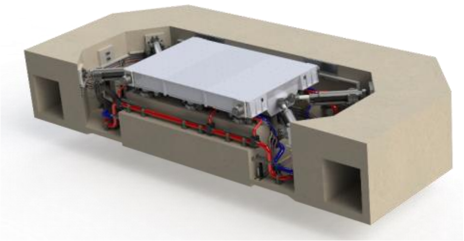
National Science Foundation

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 – Eighth User/Researcher Training Workshop



December 16-17, 2021
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 16, 2021): 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	Prof. Joel Conte
9:45 – 10:00 am	Education and Community Outreach	Prof. Lelli Van Den Einde Dept. of Structural Engineering, UC San Diego
10:00 – 10:30 am	DesignSafe Tools and Capabilities (Including Best Practices for Successful Upload/Organization of Data Depot)	Dr. Tim Cockerill DesignSafe Deputy Project Director, Texas Advanced Computing Center Prof. Gilberto Mosqueda Dept. of Structural Engineering, UC San Diego
10:30 – 10:50 am	Q&A and Open Discussion	
10:50 – 11:00 am	Break	
11:00 – 11:30 am	Preparing an NSF Proposal to Utilize NHERI@UC San Diego	Prof. Tara Hutchinson Dept. of Structural Engineering, UC San Diego
11:30 – 11:45 am	Virtual Walkthrough of LHPOST6	
11:45 – 12:15 am	Structural Systems: List of Open Issues and Scope of Problems and Example Use of Facility to Address Scientific Needs	Prof. Jose Restrepo Dept. of Structural Engineering, UC San Diego
12:15 – 12:30 am	Q&A and Open Discussion	
12:30 pm	Concluding Remarks	Prof. Joel Conte

Workshop Program – Friday

Day 2 (Dec 16, 2021): 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 – 9:30 am	Modular TestBed Building (MTB^2): A Reconfigurable Shared-Use Equipment Resource for Use by Researchers at LHPOST6	Prof. Tara Hutchinson Dept. of Structural Engineering, UC San Diego Prof. Chris Pantelides Dept. of Civil & Environmental Engineering, The University of Utah
9:30 – 10:30 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
10:30 – 10:45 am	Break	
10:45 – 11:15 am	NSF NHERI Facilities and Research Programs Q&A	Dr. Gianluca Cusatis National Science Foundation
11:15 – 11:45 am	Dr. Kalinina: Plans for the Shake Table Test of a Full-Scale Dry Storage System of Spent Nuclear Fuel Mr. Klymyshyn: Preliminary Pre-Test Modeling and Simulation Results	Dr. Elena Kalinina Sandia National Laboratories Mr. Nicholas Klymyshyn Pacific Northwest National Laboratory
11:45 – 12:15 pm	IT Resources, Cybersecurity, and Instrumentation/DAQ	Dr. Koorosh Lotfizadeh Dept. of Structural Engineering, UC San Diego
12:15 – 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.
- 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.
- 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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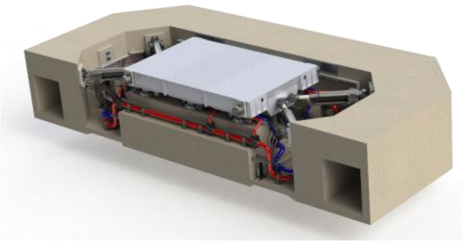
Structural Engineering

NHERI@UC San Diego: Facility Description and Capabilities

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



NHERI@UC San Diego User Training Workshop

December 16-17, 2021
University of California, San Diego

NHERI@UC San Diego Personnel

Joel Conte
PI

Lelli Van Den Einde
Co-PI

Gilberto Mosqueda
Co-PI

Benson Shing
Co-PI

Tara Hutchinson
Co-PI

José Restrepo
Senior Personnel

Enrique Luco
Senior Personnel

Koorosh Lotfizadeh
Site Op. Mngr.

Melissa Zhang
Financial Mgr.

