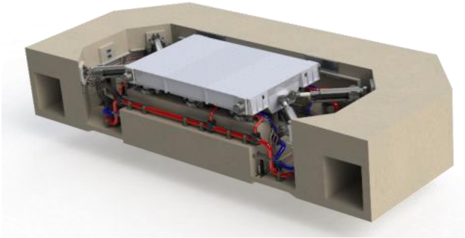
National Science Foundation

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 – Ninth User/Researcher Training Workshop



December 15-16, 2022
University of California, San Diego

General Housekeeping Items

- Workshop materials (workshop agenda, flyer, presentation PDFs, videos, etc.) can be downloaded from Google drive (link is provided in the agenda):

  https://drive.google.com/drive/folders/1N57_4xe2nqeROzVrLAkRmRTbu2qqIkBP

- To request PDH Credit Certificate, please contact:

  Dr. Koorosh Lotfizadeh

  E-mail: klotfiza@ucsd.edu

- For any problems and technical difficulties, please contact:

  Dr. Koorosh Lotfizadeh

  E-mail: klotfiza@ucsd.edu

Workshop Program – Thursday

Day 1 (Dec 15, 2022): Facility Capabilities, Past Projects, and Best Practices for Proposal Preparation

Time (PST)	Topic	Speaker
8:30 – 8:40 am	Welcome, Introduction & Workshop Schedule	Prof. Joel Conte, Dept. of Structural Engineering, UC San Diego
8:40 – 9:45 am	NHERI@UC San Diego: Facility Description and Capabilities, Research Enabled by LHPOST6	Prof. Joel Conte
9:45 – 10:15 am	Preparing an NSF Proposal to Utilize NHERI@UC San Diego	Prof. John van de Lindt, Colorado State University
10:15 – 10:30 am	Break	
10:30 – 11:30 am	DesignSafe Tools and Capabilities (Including Best Practices for Successful Upload/Organization of Data Depot)	Prof. Ellen Rathje DesignSafe Project Director, University of Texas at Austin Prof. Gilberto Mosqueda Dept. of Structural Engineering, UC San Diego
11:30 am – 12:00 pm	NSF NHERI Facilities and Research Programs, Q&A	Dr. Joy Pauschke National Science Foundation
12:00 – 1:00 pm	Lunch	
1:00 – 3:30 pm	Shake Table Tour (including 30 min travel to and from ESEC each way, 10-person group tours)	
3:30 – 4:00 pm	Structural Earthquake Engineering: List of Open Issues and Scope of Problems, Example Use of Facility to Address Scientific Needs	Prof. Jose Restrepo Dept. of Structural Engineering, UC San Diego
4:00 – 4:30 pm	Geotechnical Earthquake Engineering: List of Open Issues and Scope of Problems, Example Use of Facility to Address Scientific Needs	Prof. John McCartney Dept. of Structural Engineering, UC San Diego
4:30 – 5:00 pm	Keynote on Soil-Structure Interaction Issues	Prof. Scott Brandenberg, UC Los Angeles
5:00 – 5:30 pm	Q&A and Discussion	
5:30 – 5:45 pm	Closing Remarks	Prof. Joel Conte
6:00 – 7:30 pm	Dinner and Social Interaction	

Workshop Program – Friday

Day 2 (Dec 16, 2022): New Capabilities, Equipment, Future Projects, and Payload Opportunities

Time (PST)	Topic	Speaker
8:30 – 8:40 am	Welcome & Workshop Schedule	Prof. Joel Conte Dept. of Structural Engineering, UC San Diego
8:40 – 9:00 am	Education and Community Outreach	Prof. Lelli Van Den Einde Dept. of Structural Engineering, UC San Diego
9:00 – 10:00 am	Upcoming Project: TallWood	Prof. Shiling Pei Dept. of Civil & Environmental Engineering, Colorado School of Mines Prof. Keri Ryan Dept. of Civil & Environmental Engineering, University of Nevada, Reno Prof. Andre Barbosa Dept. of Civil & Construction Engineering, Oregon State University
10:00 – 10:15 am	Break	
10:15 – 10:30 am	Modular TestBed Building (MTB^2): A Reconfigurable Shared-Use Equipment Resource for Use by Researchers at LHPOST6	Prof. Machel Morrison Dept. of Structural Engineering, UC San Diego Prof. Gilberto Mosqueda Dept. of Structural Engineering, UC San Diego
10:30 – 11:30 am	SimCenter Tools and Capabilities for Experimental Researchers	Dr. Adam Zsarnóczay UC Berkeley SimCenter Dr. Sang-ri Yi UC Berkeley SimCenter
11:30 – 12:00 pm	IT Resources, Cybersecurity, and Instrumentation/DAQ	Dr. Koorosh Lotfizadeh Dept. of Structural Engineering, UC San Diego
12:00 – 12:20 pm	Q&A and Discussion	
12:20 – 12:30 pm	Concluding Remarks	Prof. Joel Conte

Workshop Objectives

- Showcase the features and capabilities of the newly upgraded (6-DOF) LHPOST6 supporting advanced earthquake engineering research.
- Highlight resources and equipment available to researchers at NHERI@UC San Diego LHPOST6 and learn about the resources and capabilities of NHERI SimCenter and DesignSafe.
- Explore opportunities to use the LHPOST6 for various types of NSF research proposals and provide researchers with information on best practices for competitive proposal preparation.
- Learn about and discuss the latest trends in shake table testing of structural and geotechnical systems and soil-structure interaction.
- 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.
- Brainstorm on example uses of the facility to solve grand challenges in earthquake engineering.
- Promote collaborative team research interests to use the LHPOST6.

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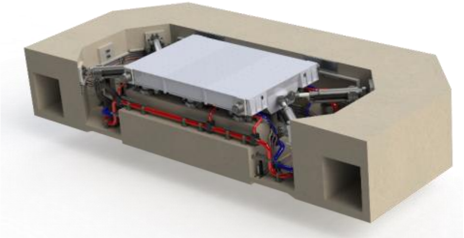
University of California at San Diego
NHERI
Natural Hazards Engineering Research Infrastructure

UC San Diego
JACOBS SCHOOL OF ENGINEERING
Structural Engineering

NHERI@UC San Diego: Facility Description and Capabilities – Research Enabled by LHPOST6

Joel Conte, Dept. of Structural Engineering, UC San Diego

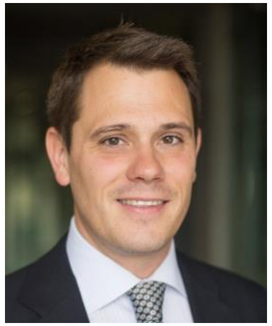


NHERI@UC San Diego User Training Workshop

December 15-16, 2021
University of California, San Diego

UC San Diego NHERI Renewal Team


Joel Conte
PI, Site Admin.


John McCartney
Co-PI, Site User Services


Machel Morrison
Co-PI, Site Operations


José Restrepo
Co-PI, Site Performance


Lelli Van Den Einde
Co-PI, ECO


Koorosh Lotfizadeh
Site Operation Mgr.


Abdullah Hamid
Dev. Engineer

TBN
Administrative Assist.


Anton Del Rosario
Financial Mgr.


Chin-Ta Lai
Ph.D. Student


Andres Rodriguez
Ph.D. Student


Robert Beckley
IT Manager


Alex Sherman
Dev. Tech./Safety Ofc.


Jeremy Fitcher
Dev. Tech.


Gilberto Mosqueda
Cap. Bld. Partn.


Georgios Tsampras
Cap. Bld. Partn.


Benson Shing
Cap. Bld. Partn.

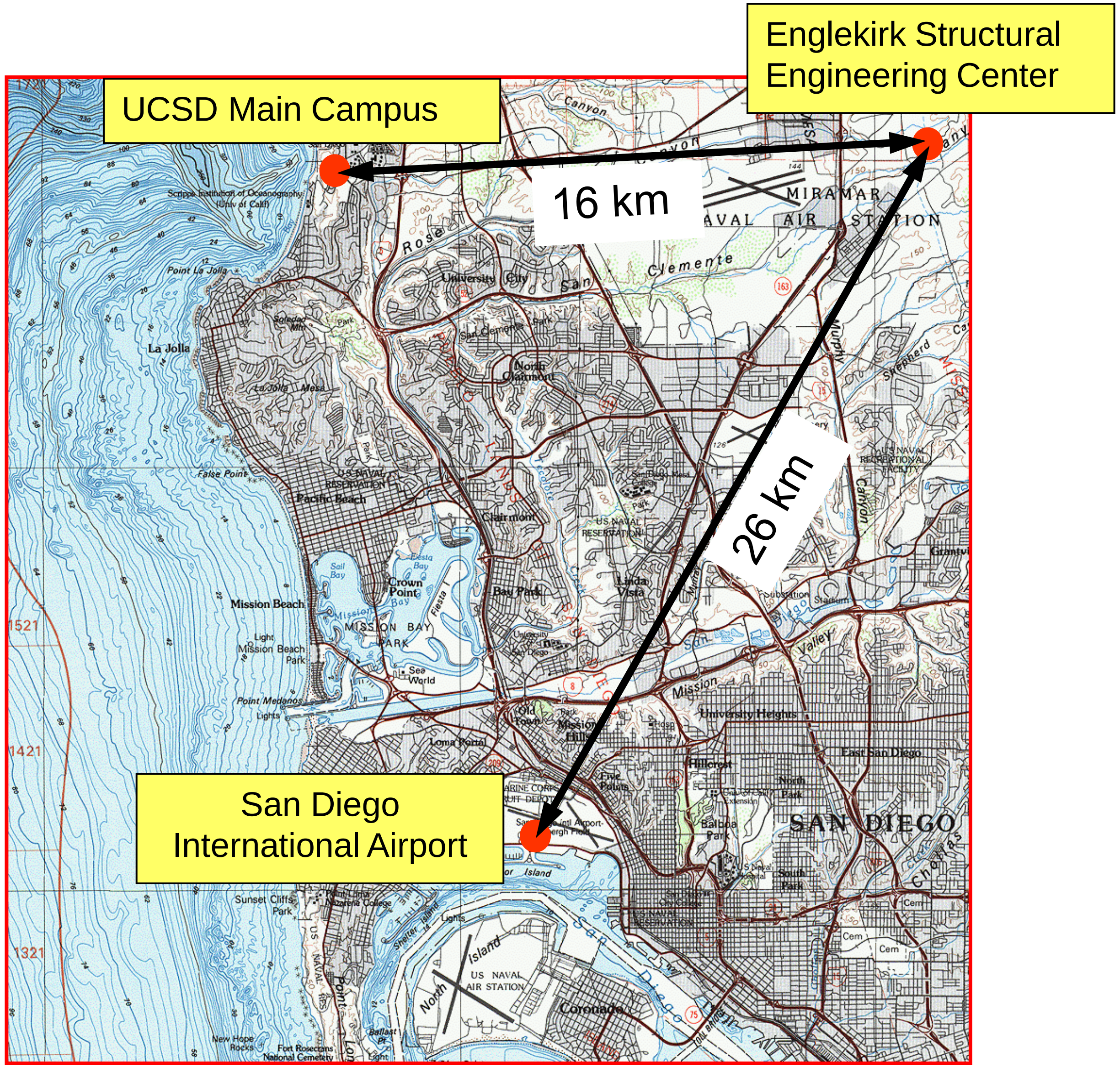

Tara Hutchinson
Cap. Bld. Partn.

Outline

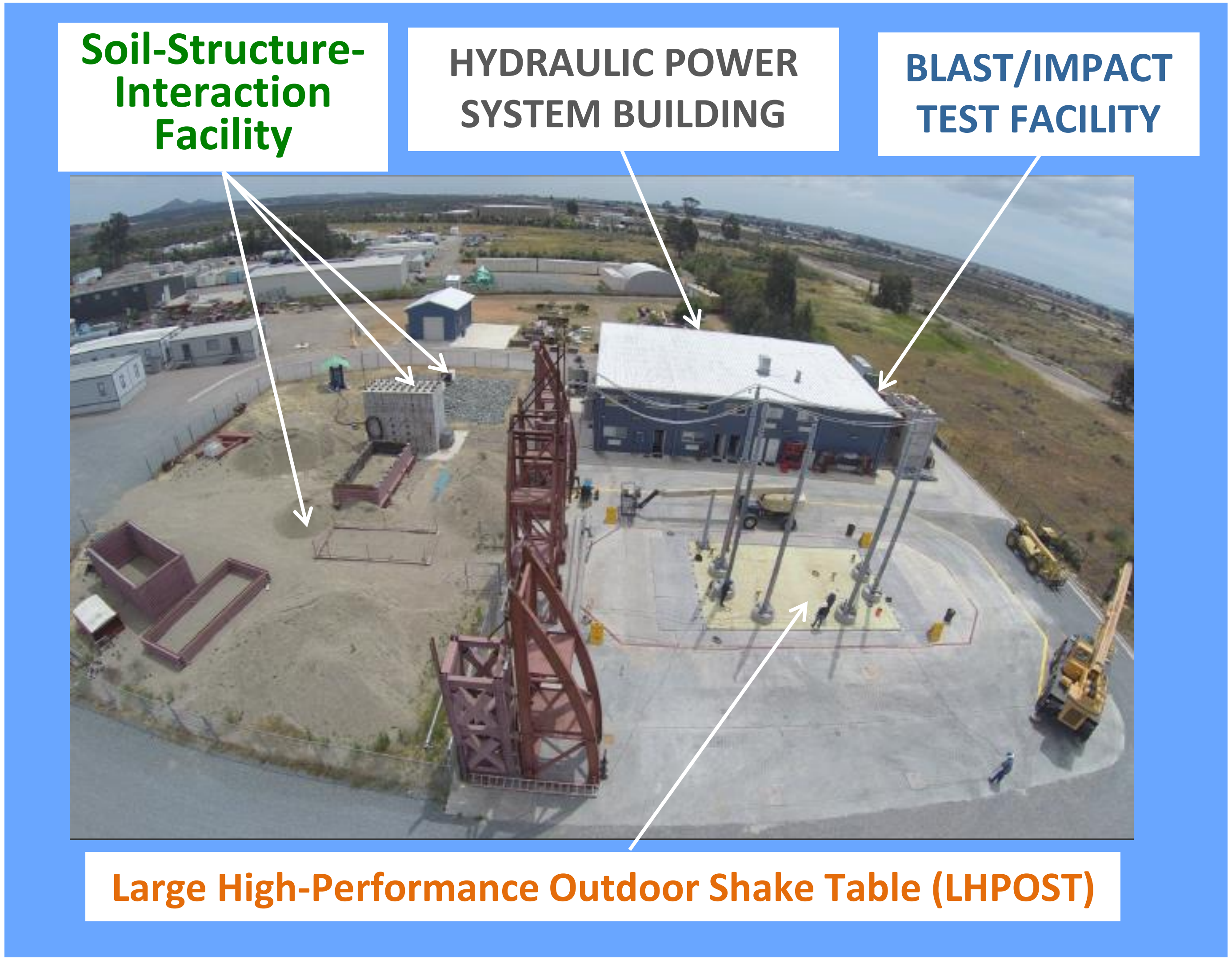
- Overview of Englekirk Structural Engineering Center
- Large High-Performance Outdoor Shake Table (LHPOST)
- Select Set of Shake Table Tests Performed on the NHERI@UC San Diego Shake Table
- Six Degree-of-Freedom (6-DOF) Upgrade of the LHPOST into the LHPOST6
  - Performance of the LHPOST6
  - Mechanics-based Numerical Model of the LHPOST6
- New Research Opportunities Made Possible by the LHPOST6

Overview of Englekirk Structural Engineering Center (ESEC)

Englekirk Structural Engineering Center (ESEC)



Englekirk Structural Engineering Center (ESEC)



Soil-Foundation-Structure Interaction Facility

Bridge Abutment - Soil Interaction (Caltrans)

Pile – soil interaction (Port of Los Angeles)

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

Large High-Performance Outdoor Shake Table (LHPOST)

Objectives of the NHERI@UC San Diego Experimental Facility

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

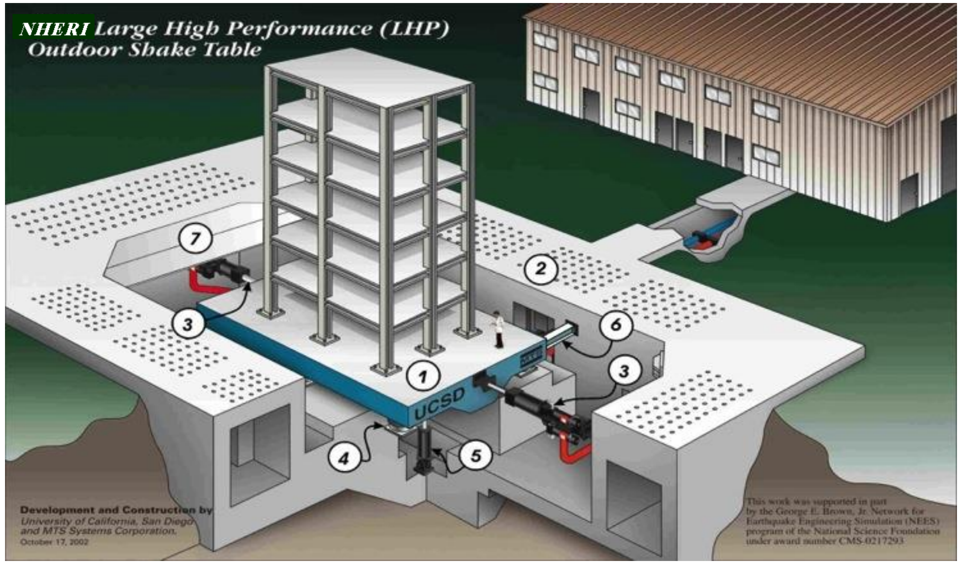
(1) Fundamental knowledge for understanding the **system-level behavior** of **buildings**, **critical facilities**, **bridges**, and **geo-structures** during earthquakes, **from the initiation of damage to the onset of collapse,** including the **effects of soil-structure interaction** and the **contributions of lateral and gravity load-resisting systems** and **non-structural systems**.

(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 design and performance assessment of civil infrastructure systems subjected to earthquake hazards.

(3) **Data and fragility information** to achieve the **full realization of Performance-Based Design**.

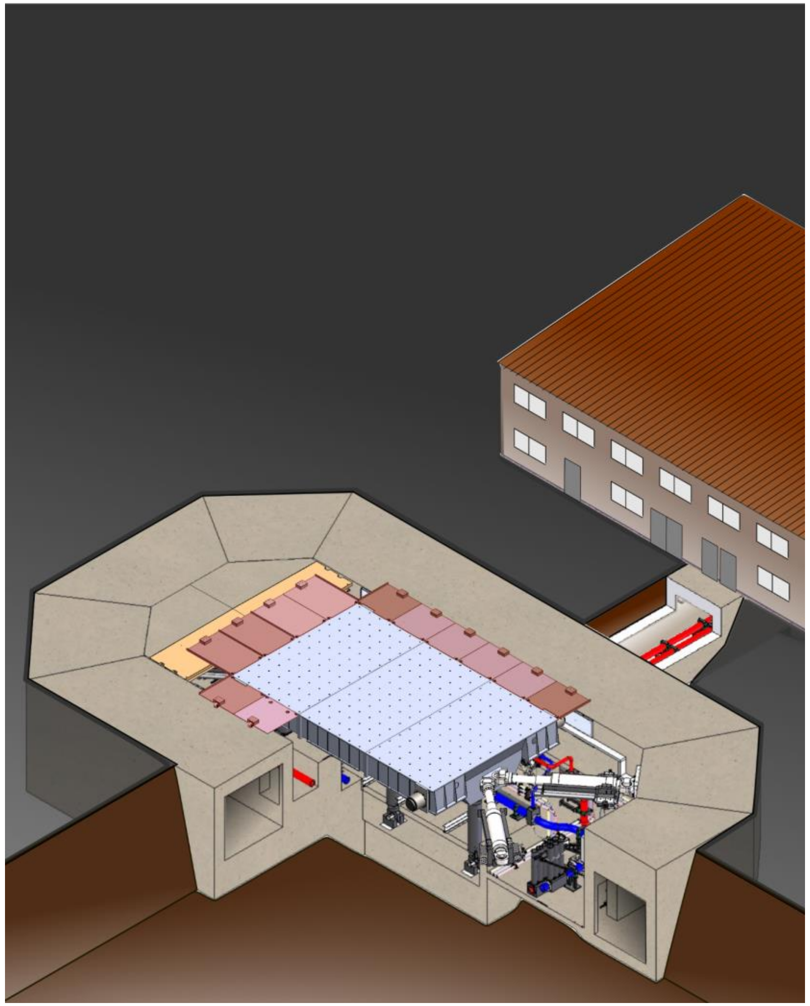
(4) **Ultimate validation tests** for protective systems, retrofit methods, and the use of innovative materials/components/systems, and construction/manufacturing methods that can protect civil infrastructure systems against earthquake hazards.

