)
  - Close collaboration with industry partners (SMS steel & BRB manufacturer CoreBrace)
  - Community input (via NHERI workshops)
- ***Unique features:*** Designed to be reconfigurable & reusable enabling low-cost testing of components and systems under simulated dynamic 3D loading
- ***Potential uses:*** Seismic protective systems, lateral force resisting systems, nonstructural systems and payload opportunities

SME STEEL CoreBrace NSF University of California at San Diego NHERI Natural Hazards Engineering Research Infrastructure THE UNIVERSITY OF UTAH®

Design Features

Reconfigurable 3-D full-scale three-story steel building designed to accommodate wide range of seismic behavior of buildings:

- Moment frame behavior with **shear fuse** type plastic hinge
- Braced frame behavior with **buckling restrained braces** (BRBs) at the built-in gusset plates at joints



Buckling restrained braces

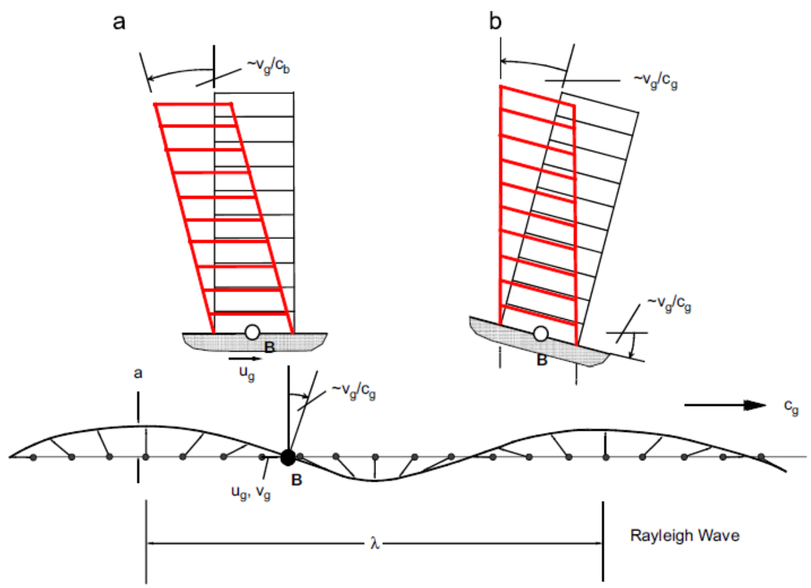
Special moment frame joints (shear fuses)

New Research Opportunities Made Possible by the LHPOST6

Research Made Possible by the LHPOST6

- 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 behavior**, 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 LHPOST6

- **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 LHPOST6

- **Real-Time Hybrid Shaking Table Testing**
  - **Expand the complexity of large-scale structural, geotechnical and soil-foundation-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 LHPOST6

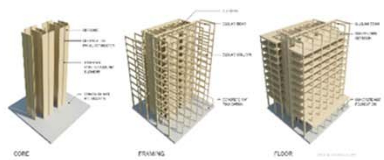
- **Non-structural components and systems (NSCs).**
  - Architectural, mechanical, electrical and plumbing, or building contents.
  - Improve our understanding of the seismic response of NCSs under multi-directional earthquake excitation.
  - Advance the development of a reliable, unified design methodology 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.

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

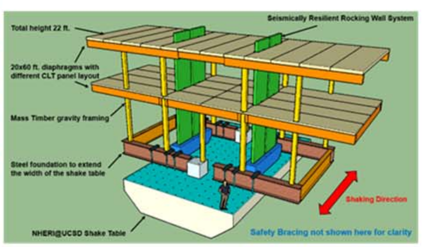
NHERI TallWood

Nheritallwood.mines.edu spei@mines.edu

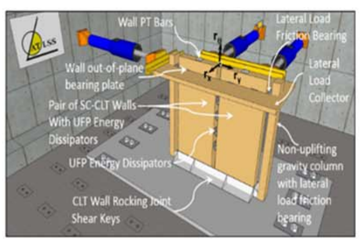


Define Tall Wood Archetypes

Investigative testing at system level

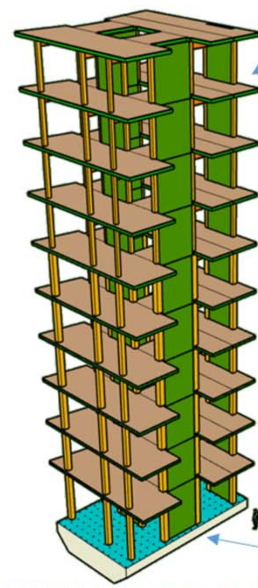


Two-story test at NHERI@UCSD 2017 Summer

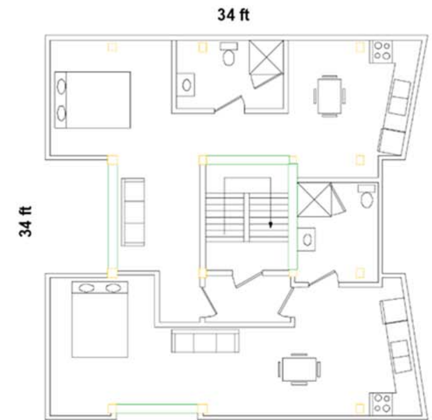


Assembly test at NHERI@Lehigh 2019

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

For More Information about the NHERI@UC San Diego Experimental Facility

- https://ucsd.designsafe-ci.org
- Contact one of the NHERI@UC San Diego team member:
  - Joel Conte, jpconte@ucsd.edu
  - Gilberto Mosqueda, gmosqueda@eng.ucsd.edu
  - Benson Shing, pshing@ucsd.edu
  - Lelli Van Den Einde, lellivde@ucsd.edu
  - Jose Restrepo, jrestrepo@ucsd.edu
  - Koorosh Lotfizadeh, klotfiza@ucsd.edu
- **Upcoming Workshops:**
  - Joint Workshop with the NHERI RAPID facility, December 2020 (Virtual or Hybrid)

THE NHERI NETWORK IS SUPPORTED BY MULTIPLE GRANTS FROM THE NATIONAL SCIENCE FOUNDATION.

NHERI

Natural Hazards Engineering Research Infrastructure