Abdullah Hamid
Dev. Engineer

Robert Beckley
IT Manager

Alex Sherman
Dev. Tech./Safety Officer

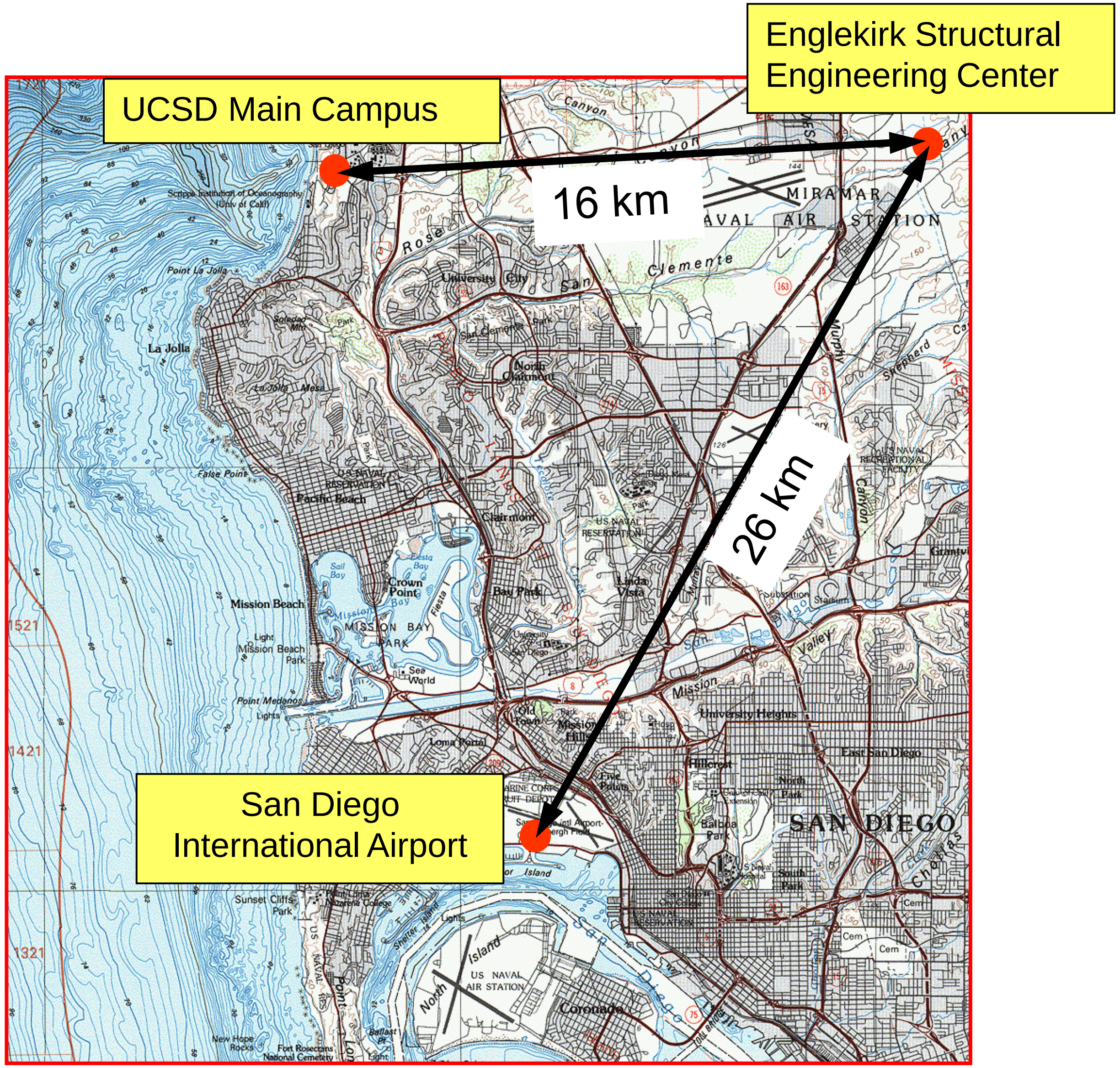
Jeremy Fitcher
Dev. Tech.

Outline

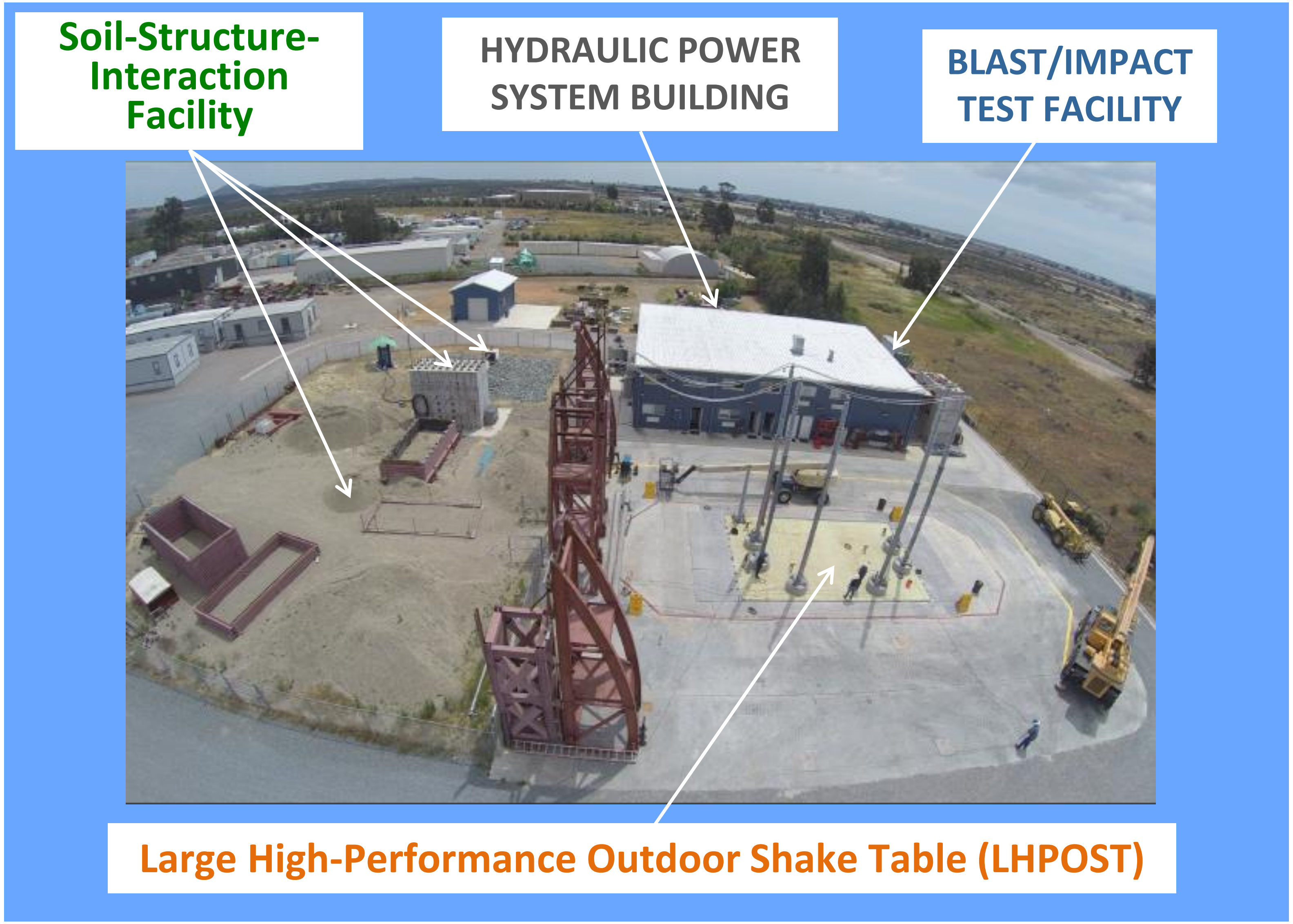
- Overview of Englekirk Structural Engineering Center
- Large High-Performance Outdoor Shake Table (LHPOST)
- Select Set of Shake Table Tests Performed on the NHERI@UC San Diego Shake Table
- Six Degree-of-Freedom (6-DOF) Upgrade of LHPOST into LHPOST6
- New Research Opportunities Made Possible by the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