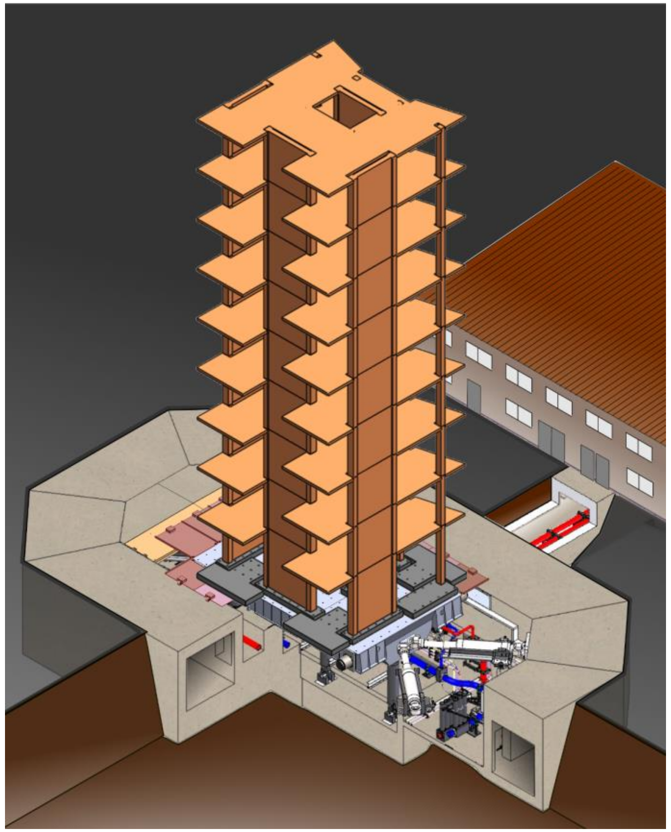
1-DOF Large High-Performance Outdoor Shake Table (LHPOST) 2004-2019



Performance Characteristics of LHPOST in Past 1-DOF Configuration (2004 – 2019)	
Designed as a 6-DOF shake table, but built as a 1-DOF system to meet 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 tonf 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)

6-DOF Large High-Performance Outdoor Shake Table (LHPOST6) 2022-Present





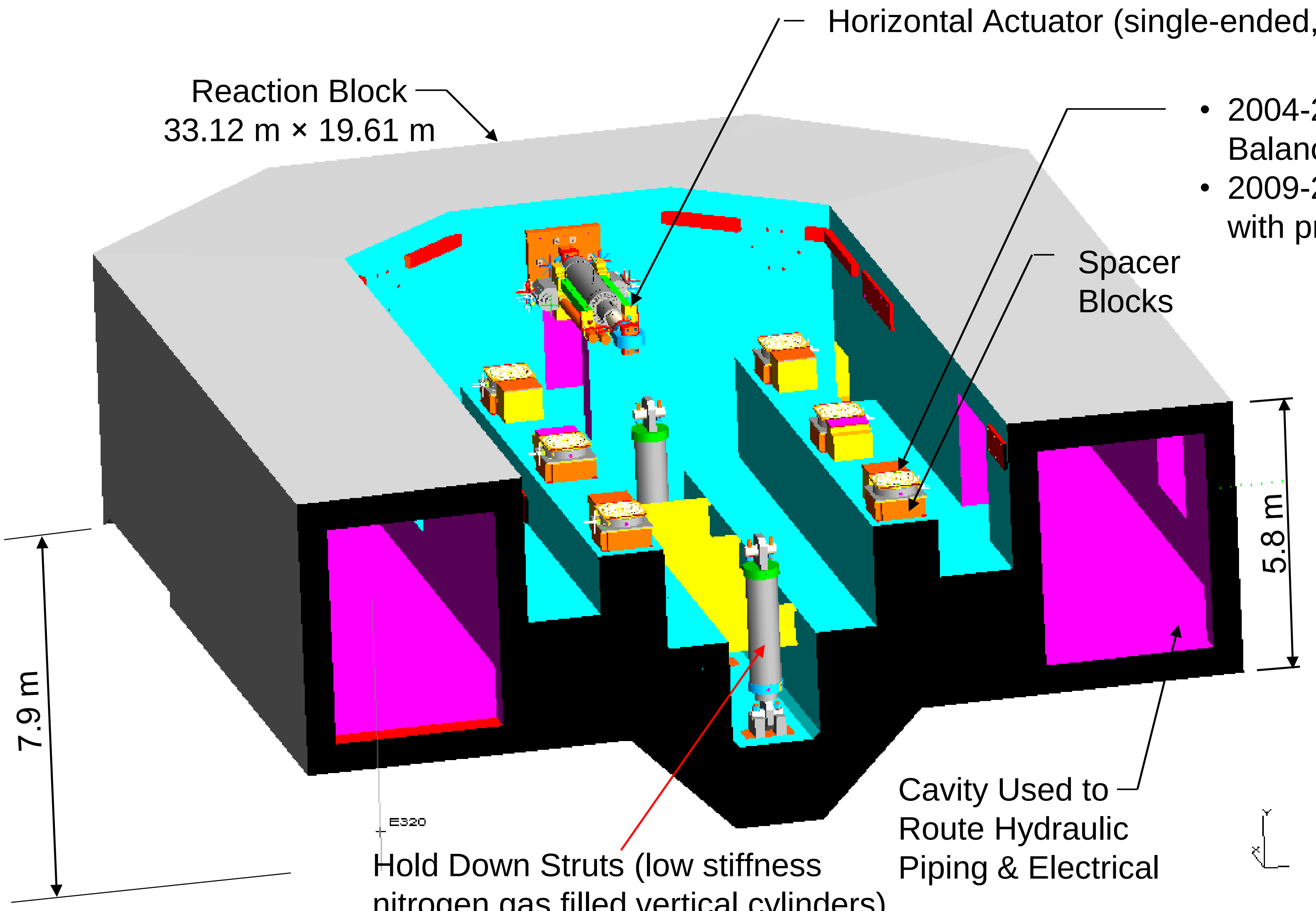
Large High-Performance Outdoor Shake Table (LHPOST)

- Designed to permit accurate simulation of severe earthquake ground motions and, particularly, strong near-source ground motions.
- Enables seismic testing of full- or very large-scale structural specimens of any height and a wide range of footprint dimensions.
- Table designed in 2001-2002, built in 2002-2004, and commissioned on October 1, 2004, as a shared-use experimental facility 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, spillway retaining walls
  - Underground structures (deep and shallow)

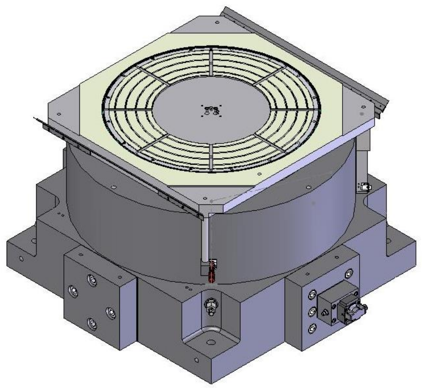
Capabilities/Provisions of the NHERI@UC San Diego LHPOST

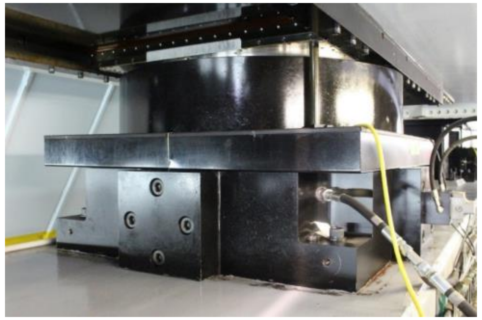
- **Simulation of near-source earthquake ground motions** which involve large acceleration, velocity and displacement pulses, **including six ground motion components (three translational and three rotational).**
- Seismic testing of **extensively instrumented large/full-scale structural specimens** 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.
- **Education** of graduate, undergraduate, and K-12 students from diverse backgropunds, as well as news media, policy makers, infrastructure owners, insurance and the general public, **about natural disasters** and the urgency of the **nation's efforts to develop effective technologies and policies to prevent these natural events from becoming societal disasters**.

1-DOF LHPOST (2004 –2019)

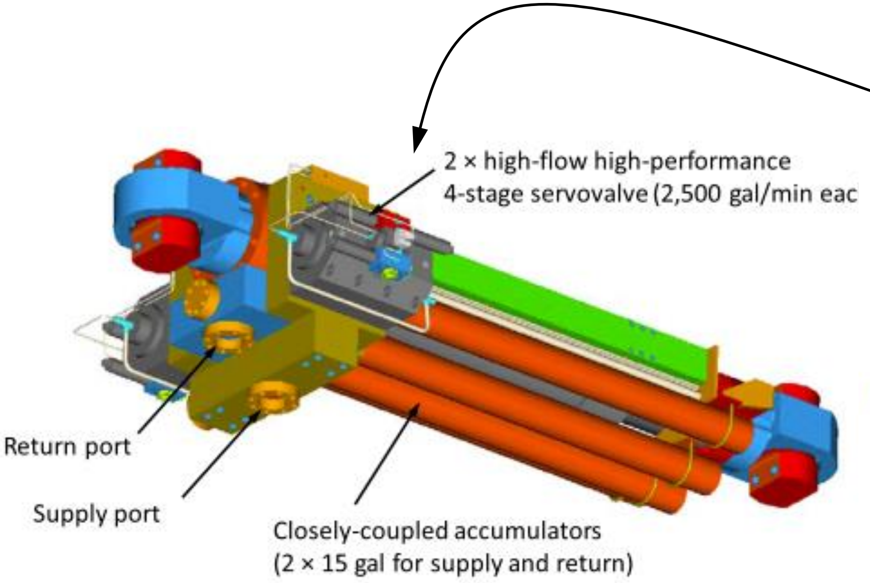


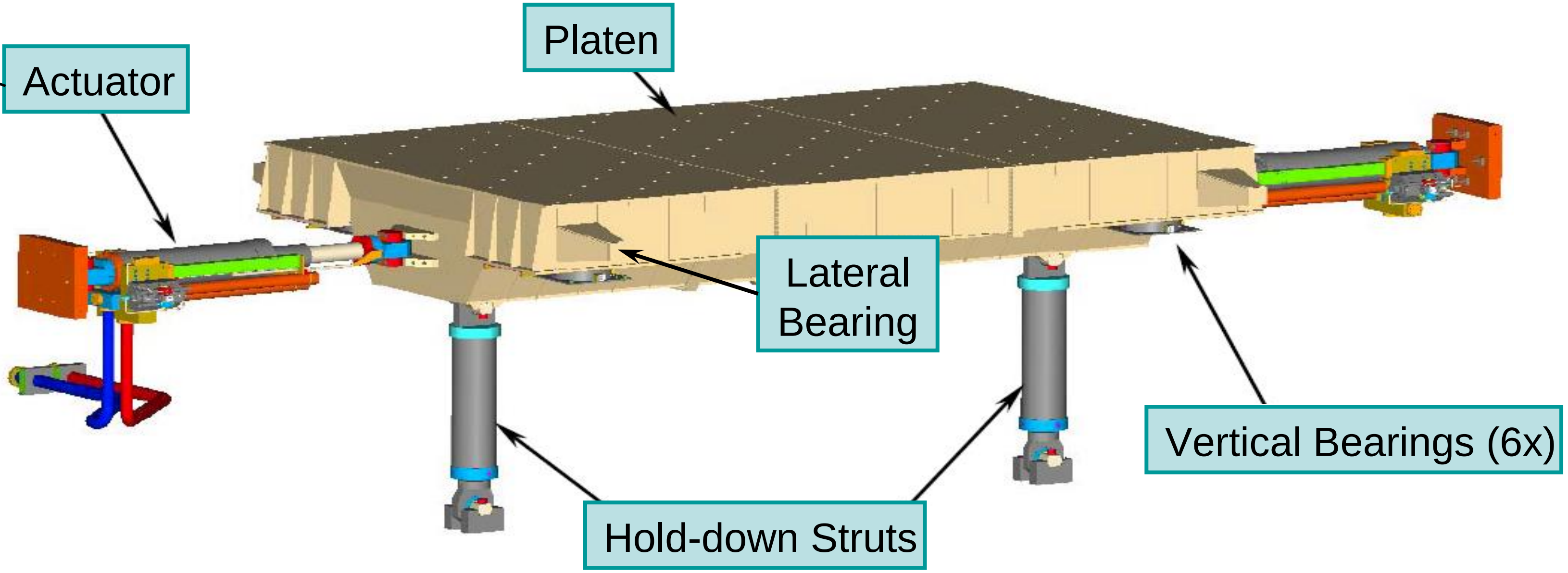
- 2004-2009: Vertical Pressure Balance Bearings
- 2009-2019: Actuators (non-ported) with pressure balanced bearings



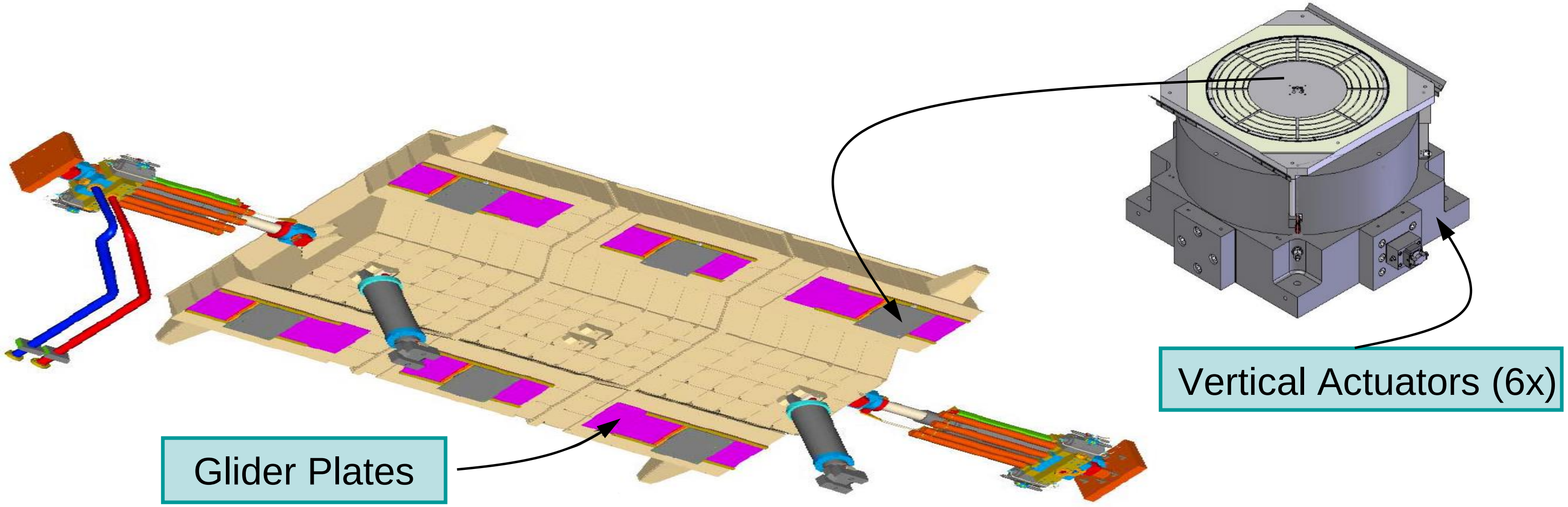


Mechanical and Servo-Hydraulic Components (1-DOF LHPOST: 2004 –2019)



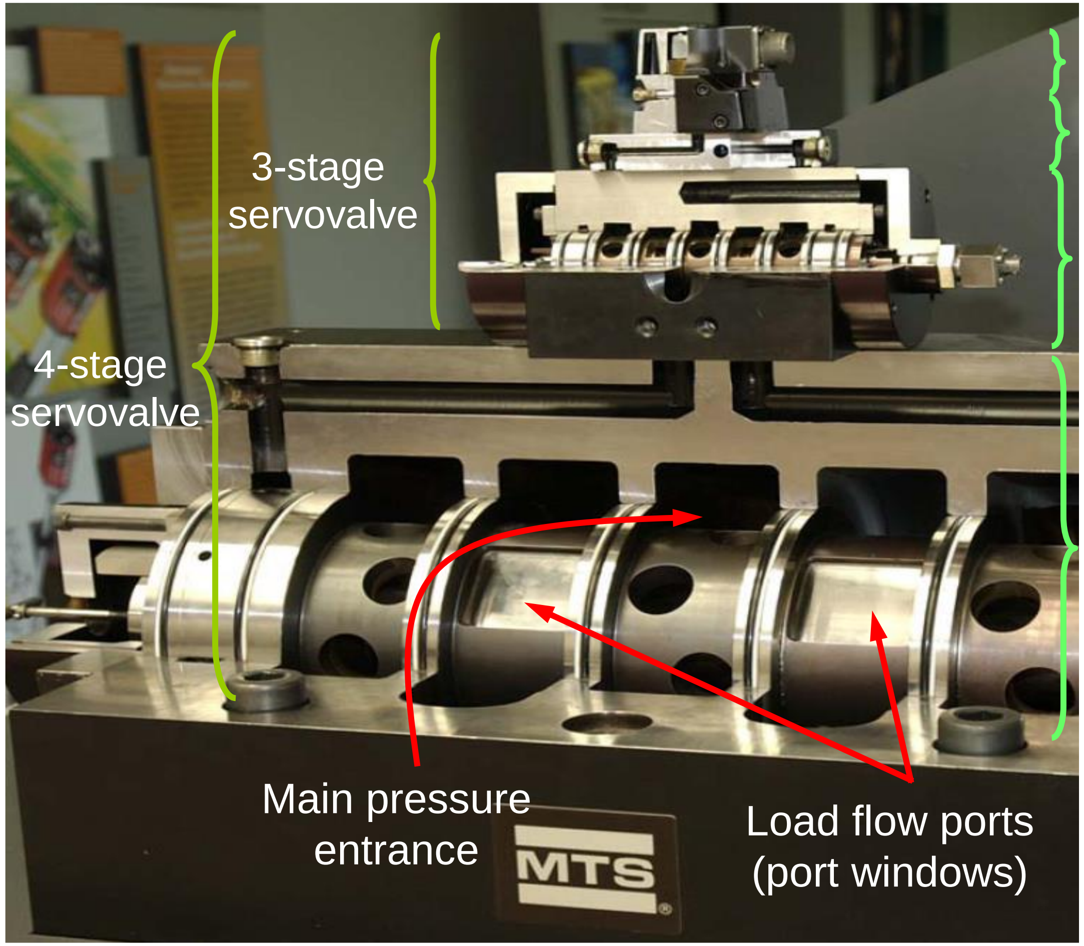


Horizontal Actuators Specification	
Dynamic stroke	+/- 0.75 m
Force Capacity (Tension/Compression)	2.7 MN / 4.2 MN
Rod diameter	0.3048 m
Piston Diameter	0.5080 m
Tension Area	0.1297 m^2
Compression Area	0.2027 m^2
Peak Extend Flow Rate	21,890 lt/min
Peak Retract Flow Rate	14,010 lt/min



High-Flow High-Performance Servovalves of Horizontal Actuators

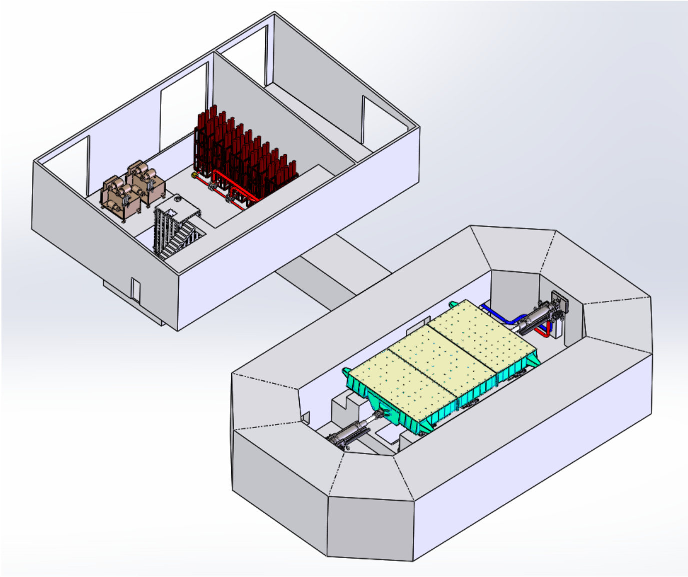
Servovalves (Qty. 2E + 2W)	
Pilot 2nd Stage Rating (Manufacturer Moog)	**19 lt/min**
Pilot 3rd Stage Rating	**630 lt/min**
4th Stage Flow Rating	**10,000 lt/min (2,500 gpm)**
Port Area Ratios	1:0.8:0.64:0.5
Valve Sleeve Windows Area Ratio	1:0.64

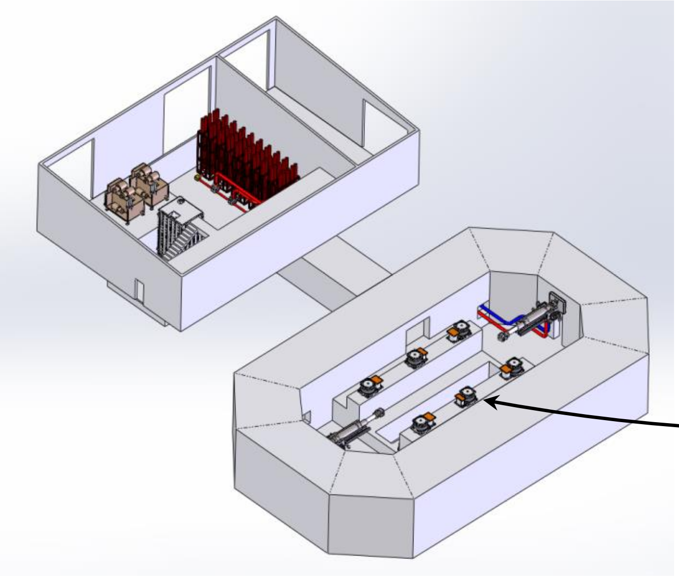


1st stage
2nd stage
Pilot valve
3rd stage
4th stage (main stage)