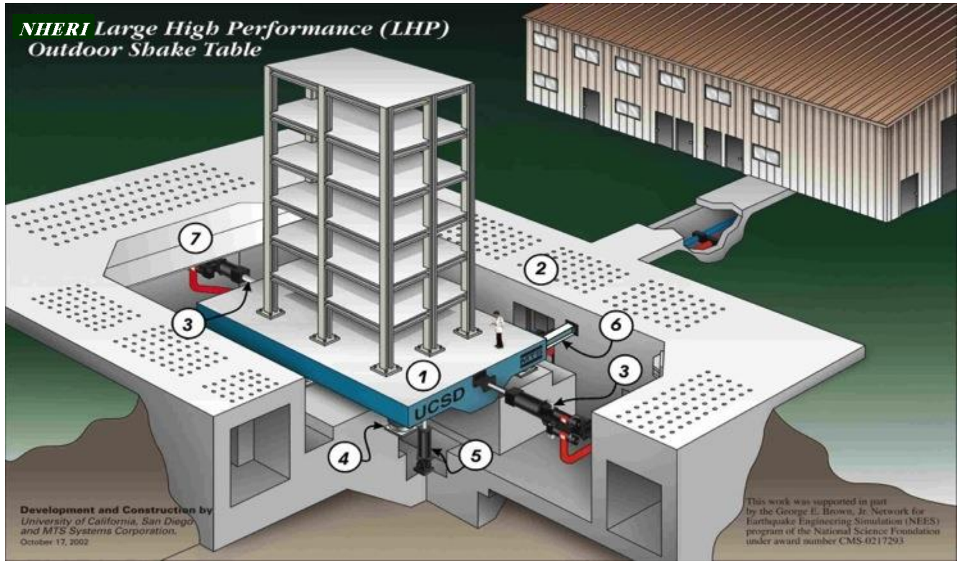
- The **vision for the NHERI@UC San Diego Shake Table experimental facility** is rooted on **three critical needs** for advancing the science, technology, and practice in earthquake disaster mitigation and prevention:

(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)



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 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 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)

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, spillway retaining walls
  - Underground structures (deep and shallow)

Capabilities/Provisions of the NHERI@UC San Diego EF

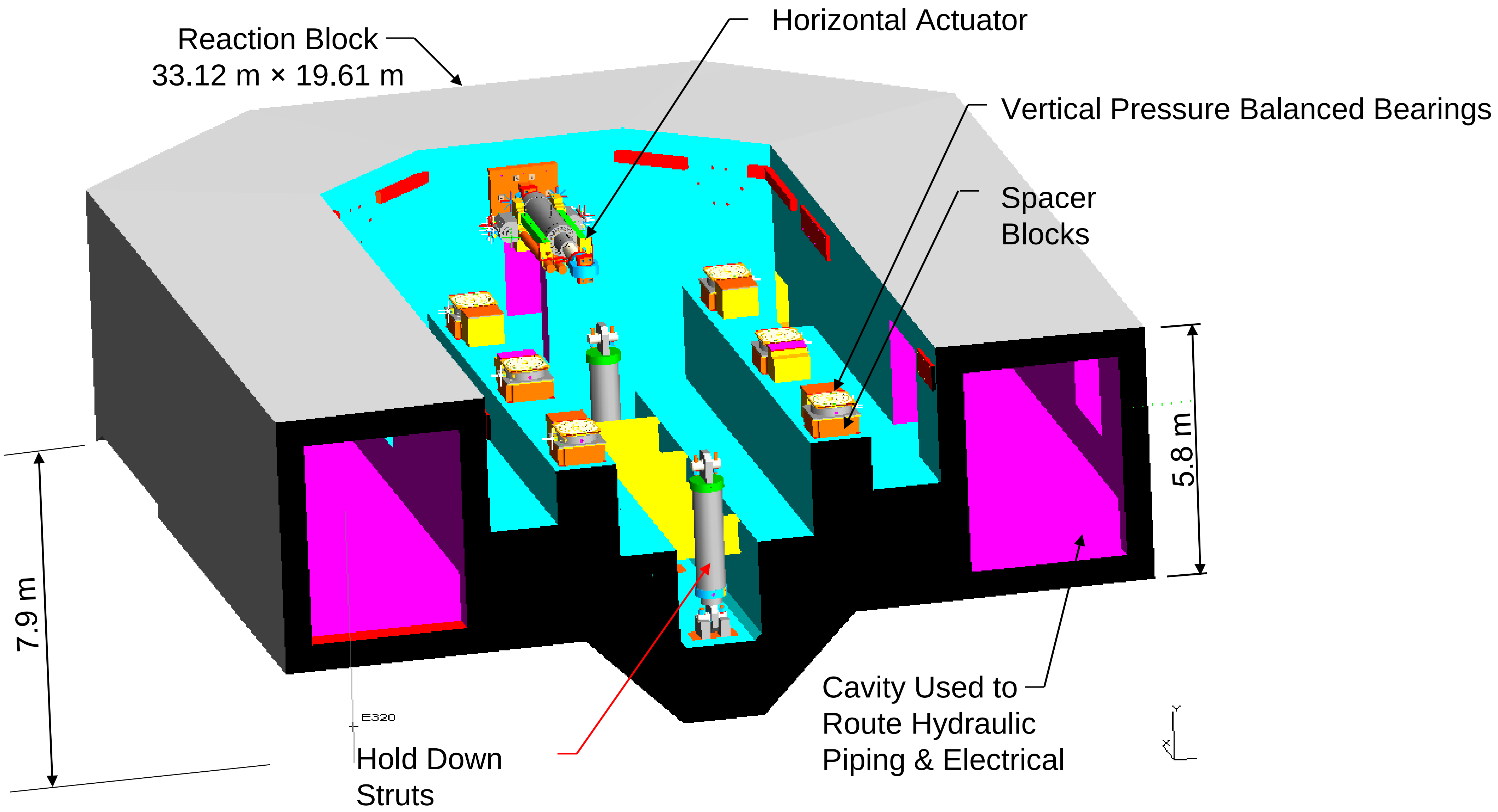
- **Simulation of near-source earthquake ground motions** which involve large acceleration, velocity and displacement pulses, **including six ground motion components (three translational and three rotational)**.

- Seismic testing of **extensively instrumented large/full-scale structural specimens** under extreme earthquake loads at near real-world conditions.

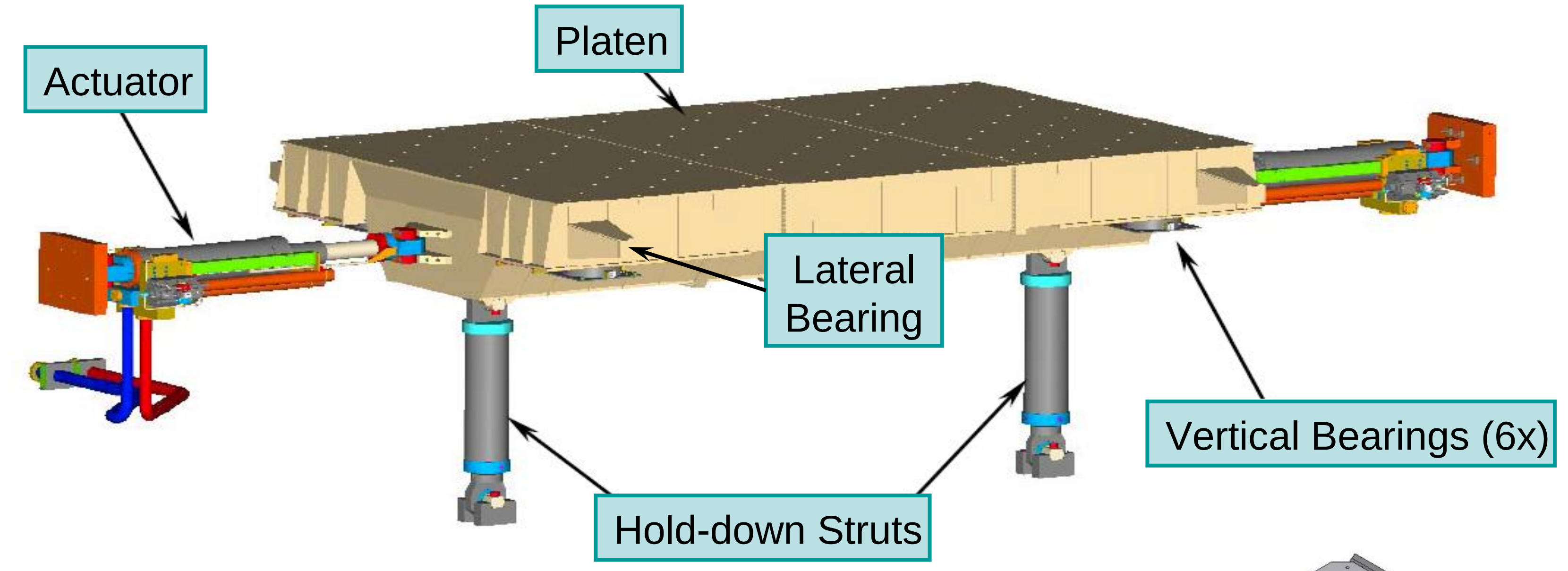
- Seismic testing of **extensively instrumented large-scale geotechnical and soil-foundation-structural systems** by using the shake table in combination with large soil boxes.