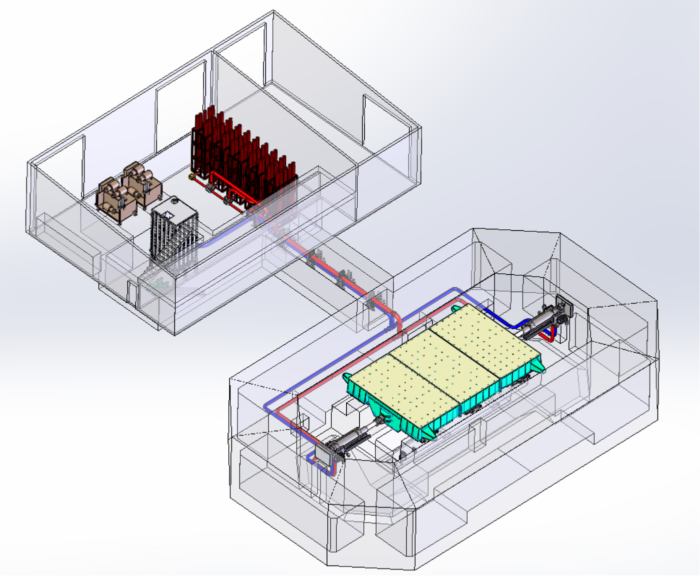
Courtesy of MTS Systems Corporation

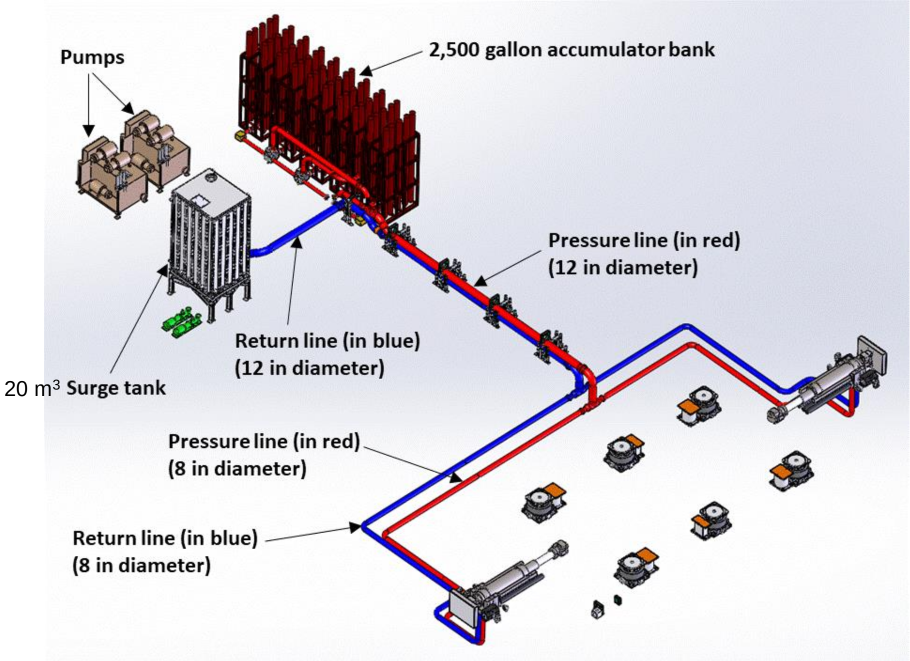
Hydraulic Power System of 1-DOF LHPOST (2004 –2019)





- 2004-2009: **Pressure balanced bearings**
- 2009-2019: **Actuators (non-ported)** with pressure balanced bearing



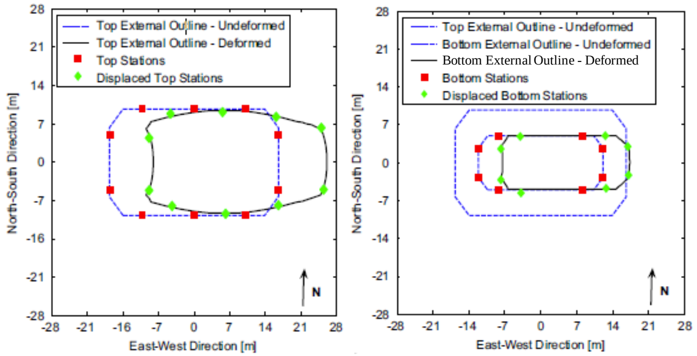


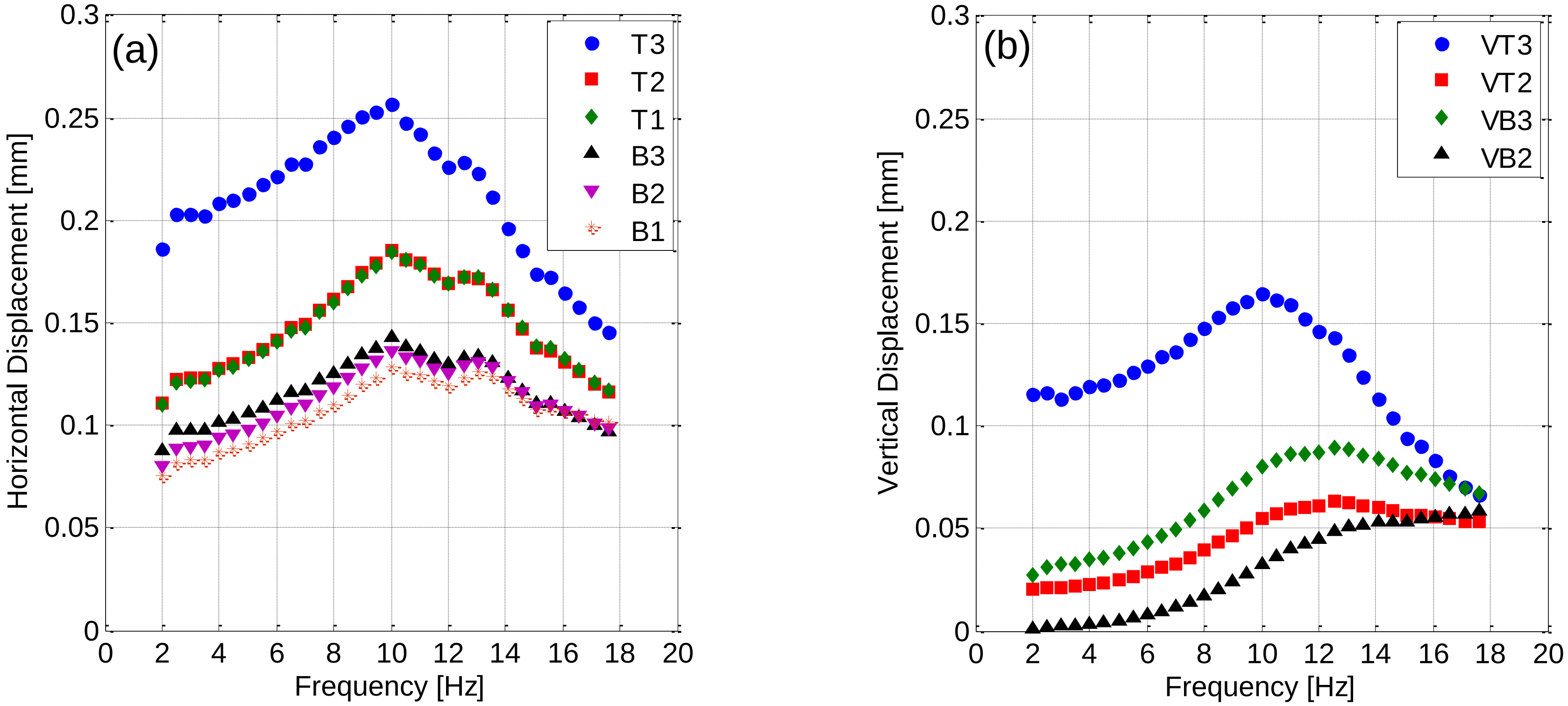
Bare Table Motion (1-DOF LHPOST)

Reaction Mass/Block

- Stiff soil conditions
- High radiation damping (effective damping ratio between 32% and 42%)
- Light reaction mass: 43.8 MN (4,380 tonf) for a vertical payload capacity of 20 MN (2,000 tonf).

Frequency Response Functions of Reaction Mass/Block





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.

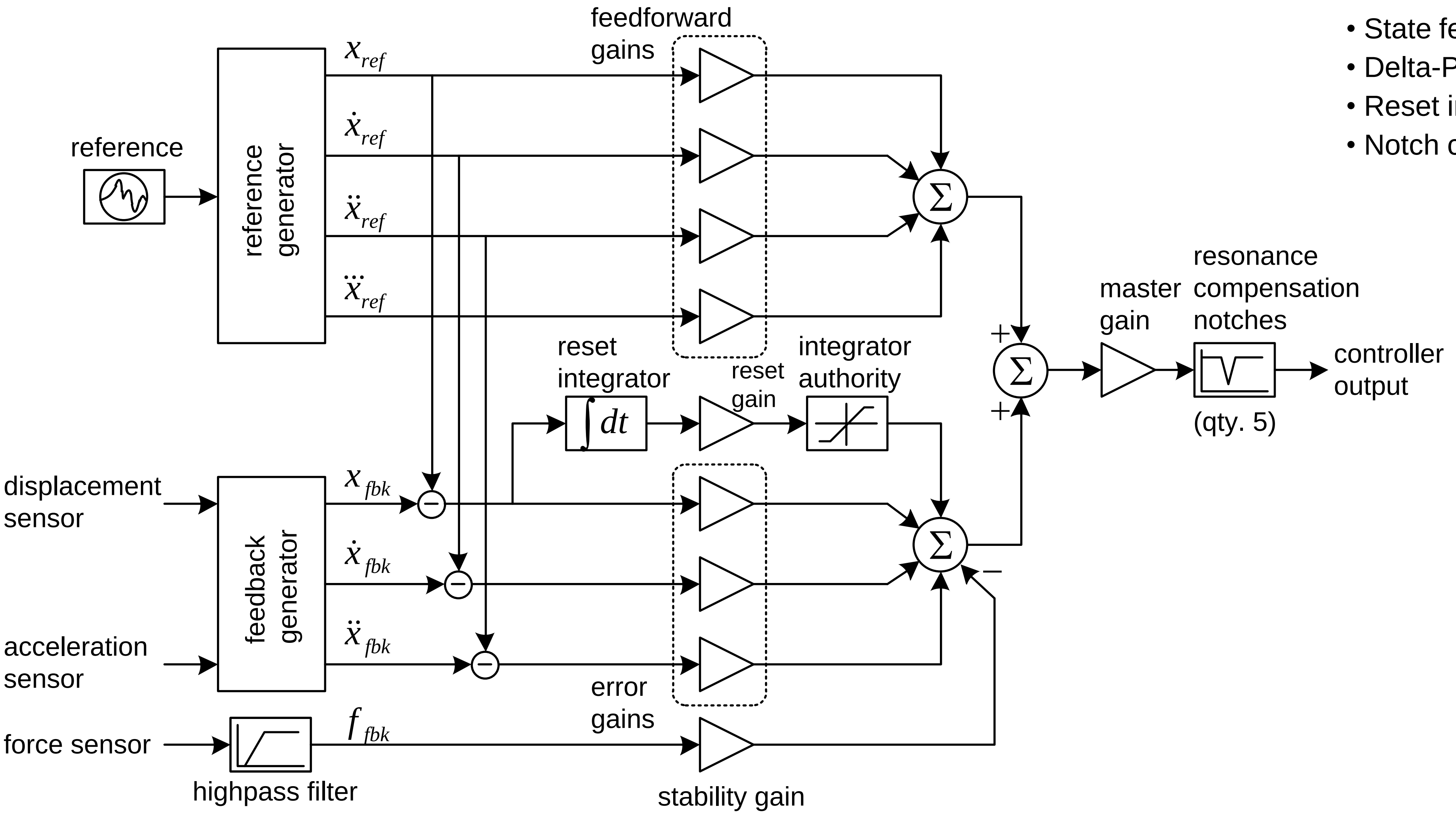
MTS Three-Variable Controller (TVC)

- **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 469D – Three-Variable Controller (TVC)

TVC = State-Variable Control + Extras



Components:

- State-variable controller
- State reference generator
- State feedback observer
- Delta-P stabilization
- Reset integrator
- Notch compensation

Courtesy of MTS Systems Corporation

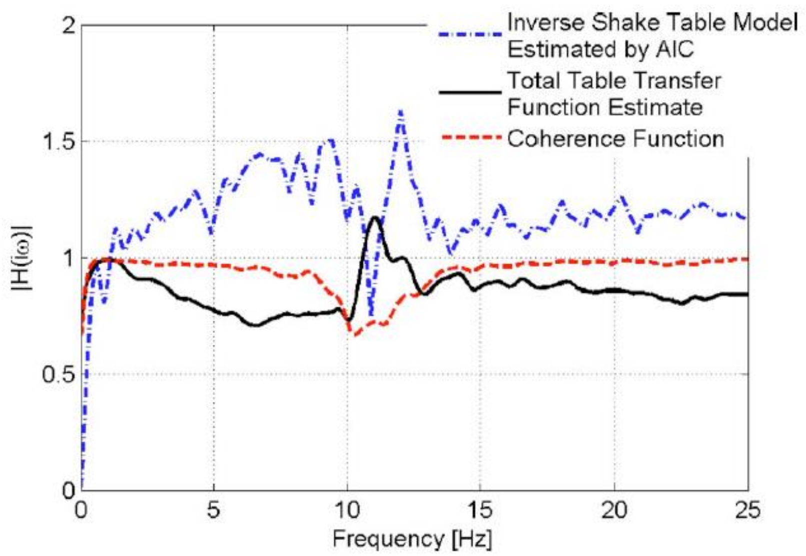
Tuning of LHPOST Controller (MTS 469D)

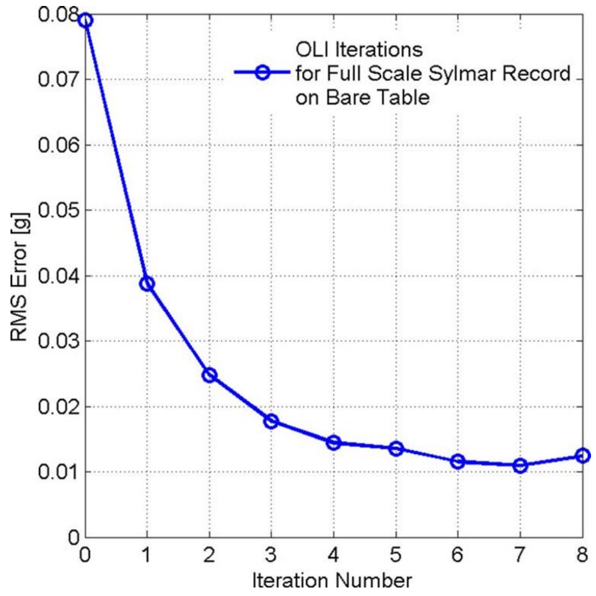
Tuning: Process of adjusting multiple control parameters (e.g., feedback and feedforward gains) and of preconditioning the input motion (through OLI) to optimize signal reproduction (tracking) capability of the shake table system.

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.

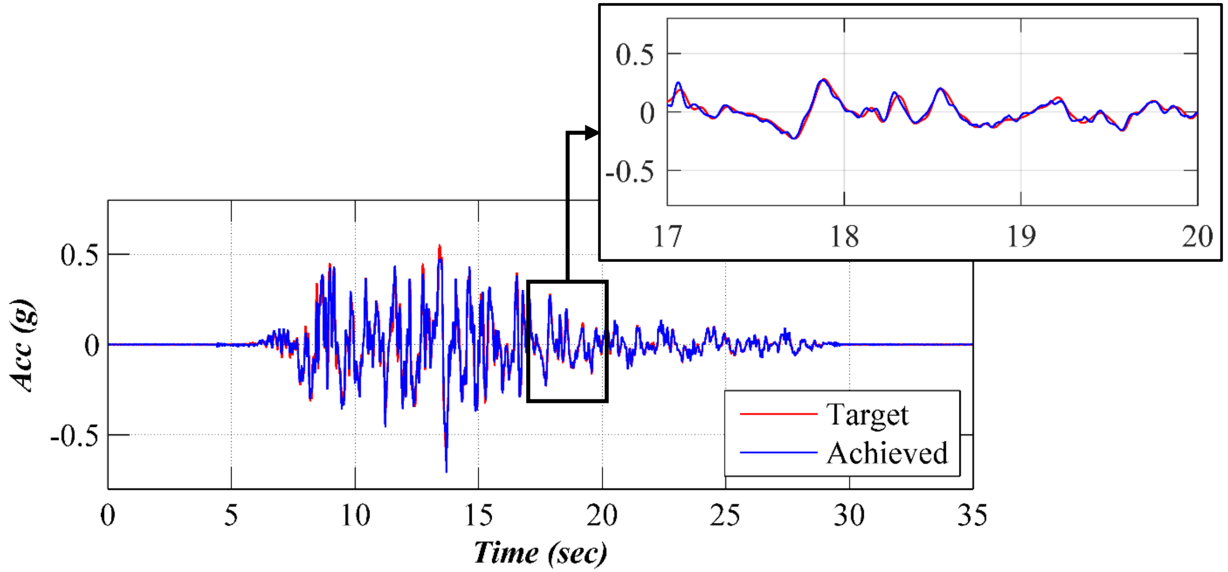
Step 2: Estimation of the inverse model of the plant using the adaptive inverse controller (AIC) technique.

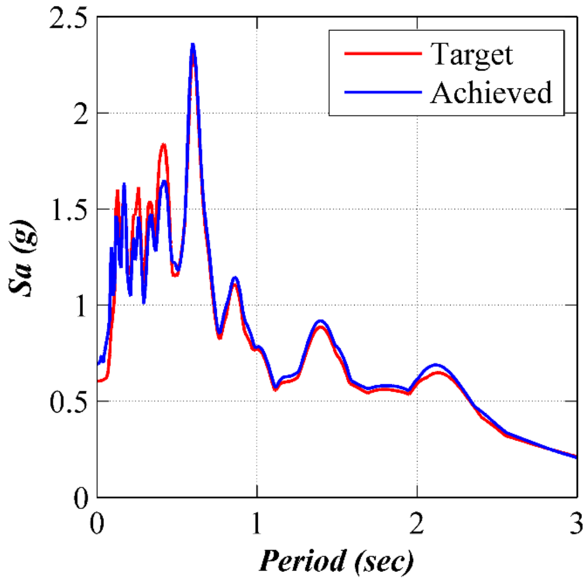
Step 3: Application of iterative time history matching technique called online iteration (OLI). The command input to the shake table controller (drive file) is repeatedly modified to optimize the match between the actual table motion and the desired/target motion (or reference signal).

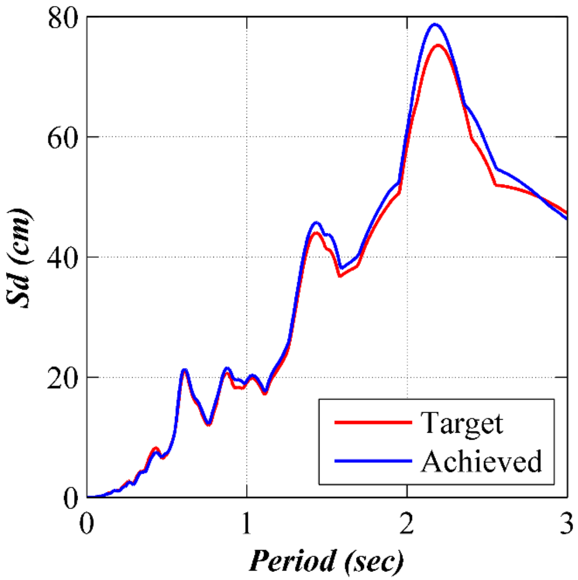




Tracking Performance of LHPOST (1-DOF)







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

Selected Shake Table Tests Performed on the LHPOST (1-DOF)

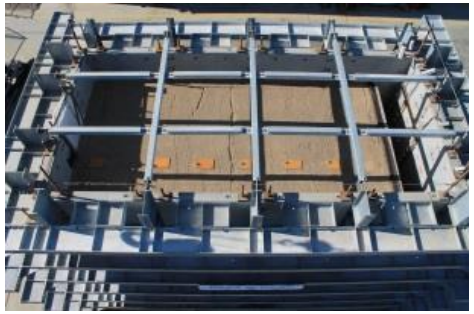
Select Set of Specimens Tested on the LHPOST (1-DOF)









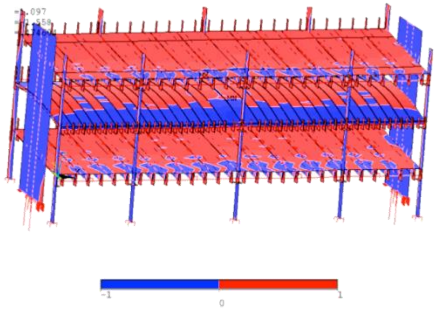




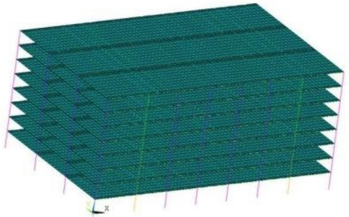
Integrated Experimental-Analytical Approach

Experimental Research
- Materials
- Structural components
- Structural systems

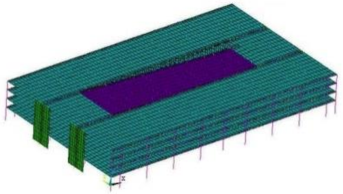
Computational Simulation
- Model development
- Model calibration
- Model validation



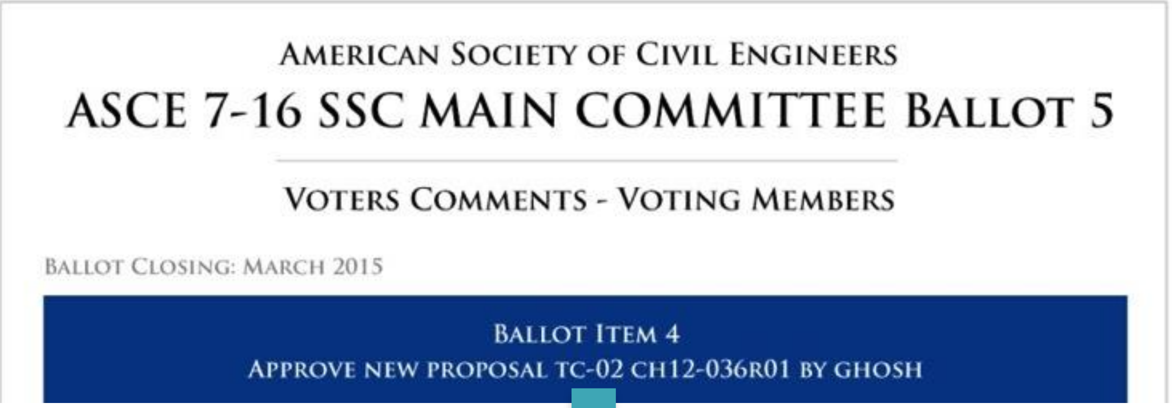
Design Provisions and Assessment Methods
- Development
- Verification through numerical simulation



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

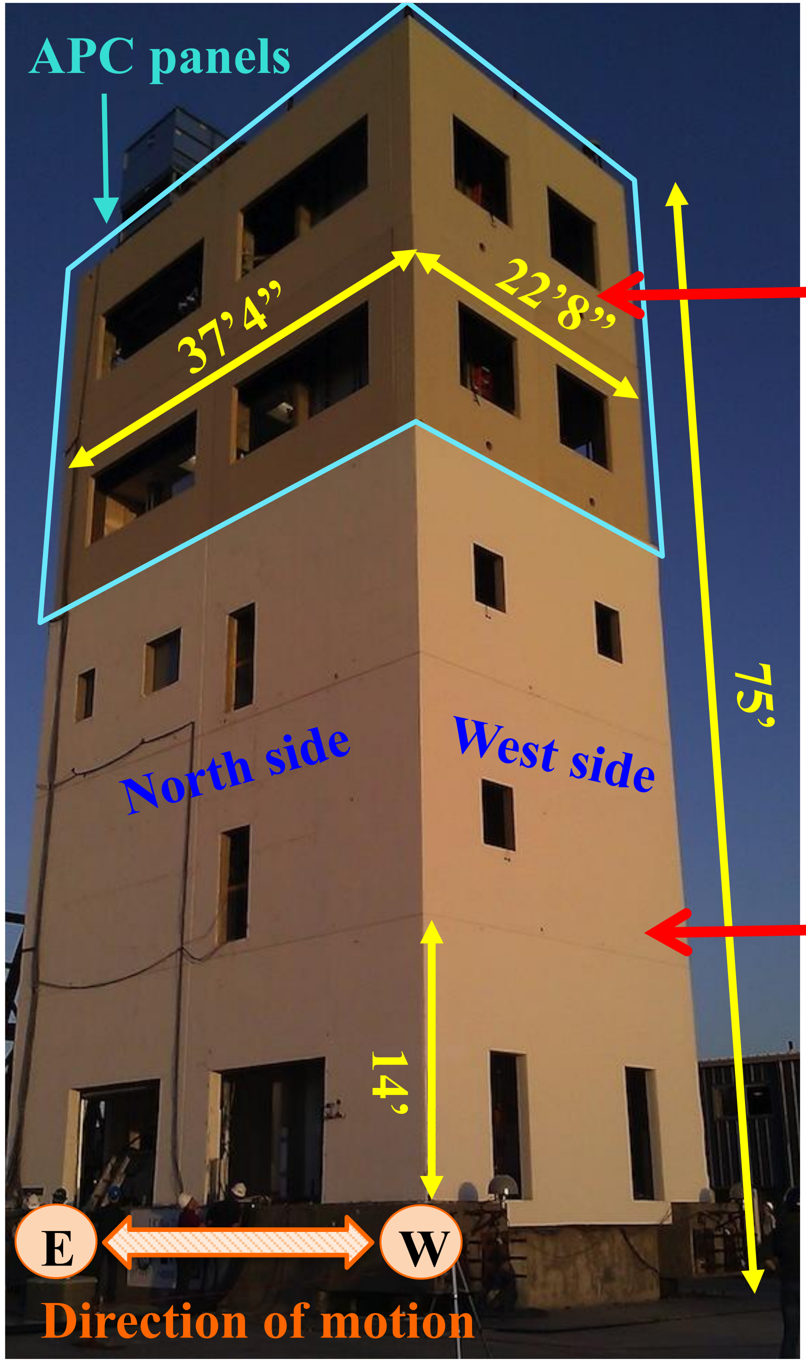
BALLOT ITEM 4
APPROVE NEW PROPOSAL TC-02 CH12-036R01 BY GHOSH

SUSTAINABLE AND SEISMIC/DISASTER RESILIENT BUILT ENVIRONMENT

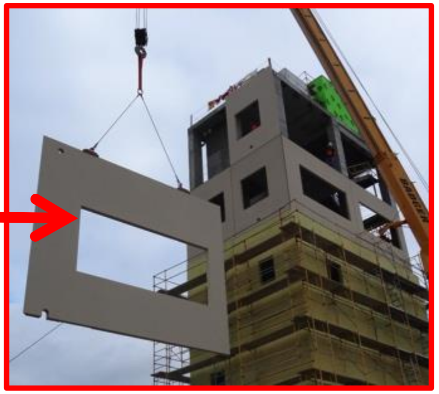
Full-scale Structural and Non-structural Building System Performance During Earthquakes

PI – Prof. Tara Hutchinson, UC San Diego

Exterior Facades



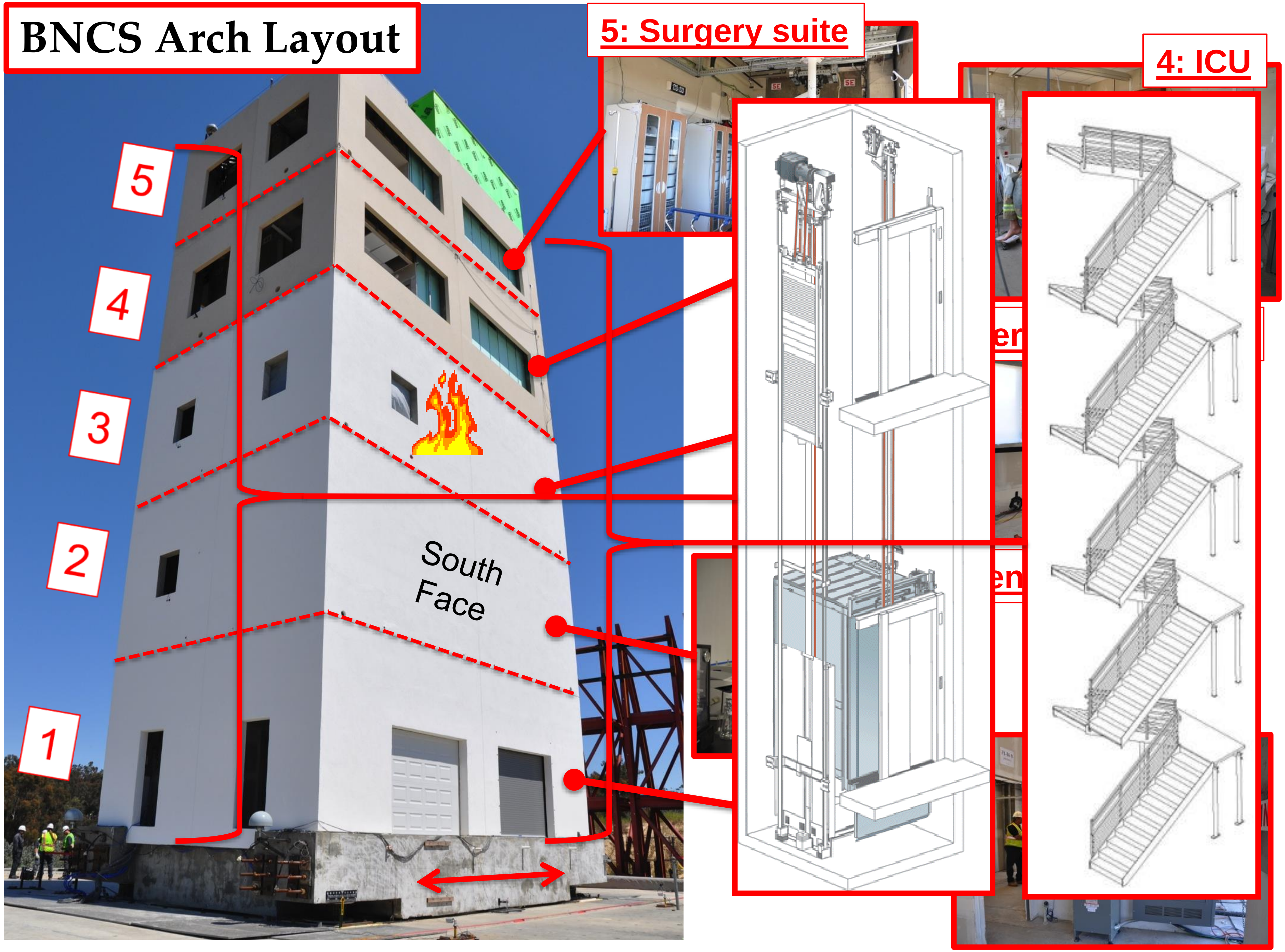
Architectural Precast Concrete Cladding



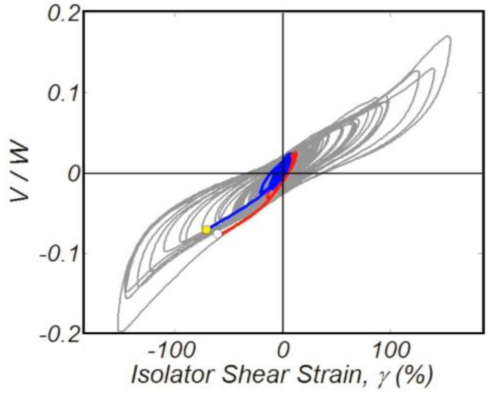
Balloon-framed metal stud+EIFS

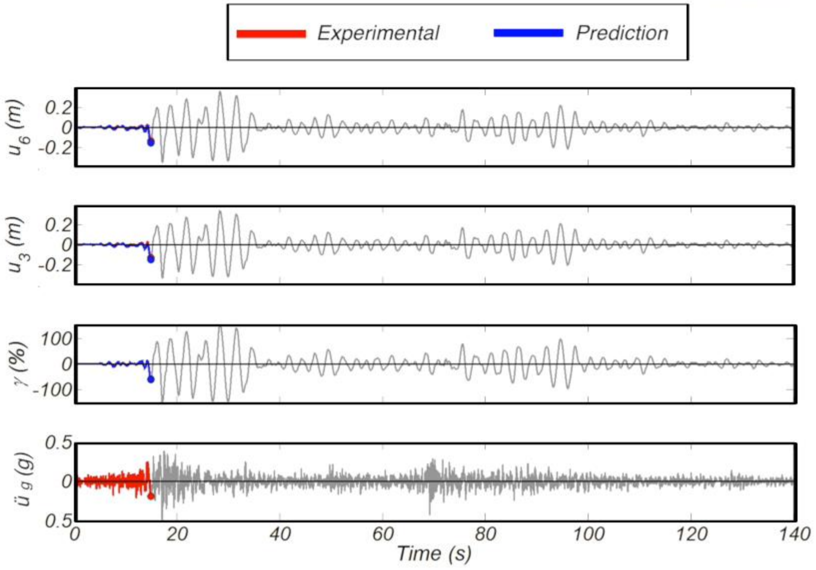
NW View

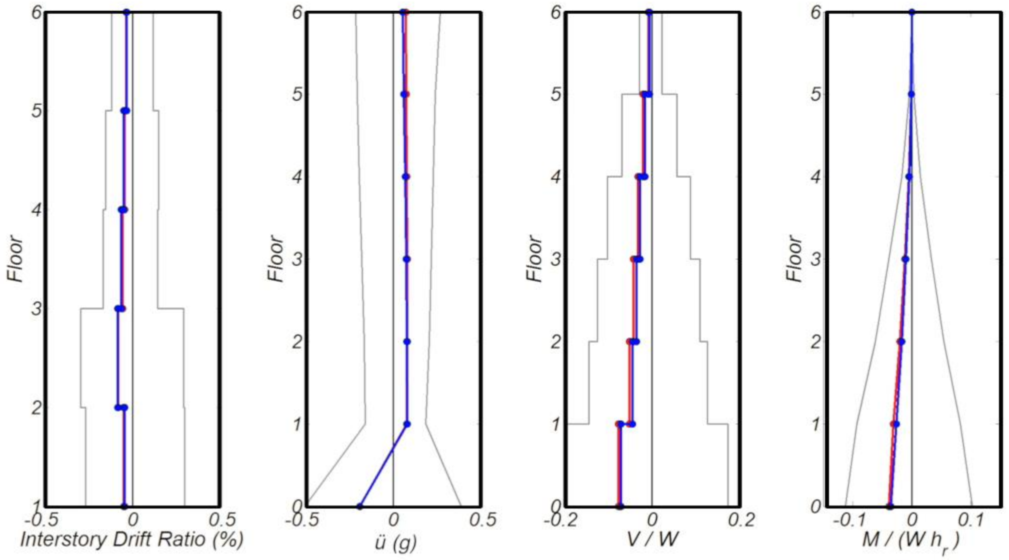
BNCS Arch Layout



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



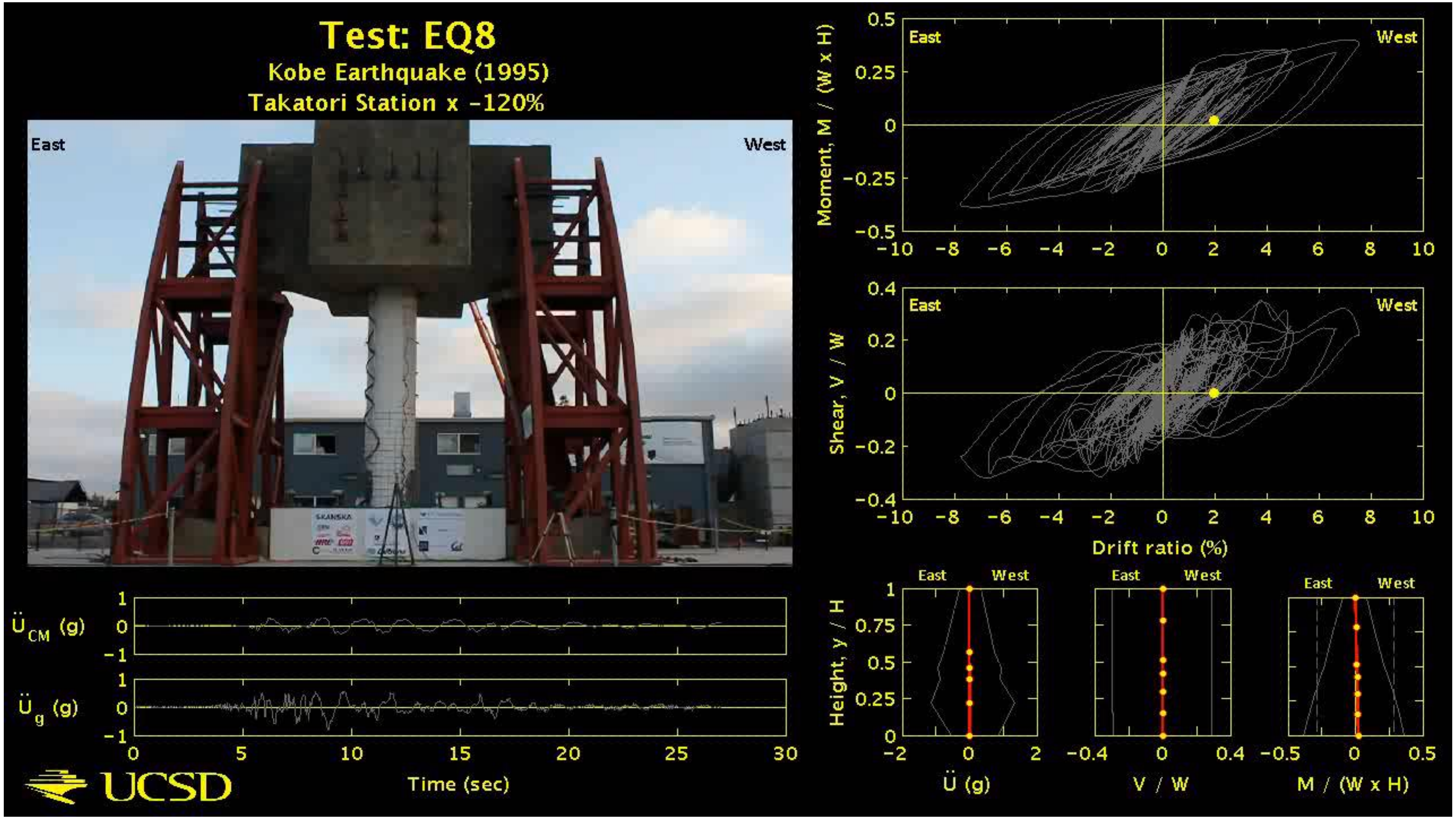


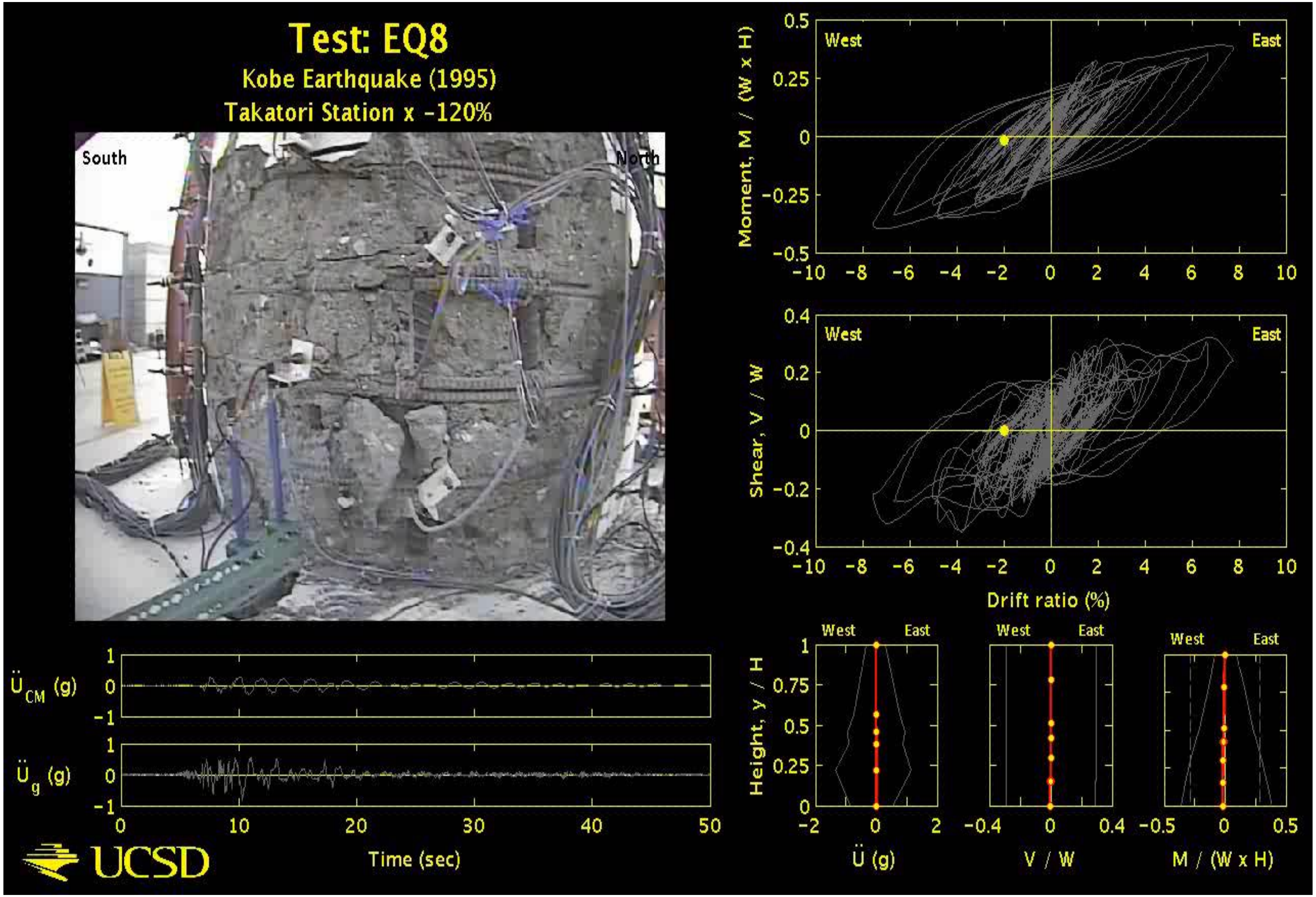


Full-Scale Structural and Nonstructural Building System Performance – Fixed Base

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
Moment, M / (W x H)
West
East
Shear, V / W
Drift ratio (%)
$\ddot{U}_{CM}$ (g)
$\ddot{U}_g$ (g)
Time (sec)
Height, y / H
$\ddot{U}$ (g)
V / W
M / (W x H)
UCSD

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

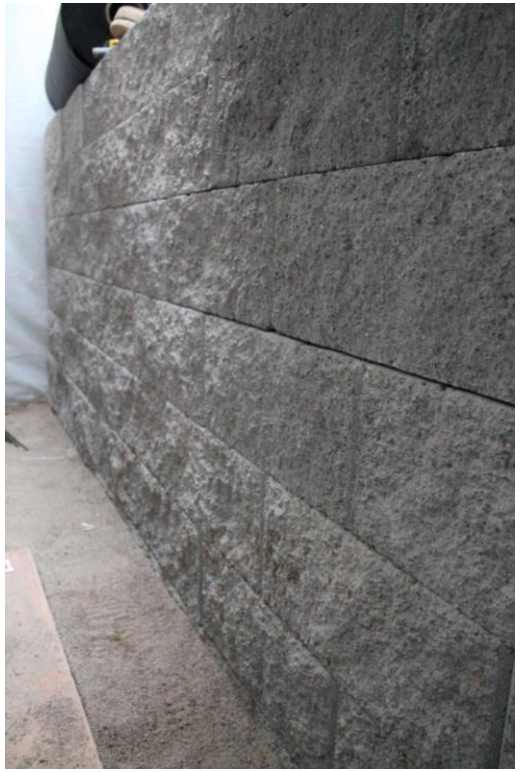
Liquefaction-Induced Lateral Spread Displacements and Soil-Pile Interaction in Multi-Layer Soil Strata