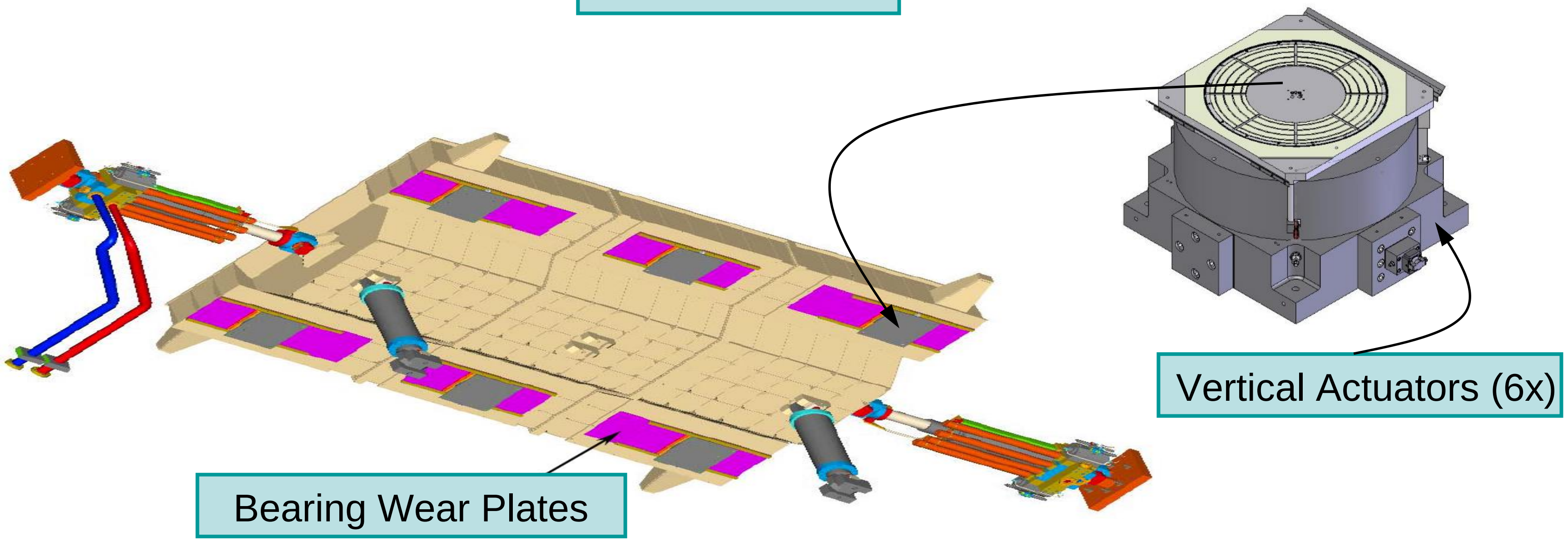
- **Education** of graduate, undergraduate, and K-12 students, as well as news media, policy makers, infrastructure owners, insurance and the general public, **about natural disasters** and the **national need to develop effective technologies and policies to prevent these natural hazard events from becoming societal disasters**.

1-DOF LHPOST (2004 –2019)



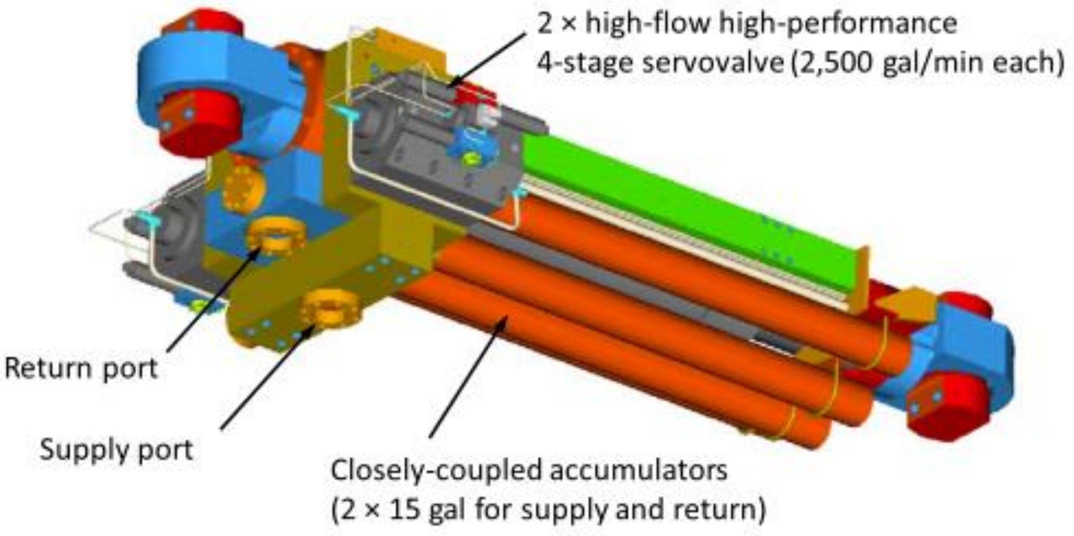
Mechanical and Servo-Hydraulic Components (1-DOF LHPOST: 2004 –2019)