PI – Prof. Ahmed Elgamal, UC San Diego

Seismic Performance Tests of Full-Scale Retaining Walls

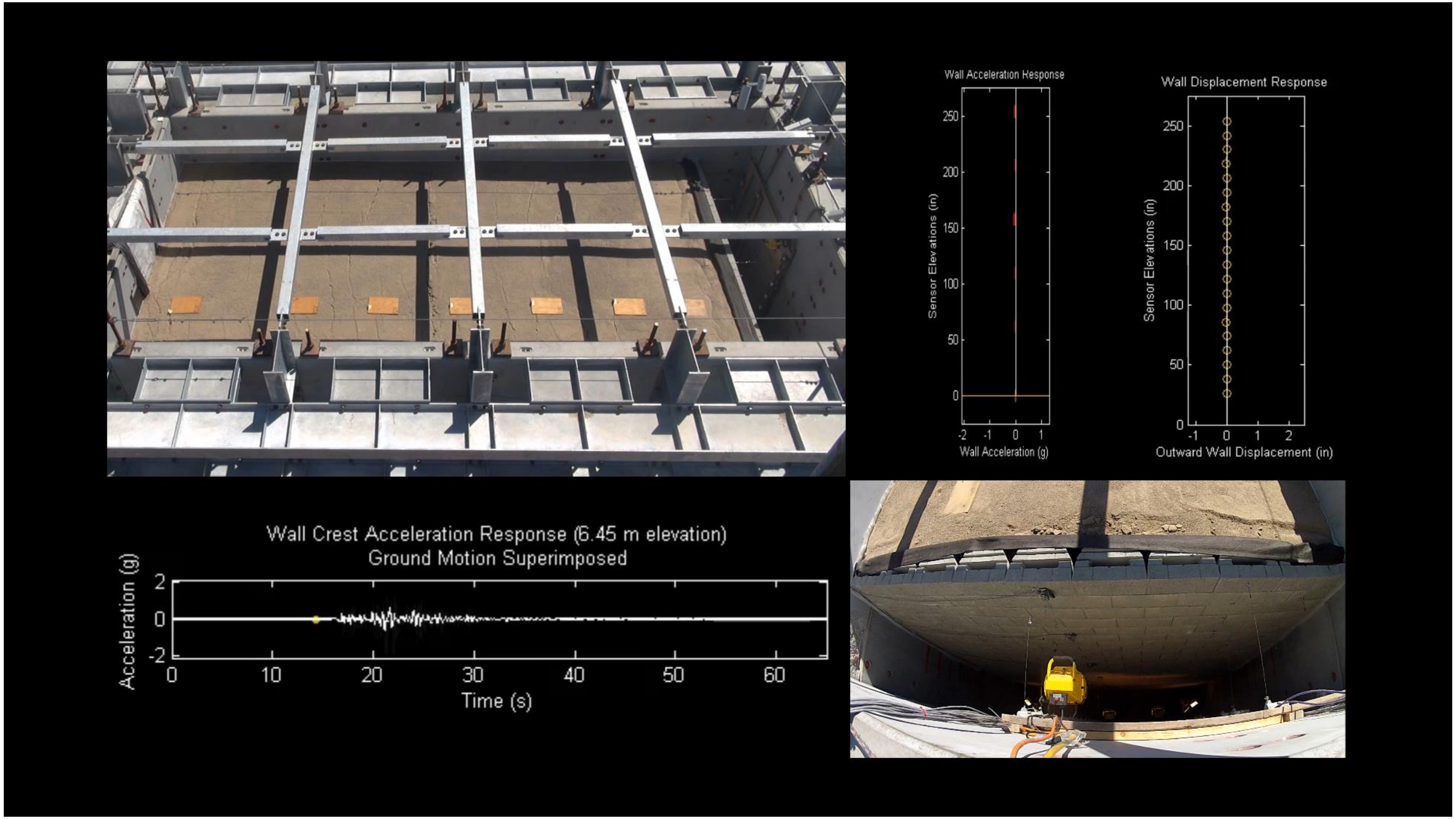
PI – Prof. Patrick Fox, UC San Diego

22 ft Above Table Elevation



Seismic Performance Tests of Full-Scale Retaining Walls

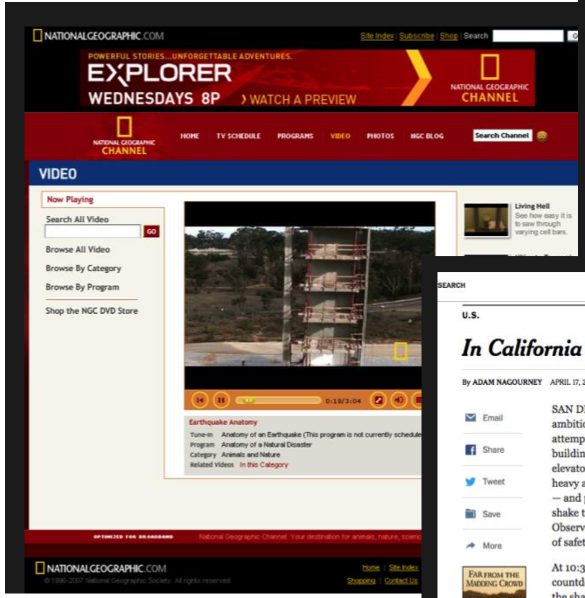
PI – Prof. Patrick Fox, UC San Diego



Staging Facility

Broad Public Dissemination

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



La estructura incluirá aisladores sísmicos chilenos:

Recrearán en EE.UU. el terremoto del 27-F en un edificio experimental de cinco pisos

La actividad forma parte de un ciclo de simulación de sismos que tendrá lugar la próxima semana en la Universidad de California, en San Diego.

Así es la mesa vibradora que replica sismos

Crece desarrollo de aisladores

Para teléfonos inteligentes:

Dos aplicaciones nacionales sacan provecho al GPS

Canal 13C: Documental sobre chilenos en Silicon Valley

Éxito de la cirugía: Edad del donante vivo no incide en un trasplante

The New York Times

U.S.

In California Quake Research, Boring Is the Hoped-for Result

By ADAM NAGOURNEY APRIL 17, 2012

SAN DIEGO — It was billed as one of the most ambitious earthquake simulations ever attempted. Engineers constructed a five-story building — complete with an operating room, an elevator, a kitchen loaded with glassware and a heavy air-conditioning unit perched on the roof — and placed it atop a platform known as a shake table on the outskirts of San Diego. Observers were issued hard hats and a strict set of safety instructions.

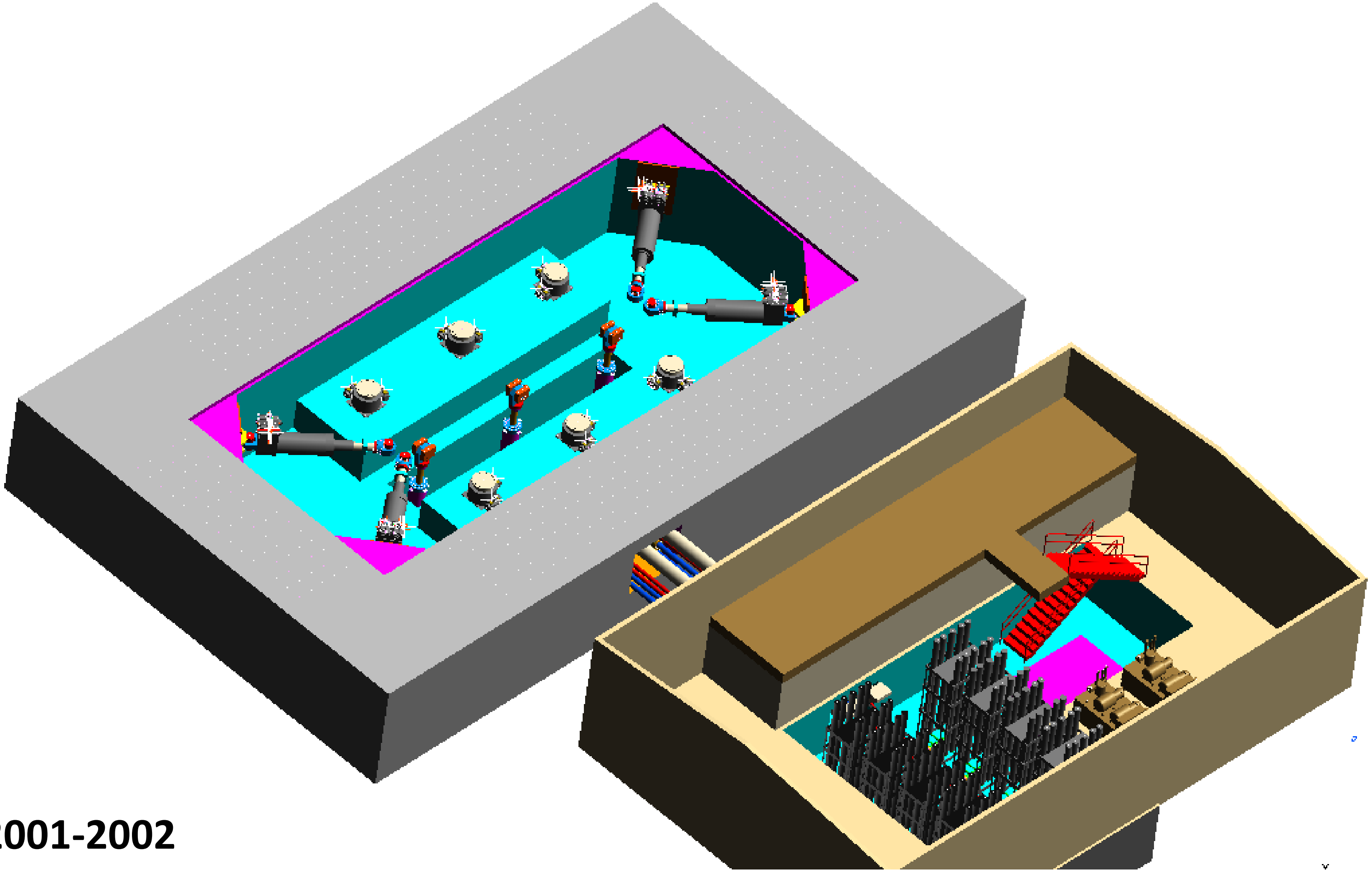
At 10:30 a.m. Tuesday, after an ominous countdown and as red warning lights whirled, the shake table unleashed the mechanical equivalent of a one-minute earthquake that replicated the 6.7-magnitude Northridge temblor that rolled through Los Angeles in 1994. It was the first of two earthquake re-enactments

Researchers conducted two earthquake simulations in San Diego on Tuesday.
Sam Hodgson for The New York Times

Six Degree-of-Freedom (6-DOF) Upgrade of LHPOST into LHPOST6

- Upgrade NSF proposal was awarded on October 1, 2018.
- Upgrade was designed in the period October 1, 2018 – September 30, 2019.
- Upgrade was built in the period October 15, 2019 – March 30, 2022

Upgrade to 6-DOF Capability Planned from the Start



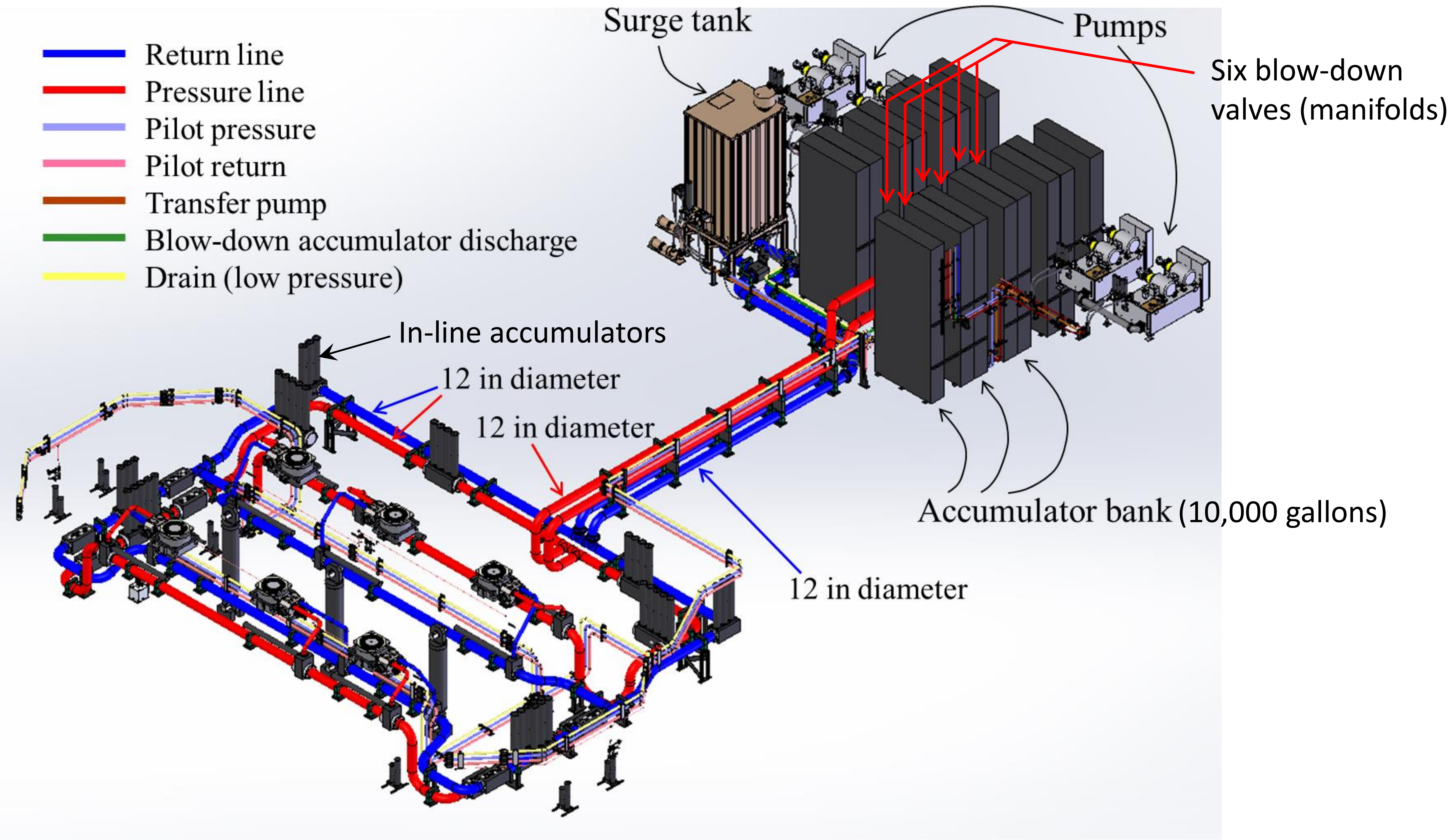
Rendering from 2001-2002

Tri-axial Strong Ground Motion Records Used to Design the 6-DOF Upgrade of the 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		-	1.01	0.96	0.71	1.04	1.13	0.77	0.22	0.21	0.12	0.70

Earthquake record	Peak flow rate [m^3/min] ([gpm])	Total flow [m^3] ([gallons])
Tabas, 1978	79.0 (20,859)	7.1 (1,872)
Chi-Chi, Taiwan, 1999	82.6 (21,815)	8.0 (2,125)
Kobe, 1995	52.5 (13,858)	5.1 (1,349)
Northridge, 1994	89.7 (23,687)	2.6 (687)
Nepal, 2015	33.8 (8,938)	8.3 (2,188)
AC-156 compatible	106.6 (28,158)	4.3 (1,130)

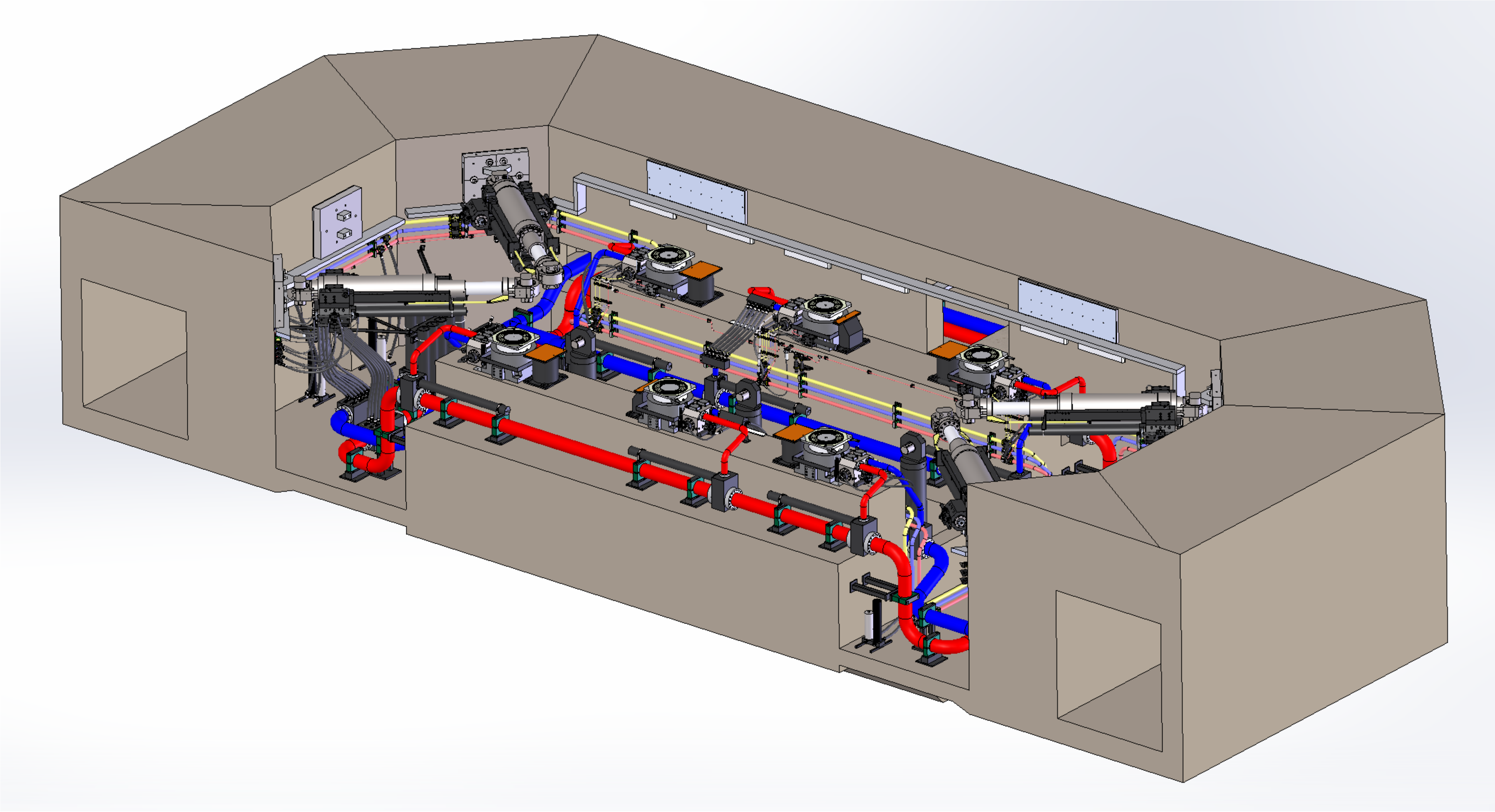
Hydraulic Power System of LHPOST6



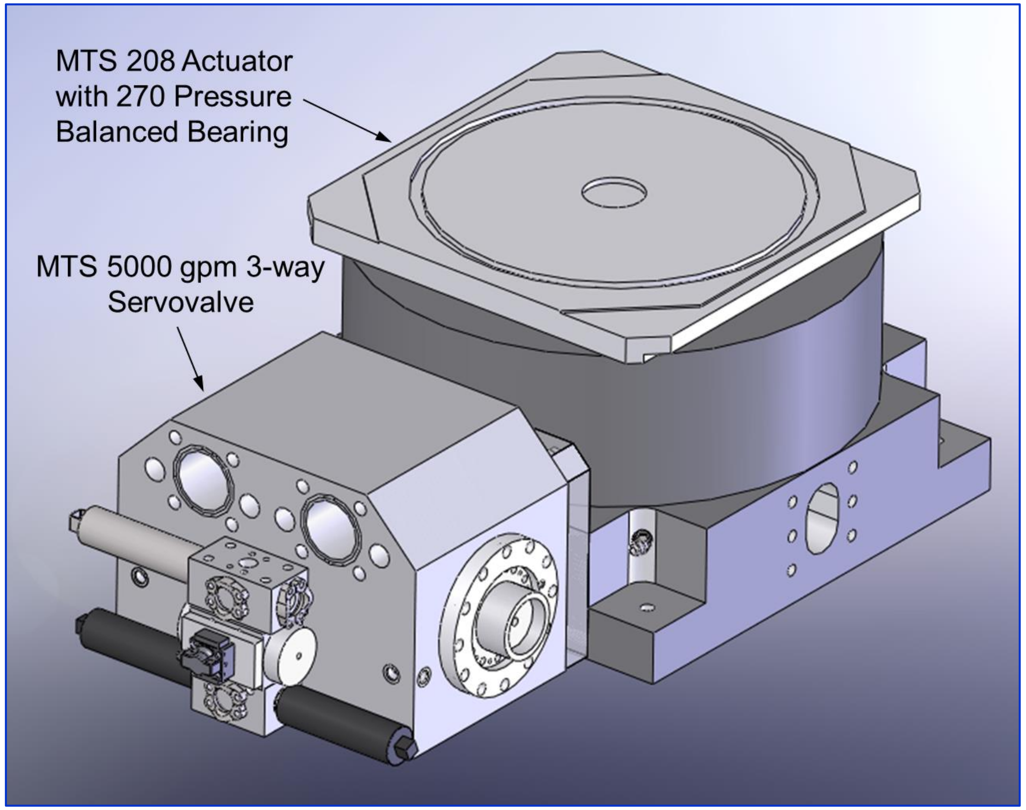
Accumulator Bank of LHPOST6

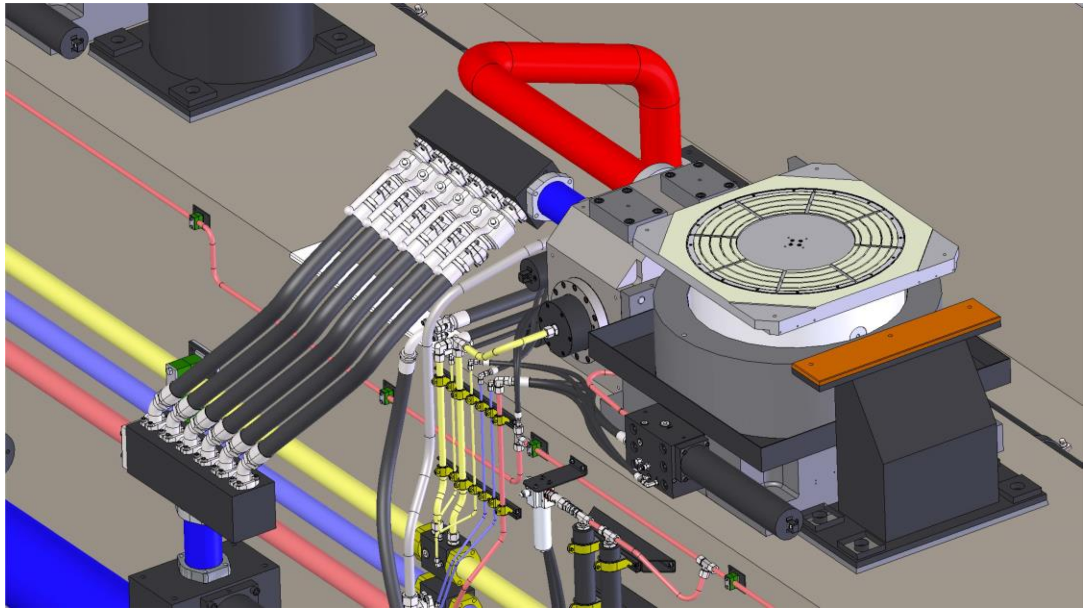
August 2020

Horizontal and Vertical Actuators of LHPOST6

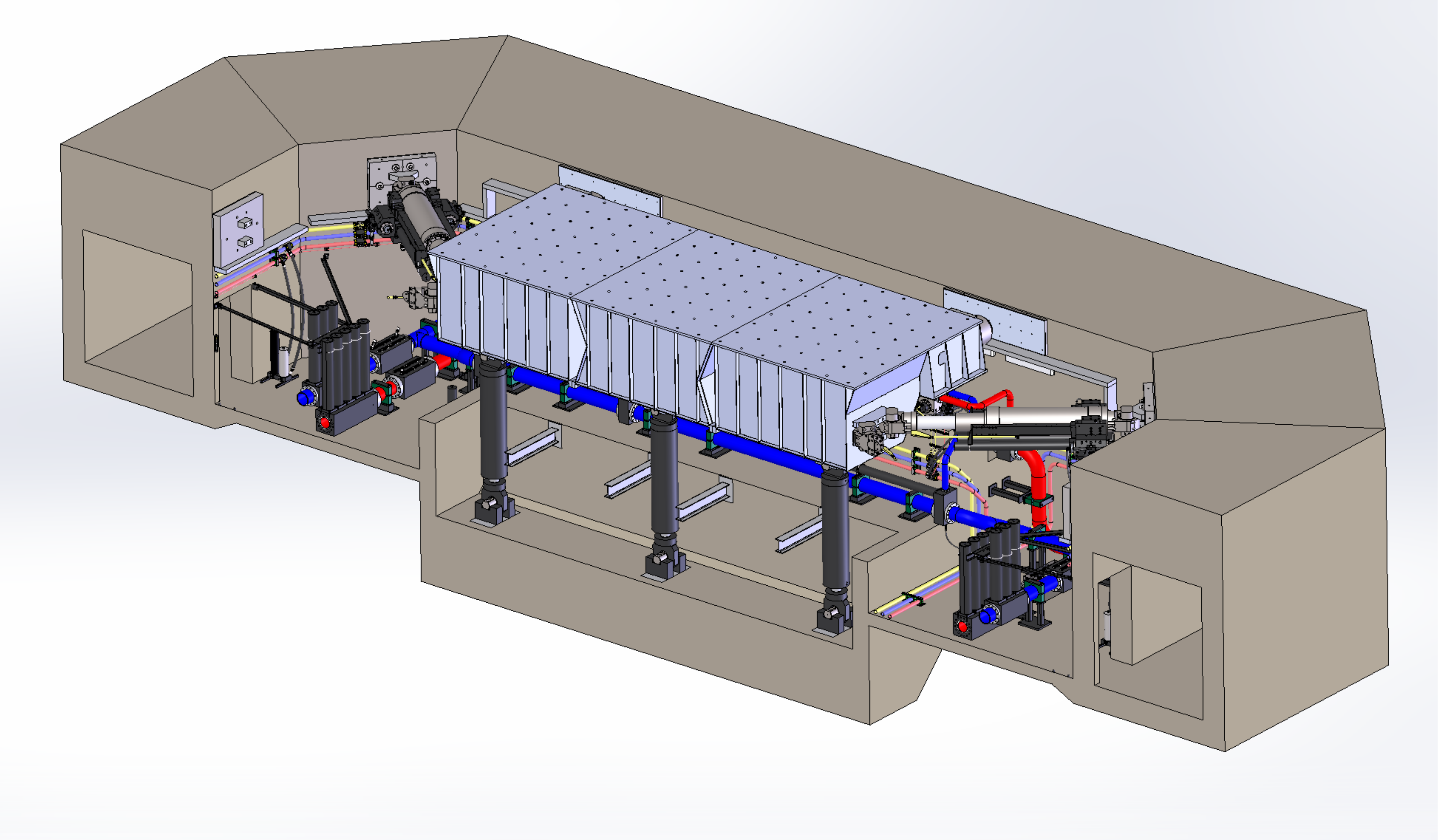


High-Flow Servovalves for Vertical Actuators

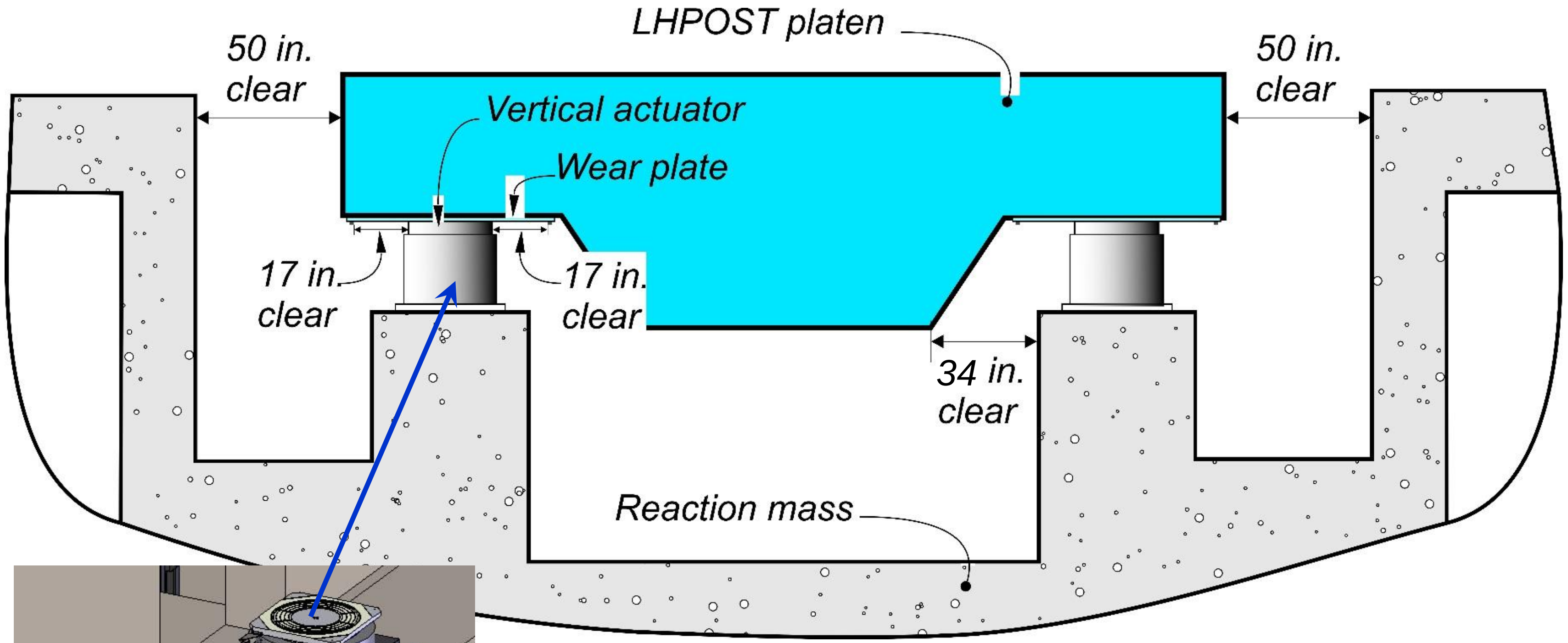


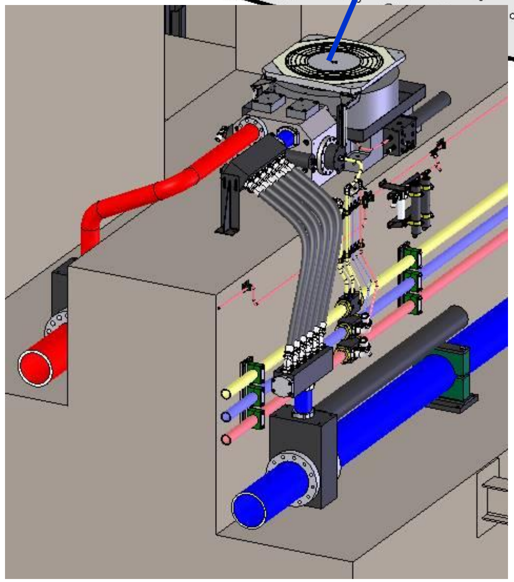


Third Nitrogen-filled Hold-down Strut



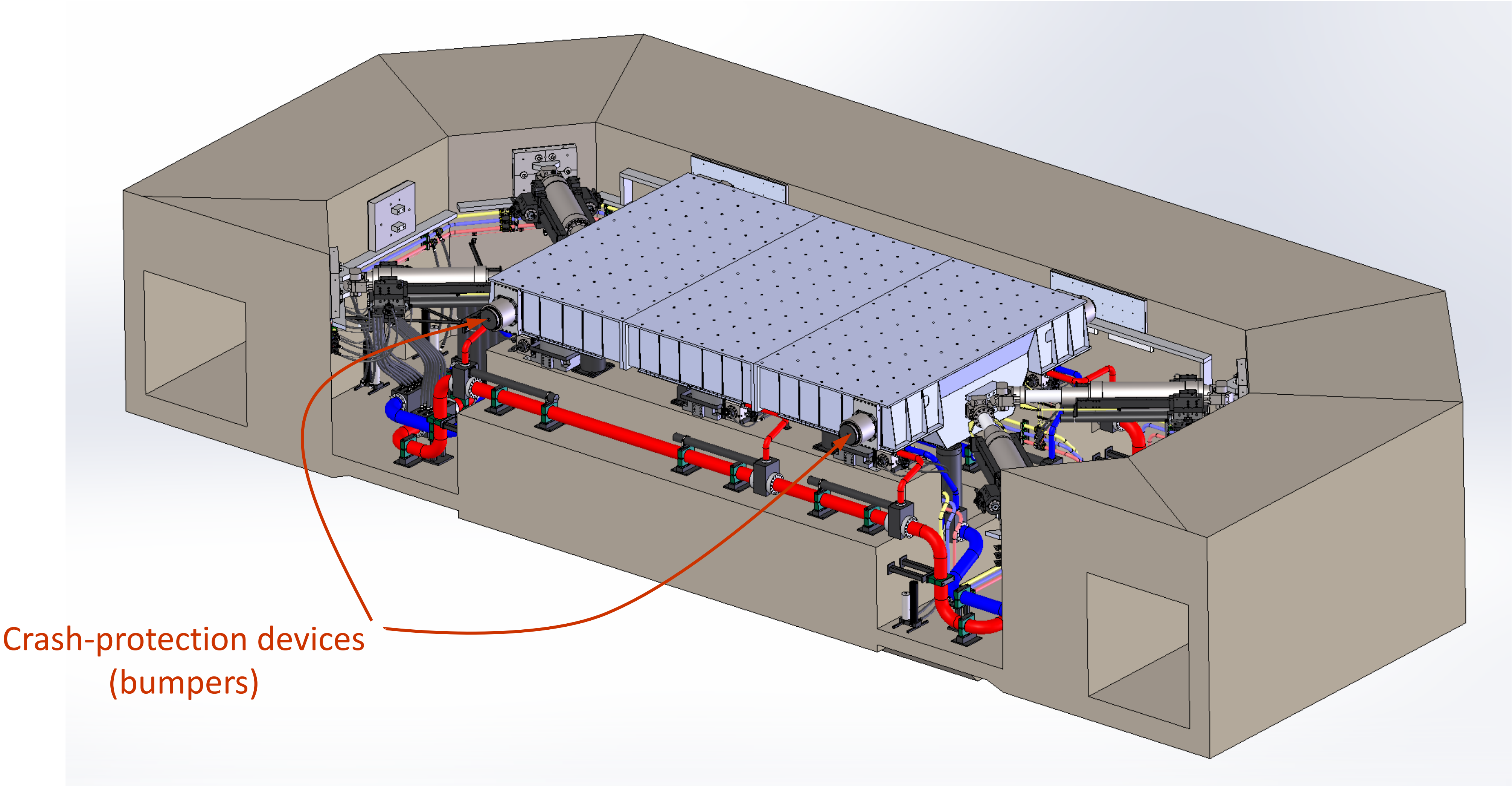
Displacement Limit in the Transverse (N-S) Direction





- Three lines of defense against potential impact:
  - Software limit detectors (interlocks)
  - Physical limit switches (LVDT's) in a PLC control loop
  - Collision/crash protection devices (last resort)

LHPOST6



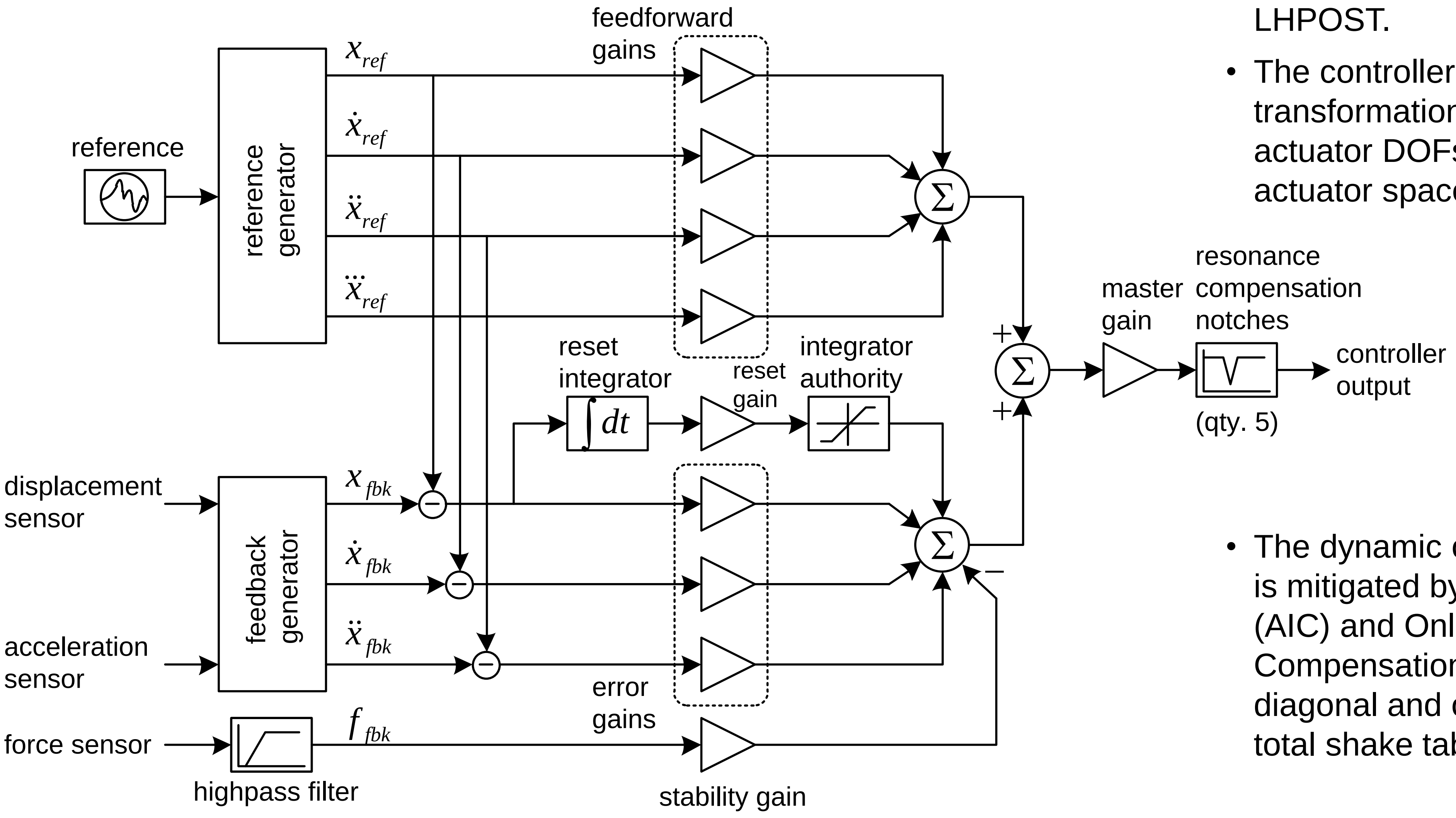
Predicted and Identified Oil Column Frequencies and Modes of LHPOST6

Predicted Oil Colum Frequency	Oil Column Mode	Identified Oil Column Frequency
f_1 = 7.40 Hz	Y/N-S/Transverse Direction	f_1 = 9.22 Hz
f_2 = 8.87 Hz	Yaw	f_2 = 11.03 Hz
f_3 = 9.33 Hz	X/E-W/Longitudinal Direction	f_3 = 11.95 Hz
f_4 = 40.66 Hz	Coupled Longitudinal (X) - Pitch (R_Y)	f_4 = 39.00 Hz
f_5 = 44.07 Hz	Z/Vertical Direction	f_5 = 40.32 Hz
f_6 = 53.03 Hz	Coupled Transverse (Y) - Roll (R_X)	f_6 = 48.34 Hz

- The predictions were obtained assuming an effective oil bulk modulus of 120,000 psi (= 60% of actual oil bulk modulus of hydraulic fluid) to account for entrained air and other sources of compliance.
- As for the 1-DOF LHPOST, the resonant peaks of the oil column modes are damped out numerically by the shake table controller using the delta-pressure feedback gains and notch filters, if necessary.

MTS 6-DOF 469D – Three-Variable Controller (TVC)

TVC = State-Variable Control + Extras



- The TVC portion of the 6-DOF 469D controller is exactly the same for each of the six DOFs and the same as for the 1-DOF LHPOST.
- The controller uses back-and-forth transformations from Cartesian DOFs to actuator DOFs (i.e., from Cartesian space to actuator space).

Courtesy of MTS Systems Corporation

- The dynamic cross-coupling between DOFs is mitigated by Adaptive Inverse Control (AIC) and Online Iterative (OLI) Compensation, which takes care of the diagonal and off-diagonal terms of the 6×6 total shake table transfer function matrix.

MTS STEX Pro

- STEX is a Motion Replication Method pioneered and perfected by MTS Systems
- Established in the automotive industry since the late 70’s and successfully applied to the seismic test industry.
- STEX-Pro supplements the real time MTS 469D digital controller by providing additional table programming capabilities.
- Compared to the MTS 469D (TVC-AIC-OLI), it has enhanced/additional capabilities:
  - Data analysis (differentiation, FFT and inverse FFT, digital filtering, spectral analysis, signal processing & analysis, signal generation/time history shaping)
  - Off-line iterative compensation (utilizes an inverse frequency response matrix model to compute motion commands to the MTS 469D)
  - Post test data processing
  - Data management

MTS STEX Pro

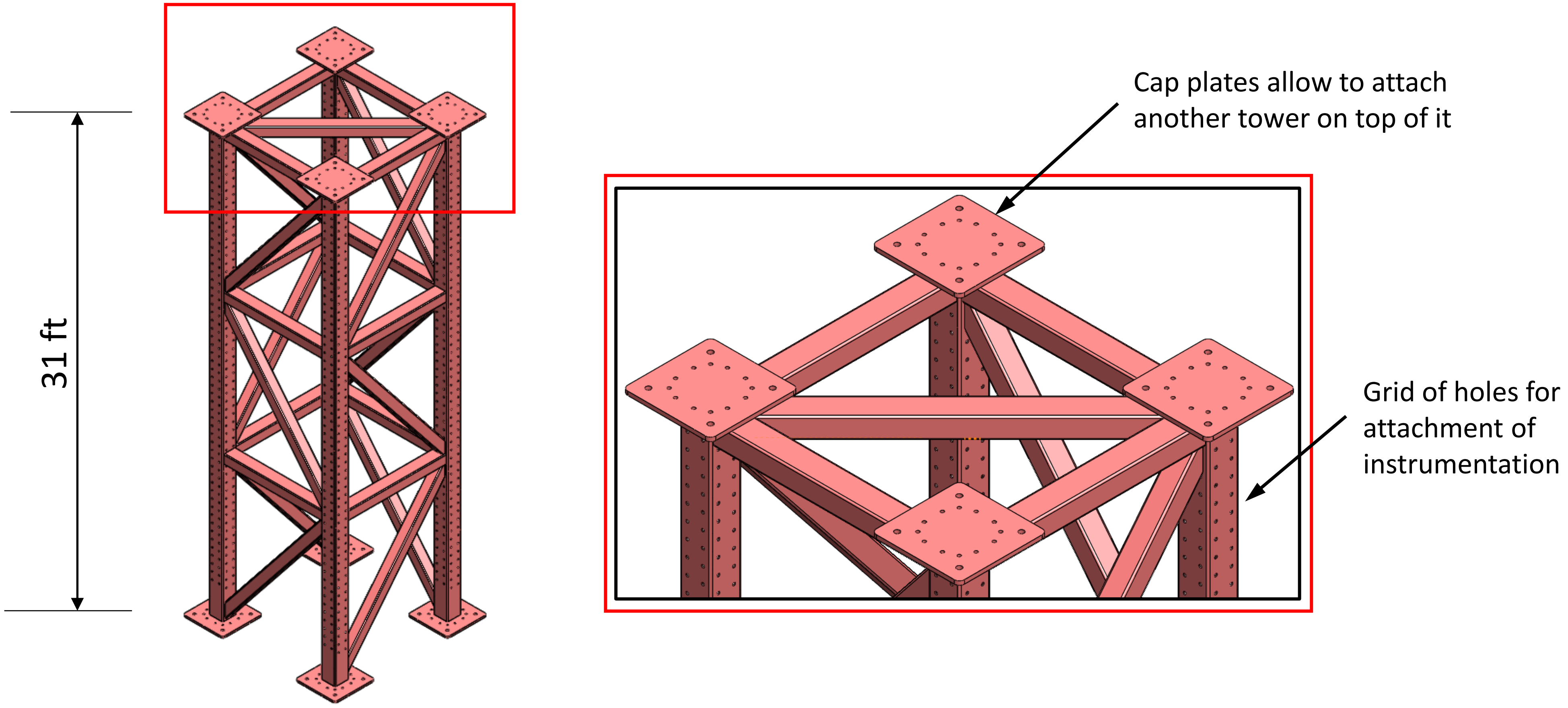
- STEX-Pro has a data playback and acquisition function that connects to the TVC Servo Controls via signal streaming service called Test Server. When Connected STEX Pro becomes the “Function Generator” to the TVC Servo Control for playback of the Compensated Earthquake records.