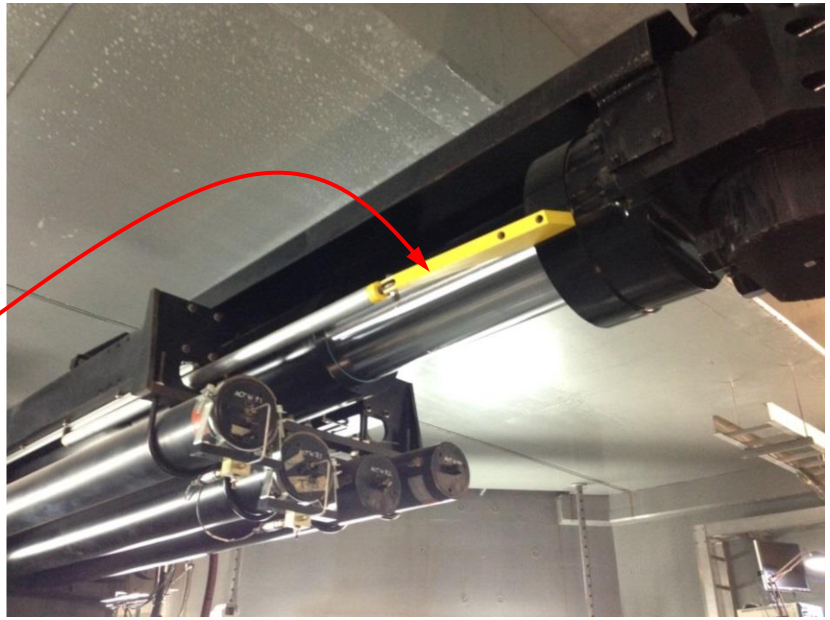




Horizontal Actuators

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

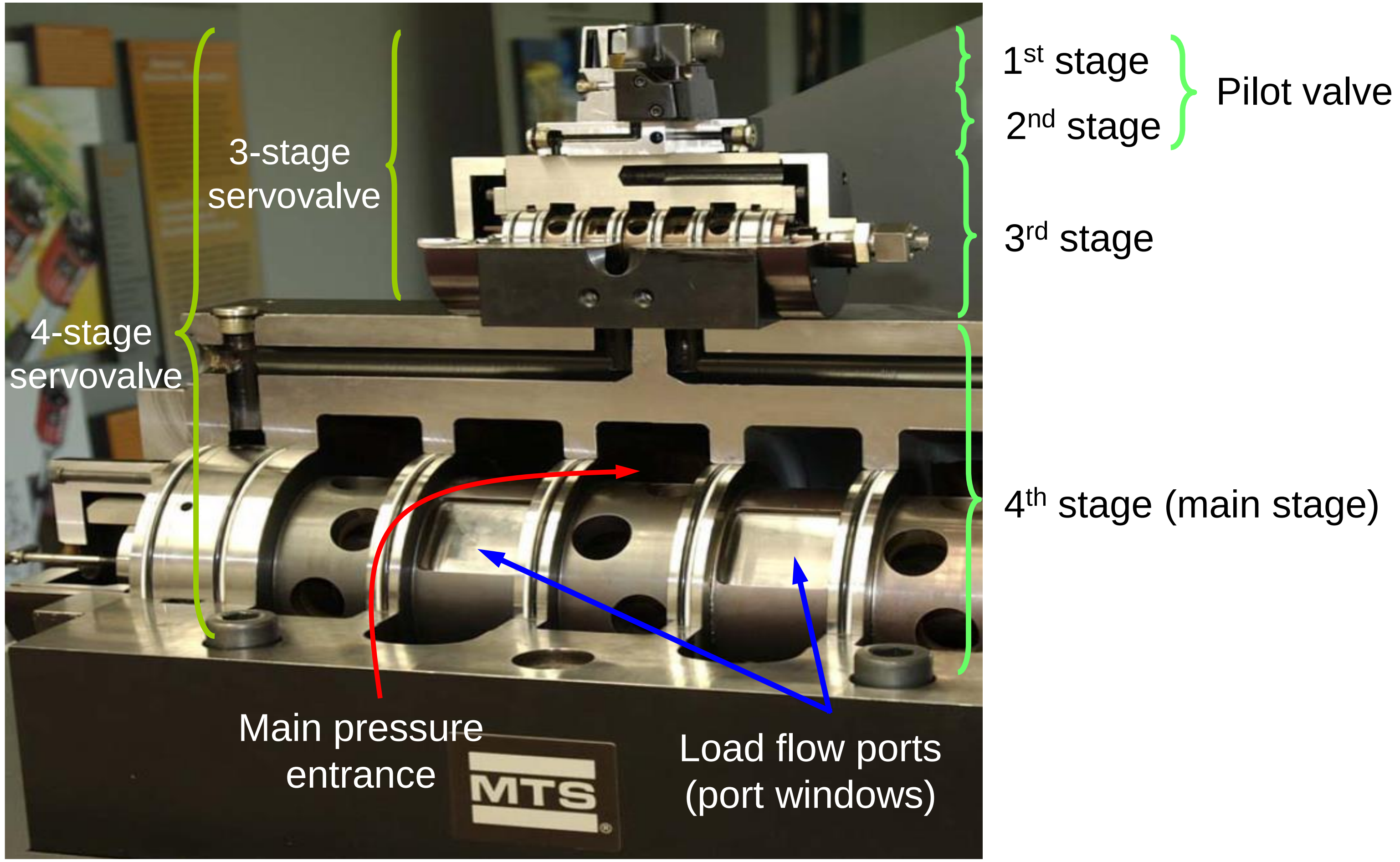




Temposonics magnetostrictive position sensor

High-Flow High-Performance Servovalves of Horizontal Actuators

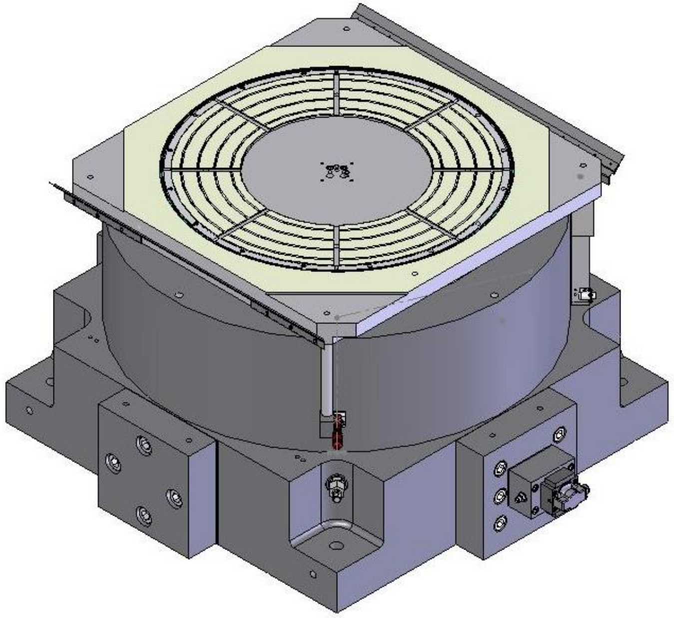
Servovalves (Qty. 2E + 2W)	
Pilot 2nd Stage Rating (Manufacturer Moog)	**19 lt/min**
Pilot 3rd Stage Rating	**630 lt/min**
4th Stage Flow Rating	**10,000 lt/min (2,500 gpm)**
Port Area Ratios	1:0.8:0.64:0.5
Valve Sleeve Windows Area Ratio	1:0.64