- Because STEX Pro is an offline compensator, the command signals and response signals can be examined in fine detail before and after the signals are sent to the table. The Turbo (Adaptive Inverse FRF) feature may be enabled during Iteration for reduced iteration count.

- STEX-Pro is recommended because of its superior ability to provide user insights into the command signal development and its ability to visualize the signal stream through user friendly wizards. As well it has a structured data organization scheme that makes for easy recall and review of data.

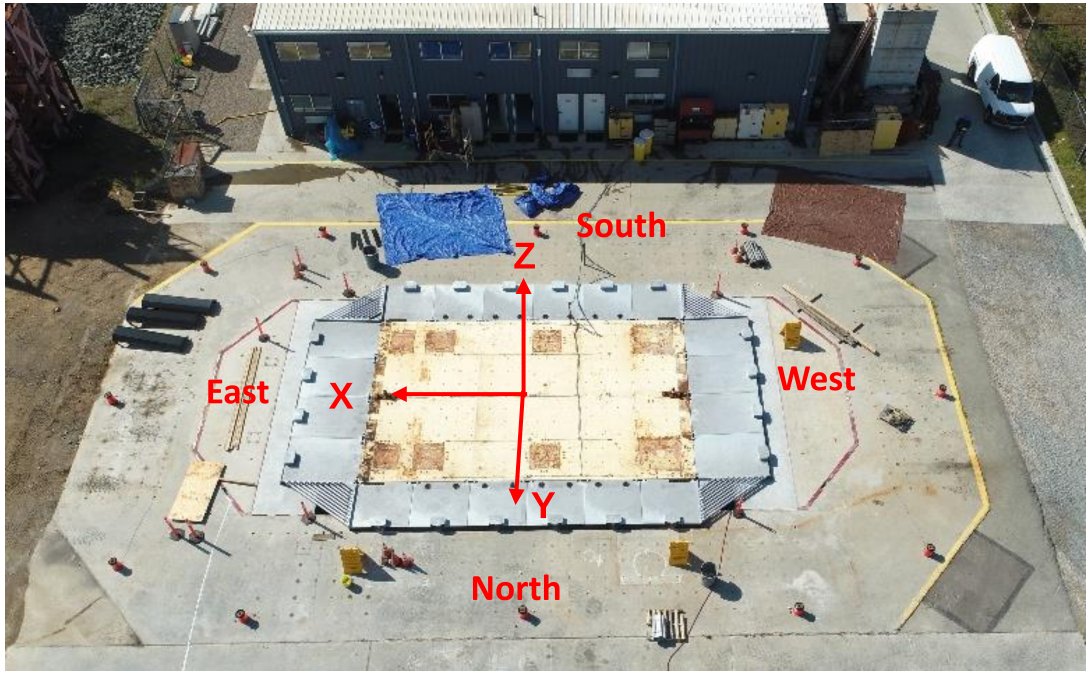
Safety Towers

- New safety towers:
  - Provide additional protection to the specimens tested on the shake table
  - Are easier to handle than previous towers



Performance of LHPOST6

LHPOST6



Performance Characteristics of LHPOST6

Uniaxial performance characteristics of the LHPOST6
Sinusoidal motions - Bare table condition - Centered rigid payload of 4.9 MN (1,100 kips)

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)					
	Sinusoidal motions - Bare table condition			Sinusoidal motions - Centered rigid payload of 4.9 MN (1,100 kips)		
	Horizontal X (E-W)	Horizontal Y (N-S)	Vertical Z (-)	Horizontal X (E-W)	Horizontal Y (N-S)	Vertical Z (-)
Peak Translational Displacement	±0.89 m (±35 in)	±0.38 m (±15 in)	±0.127 m (±5 in)	±0.89 m (±35 in)	±0.38 m (±15 in)	±0.127 m (±5 in)
Peak Translational Velocity	3.0 m/sec (118 in/sec)	2.0 m/sec (80 in/sec)	0.45 m/sec (17 in/sec)	3.0 m/sec (118 in/sec)	2.0 m/sec (80 in/sec)	0.55 m/sec (21 in/sec)
Peak Translational Acceleration	(5.8 g)[1] 3.7 g [2]	(4.7 g)[1] 1.85 g [2]	-3.4 g +31.1 g [1] +11.9 g [3]	(1.6 g)[1] 1.0 g [2]	(1.25 g)[1] 0.50 g [2]	-1.64 g +7.5 g [1] +2.5 g [2]
Peak Translational Force	10.6 MN [1] (2,380 kip)[1] 6.8 MN [2] (1,530 kip)[2]	8.38 MN [1] (1,890 kip)[1] 3.4 MN [2] (765 kip)[2]	-4.3 MN [4] +57.0 MN [5] (+12,800 kip)[5] +22.9 MN [6] (+5,150 kip)[6]	10.6 MN [1] (2,380 kip)[1] 6.8 MN [2] (1,530 kip)[2]	8.38 MN [1] (1,890 kip)[1] 3.4 MN [2] (765 kip)[2]	-4.3 MN [4] +57.0 MN [5] (+12,800 kip)[5] +22.9 MN [6] (+5,150 kip)[6]
Peak Rotation	2.22 deg [7]	1.45 deg [7]	3.8 deg	2.22 deg [7]	1.45 deg [7]	3.8 deg
Overturning Moment Capacity	32.0 MN-m (23,600 kip-ft)	35.0 MN-m (25,800 kip-ft)		45.1 MN-m (33,200 kip-ft)	50.0 MN-m (36,900 kip-ft)	

(1) Peak acceleration controlled by the actuator force capacities in the zero control position of the table.

(2) Acceleration limit controlled by the reaction mass until further studies.

(3) Acceleration limit controlled by the design strength of the steel honeycomb platen.

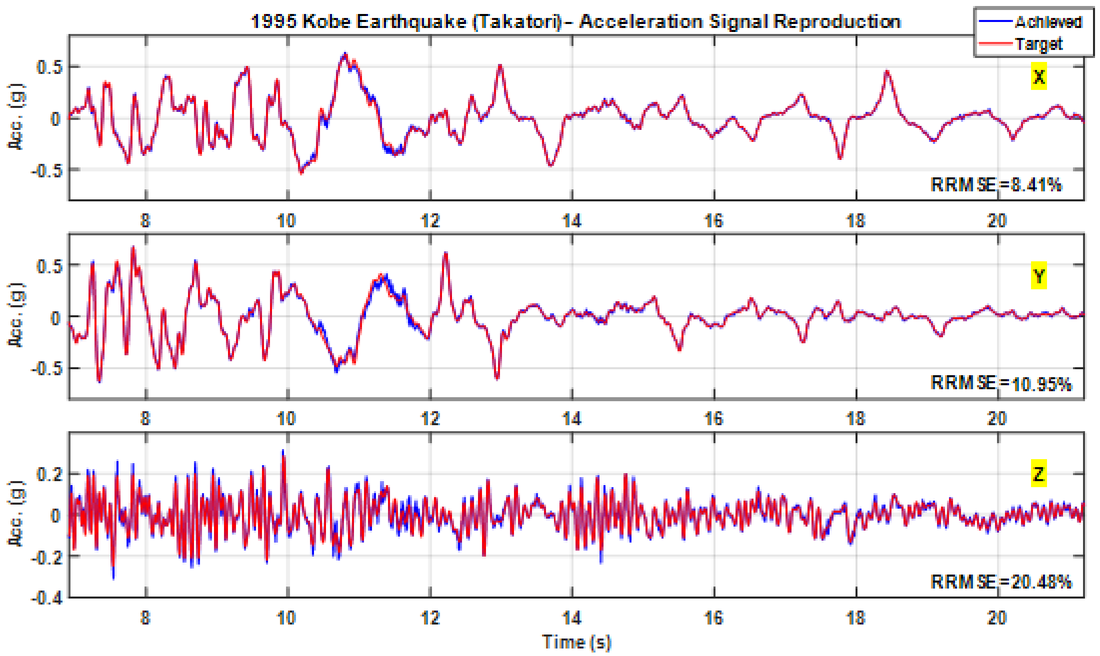
(4) Assuming a pressure of 125 psi in the chamber of each vertical actuator and accounting for the hold-down forces in the zero control position of the table.

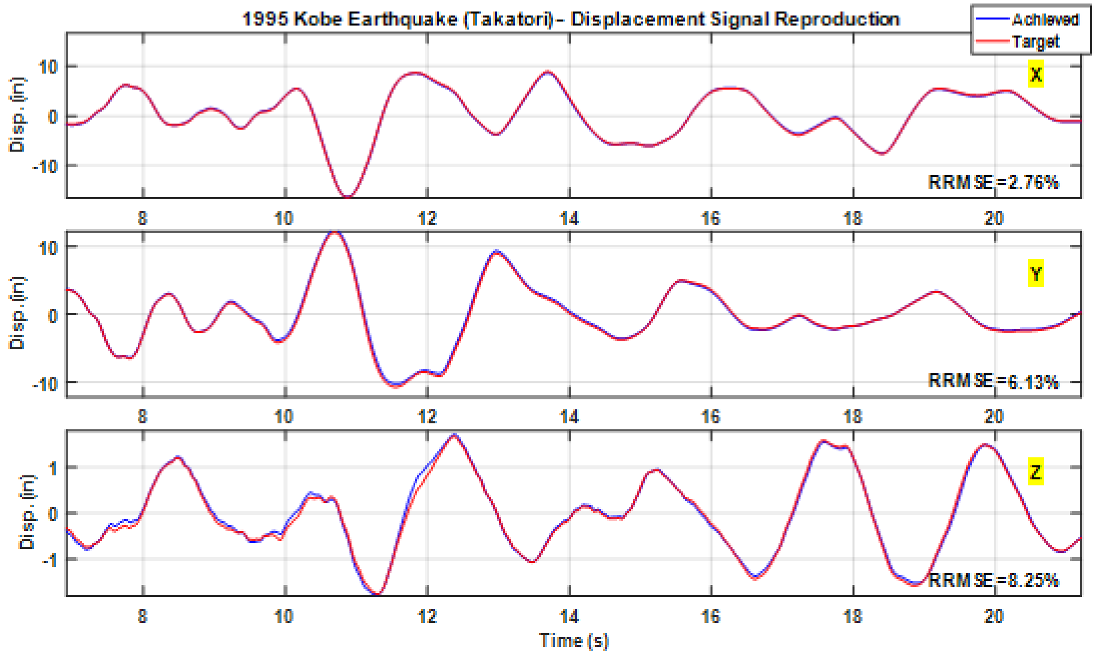
(5) Peak force controlled by the vertical actuator force capacities and accounting for the hold-down forces in the zero control position of the table.

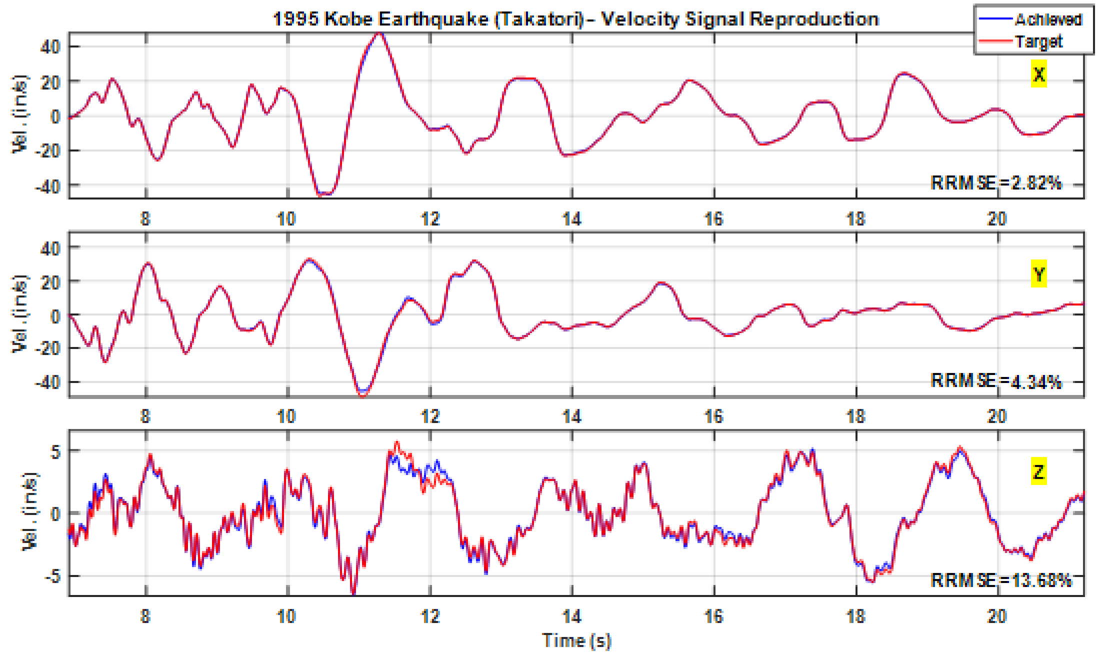
(6) Force limit controlled by the design strength of the steel honeycomb platen and accounting for the hold-down forces in the zero control position of the table.

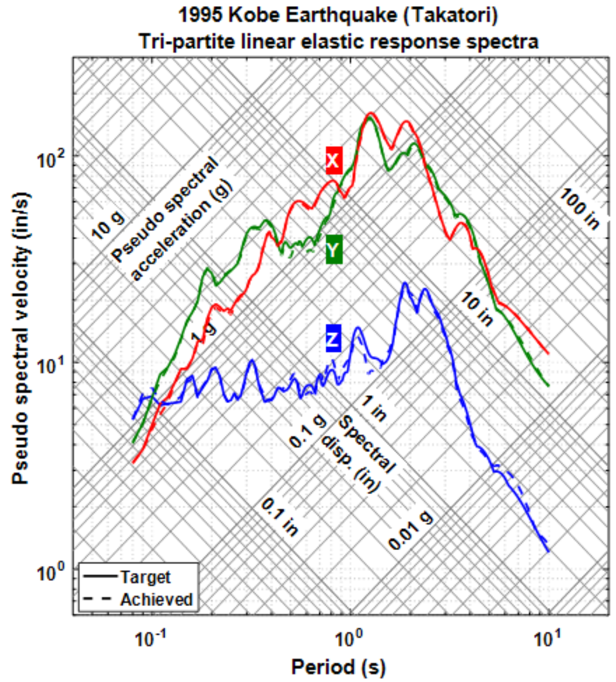
(7) Due to kinematics of the piston seals of the vertical actuators.

Target vs. Achieved Tri-Axial Ground Motion - 1995 M6.9 Kobe, Japan, Takatori Station









1978, M7.4 Tabas, Iran, Tri-Axial Ground Motion

AC-156 Compatible Earthquake, Tri-Axial Ground Motion

Synthetic Six-Axial Ground Motion

1994 Northridge Earthquake (Rinaldi Station) – Tri-axial – 100%

Shared-use Modular Test Bed Building (MTB2) Project

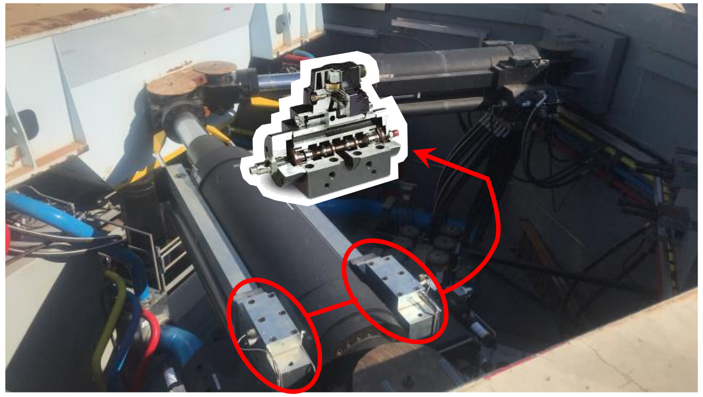
Tara Hutchinson and Gilberto Mosqueda, UC San Diego
Chris Pantelides, The University of Utah

Mechanics-Based Numerical Model of the LHPOST6

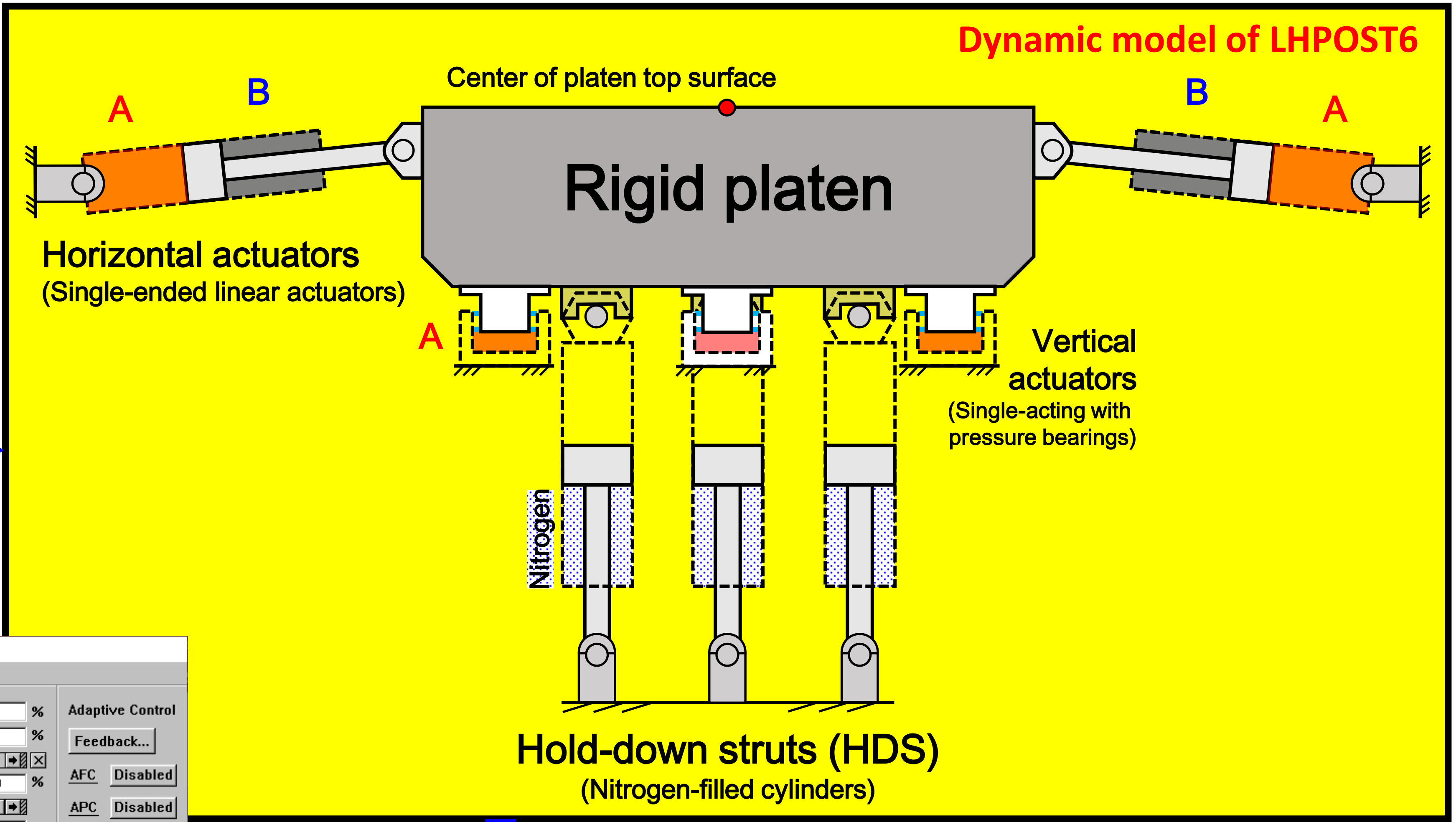
Purposes of virtual model of the LHPOST6:

- Planning and designing shake table experiments
- Pre-test simulation of shake table tests
- Investigate control-table-specimen interaction
- Off-line tuning of shake table controller
- Hybrid shake table testing
- Development of next-generation shake table controllers

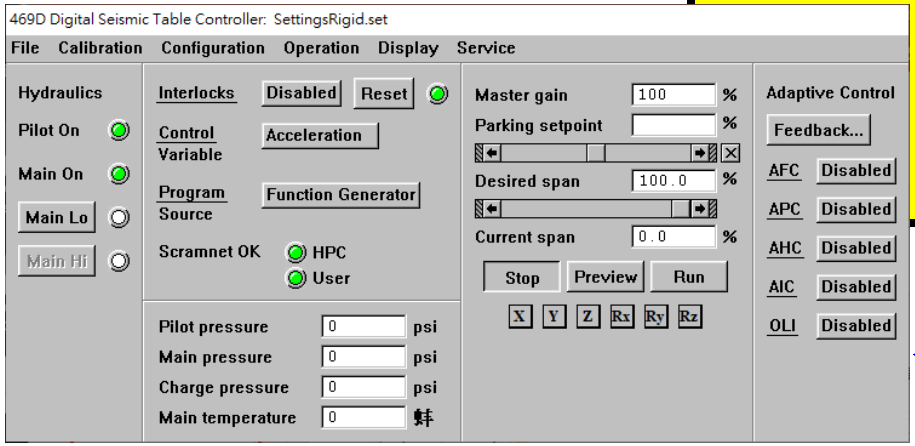
Dynamic Model of the LHPOST6



Servovalve commands



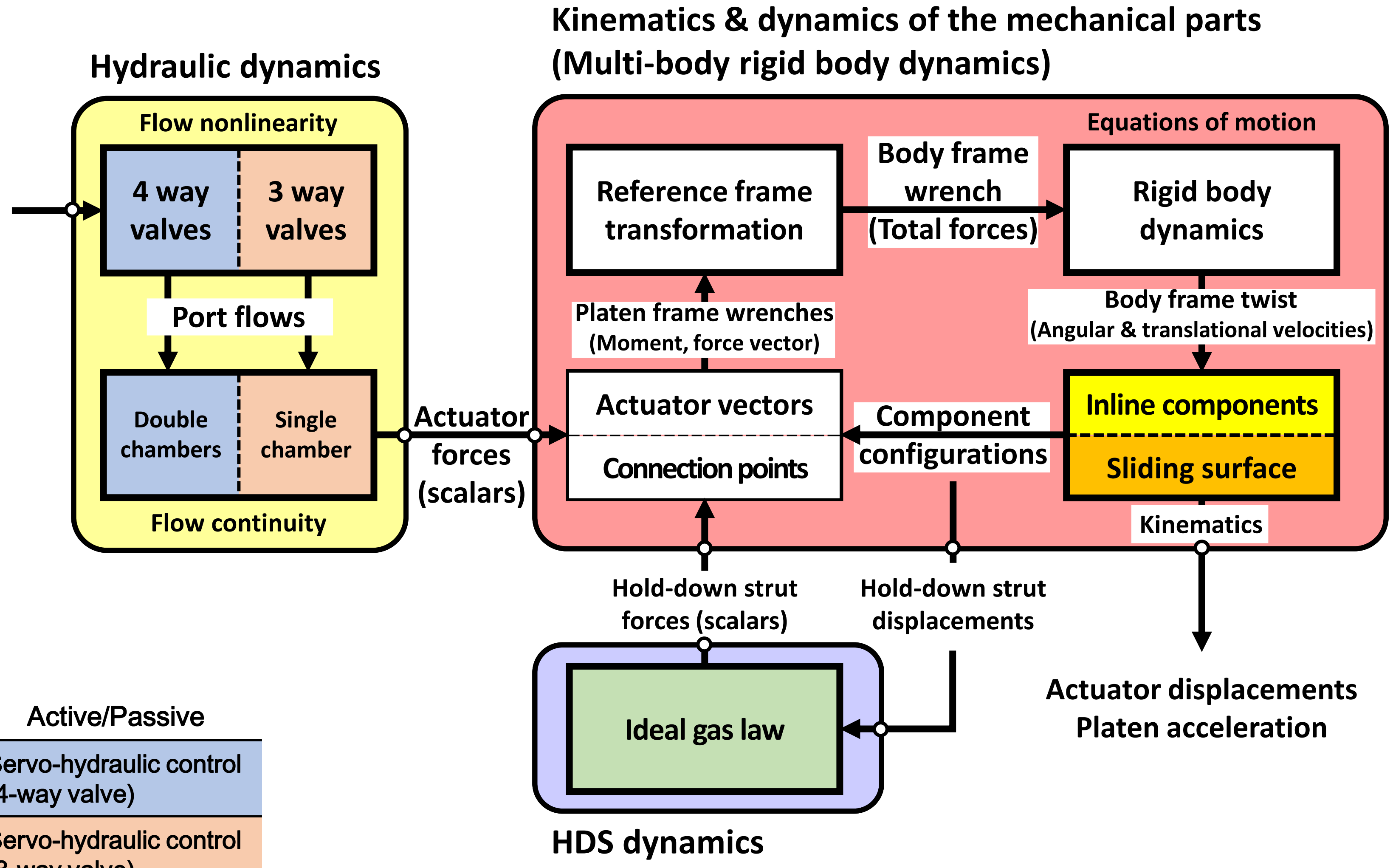
MTS 469D (6-DOF controller)

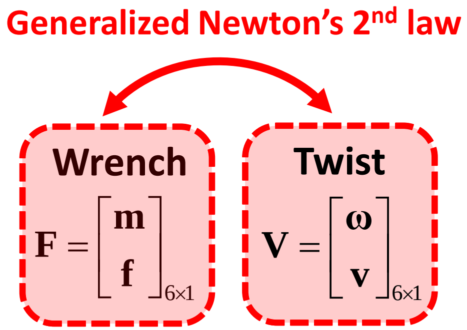


Platen motion (displacement and acceleration feedback)

Block Diagram of the Dynamic Model

MATLAB
SIMULINK®





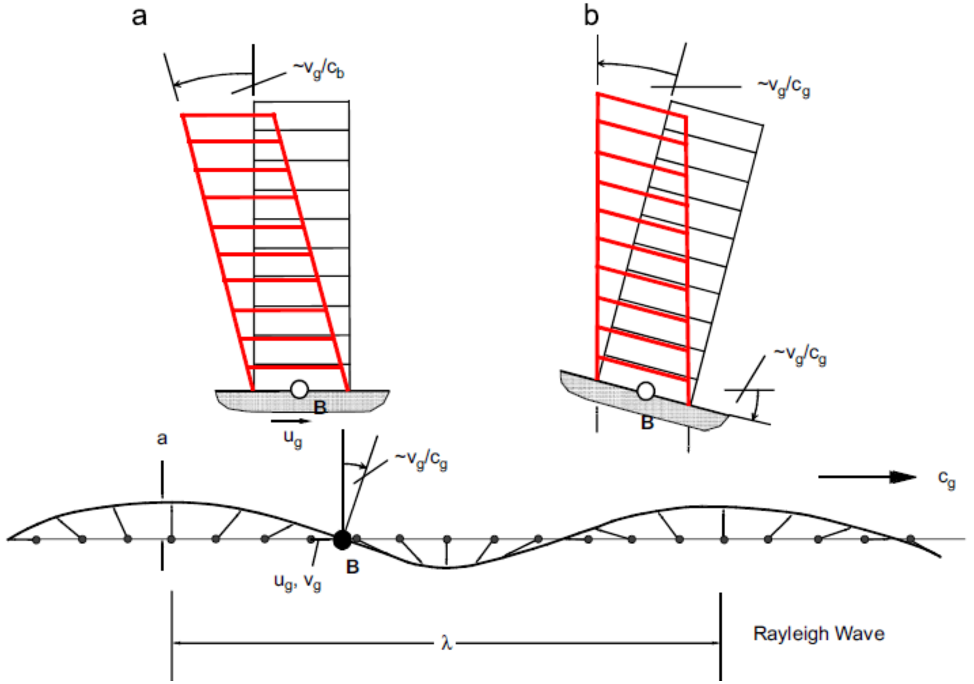
	Kinematics	Active/Passive
Horizontal Actuators	Linear actuator	Servo-hydraulic control (4-way valve)
Vertical Actuators	Sliding surface	Servo-hydraulic control (3-way valve)
Hold-down Struts	Linear actuator	Nitrogen pre-charged (passive component)

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 earthquake ground motions applied as dynamic excitation to full 3D and large/full-scale structural, geotechnical, or soil-foundation-structural systems, including the effects of SSI (both kinematic and inertial), nonlinear soil and structural behavior, soil liquefaction and seismic compression.



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 appropriate inherent damping models.

- Experimental study of dynamic soil-foundation-structure interaction and geotechnical systems:
  - Kinematic interaction of the foundation with the soil (in the absence of the superstructure).
  - Inertial interaction (➔ additional rocking and torsional components of motion of the foundation).
  - Reinforced soil systems, retaining walls, tunnels, slopes and embankments, soil improvement techniques.
  - Geotechnical issues that cannot be studied in laboratory-scale experiments, e.g., lateral spread in layered soils, liquefaction of gravelly soils, seismic response of alternative backfill materials such as tire-derived aggregates, seismic settlements of saturated soils, seismic compression of unsaturated soils.

- Two general types of experimental SSI studies become possible:
  - Verification studies under three-axial or six-axial excitation.
  - Large soil box studies under tri-axial or six-axial excitation.

Research Made Possible by the LHPOST6

- 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.
  - Development of effective retrofit and strengthening methods, and improvement of current design provisions.

- 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.
  - Actual seismic response and load-resisting mechanism of a structural system could differ significantly from what is anticipated by design standards.
  - Multi-axial shake table tests of large/full-scale structural systems are needed to investigate this problem and to improve current design codes.

Research Made Possible by the LHPOST6

- Structural Concrete and Precast Concrete Systems
  - Most research supporting seismic design with structural concrete has been limited to components or reduced-scale models of building systems.
  - In the US, only three landmark building tests were performed at large- or full-scale on a shaking table but under single-axis excitation.
  - Research is needed on innovative, resilient, seismic-resistant concrete systems under multi-axial seismic base excitation, specifically to validate earthquake protective systems under more realistic conditions and improve modeling and analysis capabilities for component and system behavior.
  - Influence of dynamic shear behavior on flexural deformation capacity in RC structural systems.
  - Complex dynamic system interactions in the context of realistic multi-component earthquake base excitations to improve our current ability to model system behavior.
  - Use of high-strength (or ultra-high performance) materials (reinforcing bars and concrete) and advanced materials (e.g., fiber-reinforced concrete).
  - Seismic performance of commercial tilt-up buildings (which behaved poorly during the 1994 Northridge Earthquake).
  - Research using the LHPOST6 on building systems incorporating precast braced frames has the potential to impact significantly the precast concrete industry.

Research Made Possible by the LHPOST6

- Structural Steel Systems
  - Past extensive research on the seismic performance of hot-rolled structural steel and cold-formed steel systems in the areas of structural stability and progressive collapse.
  - Additional research is needed to assess interactions in building systems undergoing earthquakes, e.g., competing inelasticity in vertical and horizontal lateral-force resisting systems, overstrength and system effects derived from the participation of gravity and non-structural framing in lateral response.
  - Development of innovative low damage seismic resistant steel structures, modeling, and analysis of floor diaphragms, chords, and seismic collectors.

Research Made Possible by the LHPOST6

- Non-structural components and systems (NSCs).
    - Architectural, mechanical, electrical and plumbing, or building contents.
    - Improve our understanding and predictive capabilities of the seismic response of NCSs under multi-directional earthquake excitation, including nonstructural-to-nonstructural and structural-to-nonstructural interactions.
    - Scarceness of full-scale building shake table tests that incorporate NCSs limits our understanding of the seismic response of these NCSs.
    - Full-scale shake table tests are needed to advance the development of a reliable, unified design methodology accounting for multi-directional earthquake excitation.
    - Full-scale is required due to the difficulty/impossibility to obtain NSCs at reduced scale.

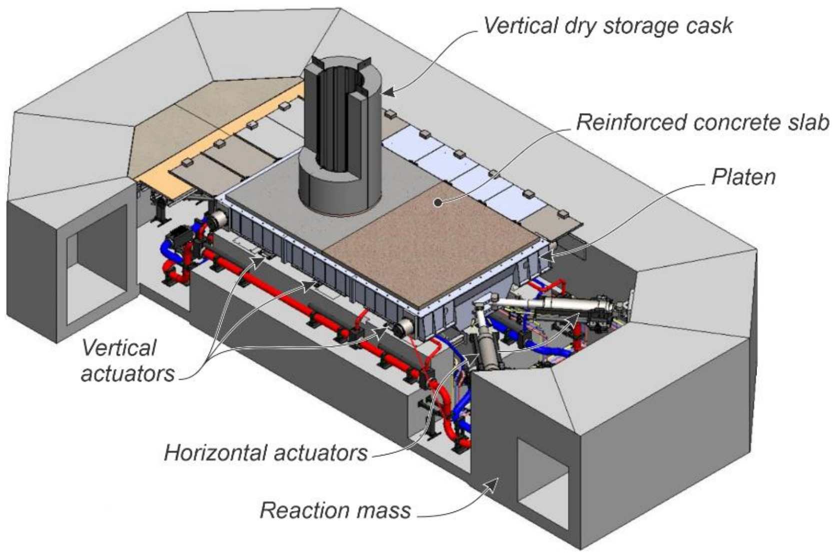
Research Made Possible by the LHPOST6

- Advanced and/or innovative earthquake protective systems (passive, semi-active):
  - Low-damage structural earthquake protective systems (e.g., base isolation, dampers, buckling-restrained braces, rocking foundations and systems, self-centering systems, inertial force-limiting floor anchorage systems, new materials) for mass timber, concrete and steel structures.
  - Investigate the response behavior of these high-performance systems (with complex kinematics) under multi-directional earthquake input excitation.
  - Testing of a wide range of promising/innovative passive and semi-active seismic response modification devices in large/full-scale systems for ultimate validation and acceptance in real-world structural seismic design.

- Building structures:
  - Multi-axial large/full-scale shake table tests of building structures are needed to understand their response in 3-D, including the effects of rotational components of earthquake ground motions, and support the development of future design codes.
  - Investigate the interactions between the lateral and gravity force resisting systems and non-structural systems.
  - Validation (at large-scale) of innovative seismic retrofit systems/strategies for older non-ductile non-code compliant (wood, masonry, concrete, and steel) building structures.

Research Made Possible by the LHPOST6

- Energy/power structures:
  - Infrastructure supporting renewable energy sources:
    - Wind turbine farms, including the effects of SSI on the dynamic response of these tall and slender structural systems.
    - Solar arrays.
    - Hydroelectric concrete dams.
    - Electrical power network structures (e.g., electrical substations, large transformers, transmission poles/lines).
    - Seismic performance of nuclear structures, systems, and components (SSCs) including dry storage casks of spent nuclear fuel.
    - Experimental seismic tests of nuclear SSCs have been performed for several decades, but often facing limitations on payload capacity and/or multi-directional seismic input.



Research Made Possible by the LHPOST6

- Geo-structures:
  - Use of LHPOST6 in combination with large soil boxes (1-g shaking table tests) to:
    - Complement centrifuge tests in validating computational models of soil-foundation-structural systems.
    - Study the performance of underground structures (e.g., energy vaults, pipelines, deep and shallow tunnels, bridge abutments, earth retaining walls, levees, embankments).
    - Evaluation of soil improvement using field-implementation techniques, including biocementation or biomediation.

- New types of measuring systems:
  - The LHPOST6 will also be a key experimental facility to deploy, test, and validate new types of sensors:
    - Measure rotational components of motion (e.g., gyroscopes, inclinometers).
    - Digital image correlation using optical images (using land-based or drone-based cameras).

Research Made Possible by the LHPOST6

- Bridge structures:
  - A great challenge in the seismic design of slender columns that are part of a complex highway interchange system is to properly evaluate its response under the combined effects of vertical and bi-directional horizontal excitations.
  - Accelerated bridge construction.
  - 3D behavior of precast segmental bridge superstructures for accelerated bridge construction.
  - Bridges with hybrid sliding-rocking columns.
  - Use of smart materials in bridges.
  - High-performance steel highway bridge systems.
  - Multi-directional dynamic experimental evaluation of bridge superstructure-abutment-substructure interactions for configurations commonly employed in the Central United States.

Research Made Possible by the LHPOST6

- Structural Health Monitoring:
  - Condition assessment of structures plays a key role in supporting the decision-making process following natural or artificial hazard or aging events.
  - Damage initiation and progression cannot always be detected through visual screening and, therefore, time-consuming, costly, and invasive post-event inspection and evaluation methods are required to detect certain types of damage.
  - Use of structural health monitoring (SHM), diagnosis, and prognosis methods to help assess the damage in, and residual strength of, civil structures in the aftermath of a natural hazard.
  - Finite element (FE) model updating has emerged as a powerful methodology for structural health monitoring and damage identification of civil structures.
  - Advanced Bayesian (probabilistic) estimation methods to update a high-fidelity mechanics-based nonlinear FE model of the structure of interest, which can then be interrogated to detect, localize, classify, and assess the damage in the structure at different scales (global and local).
  - The high-quality datasets collected from future landmark experiments performed on the LHPOST6 will be invaluable for evaluating vibration-based condition/damage assessment methodologies and resolving the remaining obstacles preventing reliable real-world implementation of such methodologies.

Research Made Possible by the LHPOST6

- Why Large- or Full-Scale System Level Testing is Critically Needed?:
  - The seismic response of structures involves complex physics of heterogeneous materials with highly nonlinear constitutive properties and depends on the boundary/interface conditions, such as the interaction between the structure and the supporting/surrounding soil.
  - There are many open and profound issues and questions regarding how to accurately model these phenomena at the different length and time scales over which the physical processes develop.
  - State-of-the-art nonlinear structural analysis methods are still fairly limited in their ability to model the nonlinear dynamic response of structures, especially when approaching collapse (e.g., local buckling and fracture in steel, shear failures, connection or splice failures).
  - The boundary conditions imposed on tests of individual structural components or sub-assemblies may not be realistic as compared to their actual boundary conditions within the structural systems.
  - Scale of physical models is an issue since some design details, construction materials, and damage and failure mechanisms cannot be accurately reproduced in reduced-scale models (e.g., spacing of reinforcement, size of aggregates, quality and properties of welds, and degree of plastic strain or damage localization).

Research Made Possible by the LHPOST6

- Enable Research Needs for the Full-Realization of Performance-based and Resilient-based Design:
  - Performance-based design (PBD) was extensively developed in the mid-1990s to ensure that structures of different types, system properties and materials have a consistent level of safety and predictable performance in earthquake events.
  - PBD methodology is based on a structural reliability framework and enables engineers to design structures and facilities to meet specific performance objectives with quantifiable and acceptable risks of (i) exceeding various damage states, (ii) casualty, (iii) loss of occupancy (downtime), and (iv) economic losses in future earthquakes.
  - Although the PBD methodology has not been fully implemented in practice, simplified PBD methods have found their way into seismic design codes (e.g., AASHTO-COPRI 6 , LATBSDC, ASCE 41).
  - Risk-targeted seismic hazard maps in ASCE 7 rely not only on probabilistic seismic hazard data but also on structural fragility functions to achieve a uniform acceptable risk of structural collapse across the US.
  - The LHPOST6 facility will provide landmark experimental data at the subsystem and system levels critical to: (1) the development of reliable fragility functions, and (2) the development, calibration and validation high-fidelity simulation models that are able to predict the nonlinear behavior of structural materials, components, and systems under different hazard scenarios.

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

NHERI TallWood

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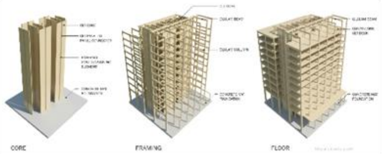
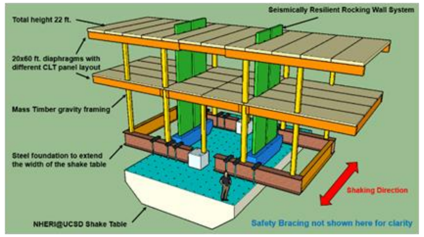
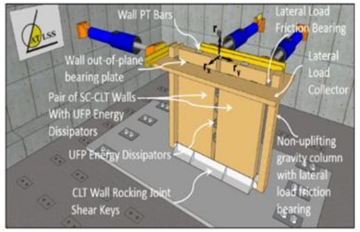


Define Tall Wood Archetypes

Investigative testing at system level



Two-story test at NHERI@UCSD 2017 Summer

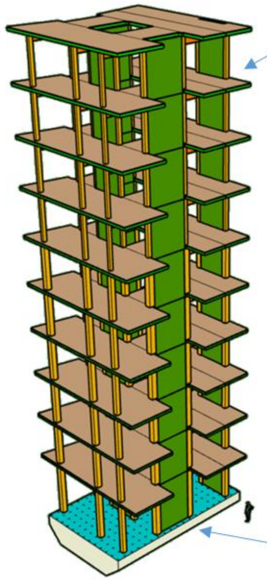


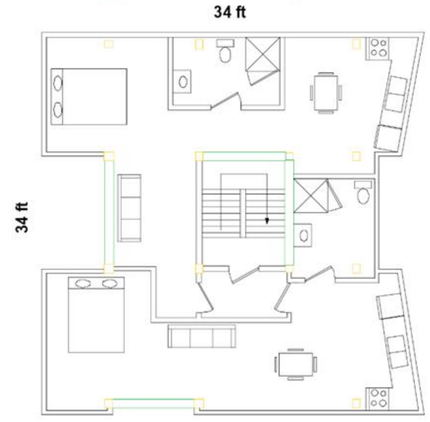
Assembly test at NHERI@Lehigh 2019

Seismic R & D
(2018~2020)

Full-scale 10-story validation Test (2021)

Mixed-Use building w/ CLT rocking wall lateral system





UCSD Shake Table

Construction of NHERI TallWood Specimen

THANK YOU !

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UC San Diego

For More Information About NHERI@UC San Diego Experimental Facility

Ozcelik, O., Conte, J. P., and Luco, J. E., "Comprehensive Mechanics-Based Virtual Model of NHERI@UCSD Shake Table - Uni-Axial Configuration and Bare Table Condition," *Earthquake Engineering & Structural Dynamics*, 50(12), 3288-3310, 2021.

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- https://ucsd.designsafe-ci.org
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Natural Hazards Engineering Research Infrastructure