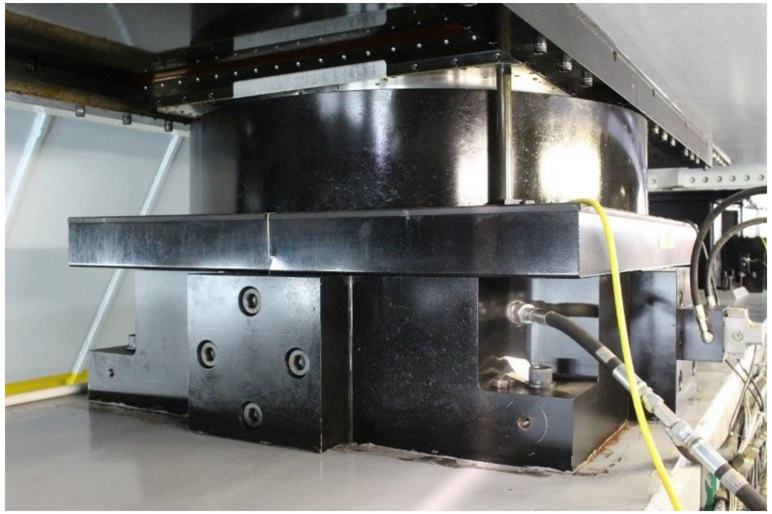


Courtesy of MTS Systems Corporation

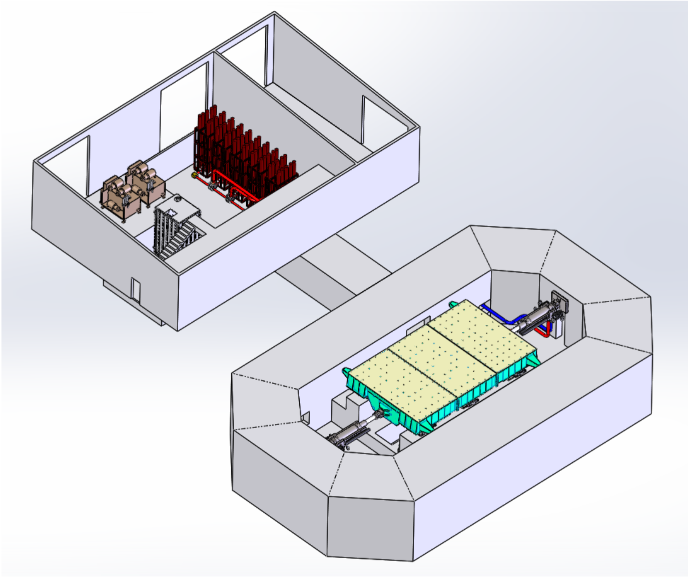
Vertical Actuators

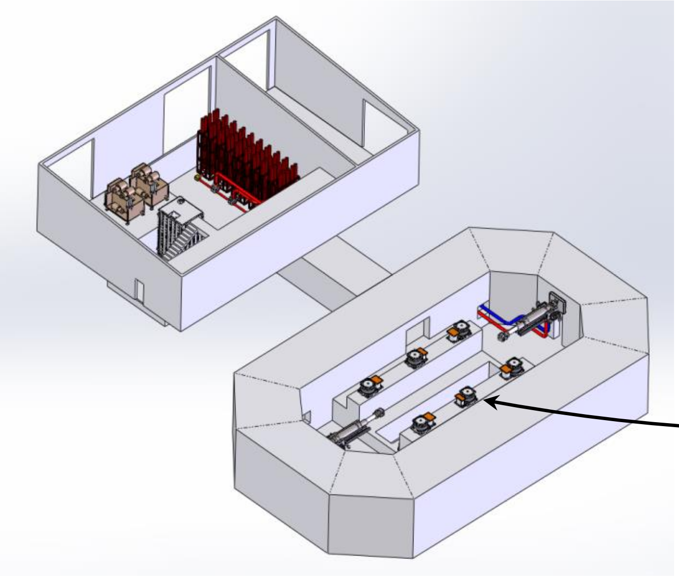
VERTICAL ACTUATORS SPECIFICATION		
	1-DOF Configuration	**6-DOF Configuration**
Piston Diameter	32 in (0.81 m)	32 in (0.81 m)
Effective area	798.31 in^2 (0.515 m^2)	798.31 in^2 (0.515 m^2)
Piston Stroke	$\pm$ 0.25 in ($\pm$ 0.0064 m)	$\pm$ 5.0 in ($\pm$ 0.127 m)
Piston Tilt	N/A	$\pm$ 2°
Force Rating	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)



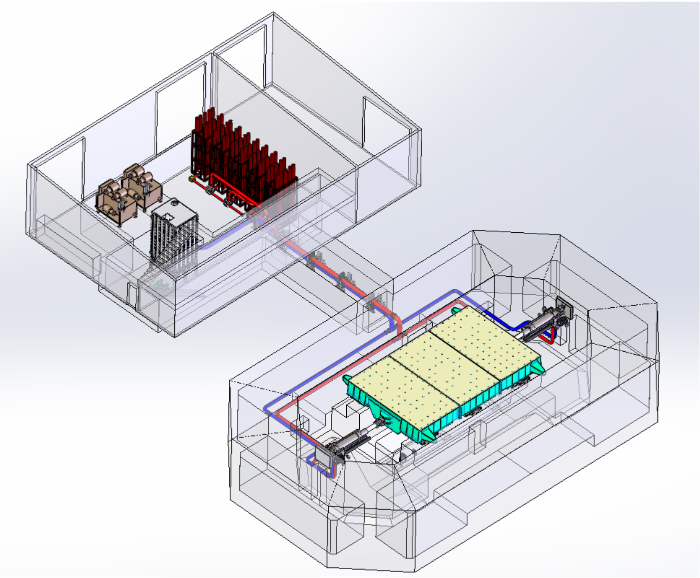


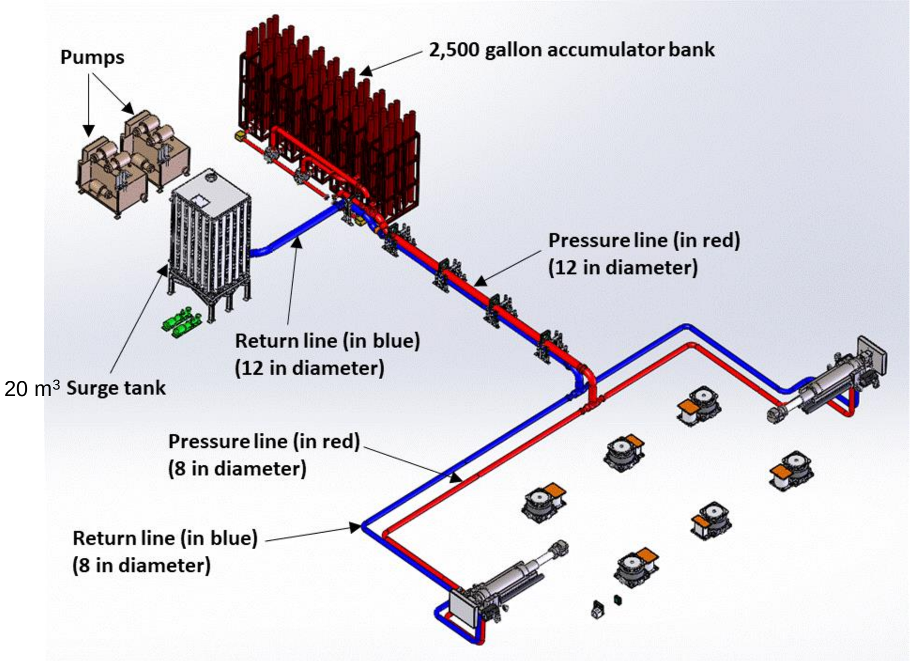
Hydraulic Power Supply System for 1-DOF LHPOST (2004 –2019)





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

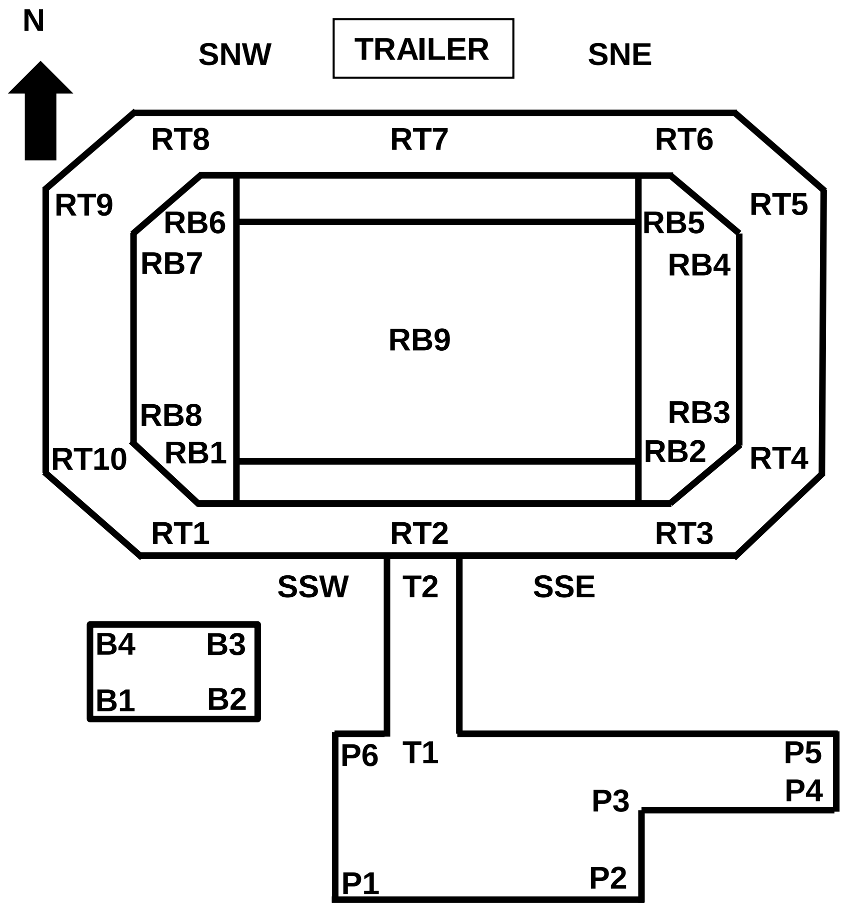




Bare Table Motion (1-DOF LHPOST)

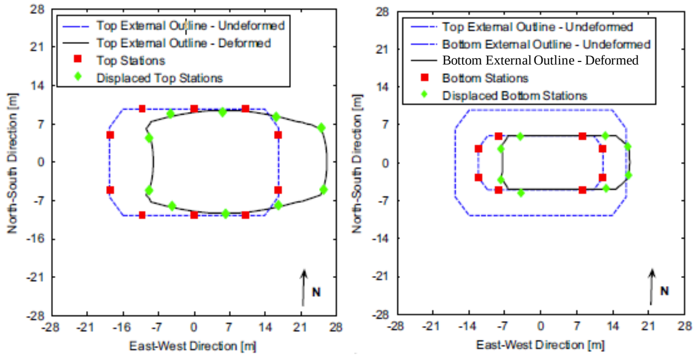
Forced Vibration Characterization Tests of the Reaction Mass/Block (2003)

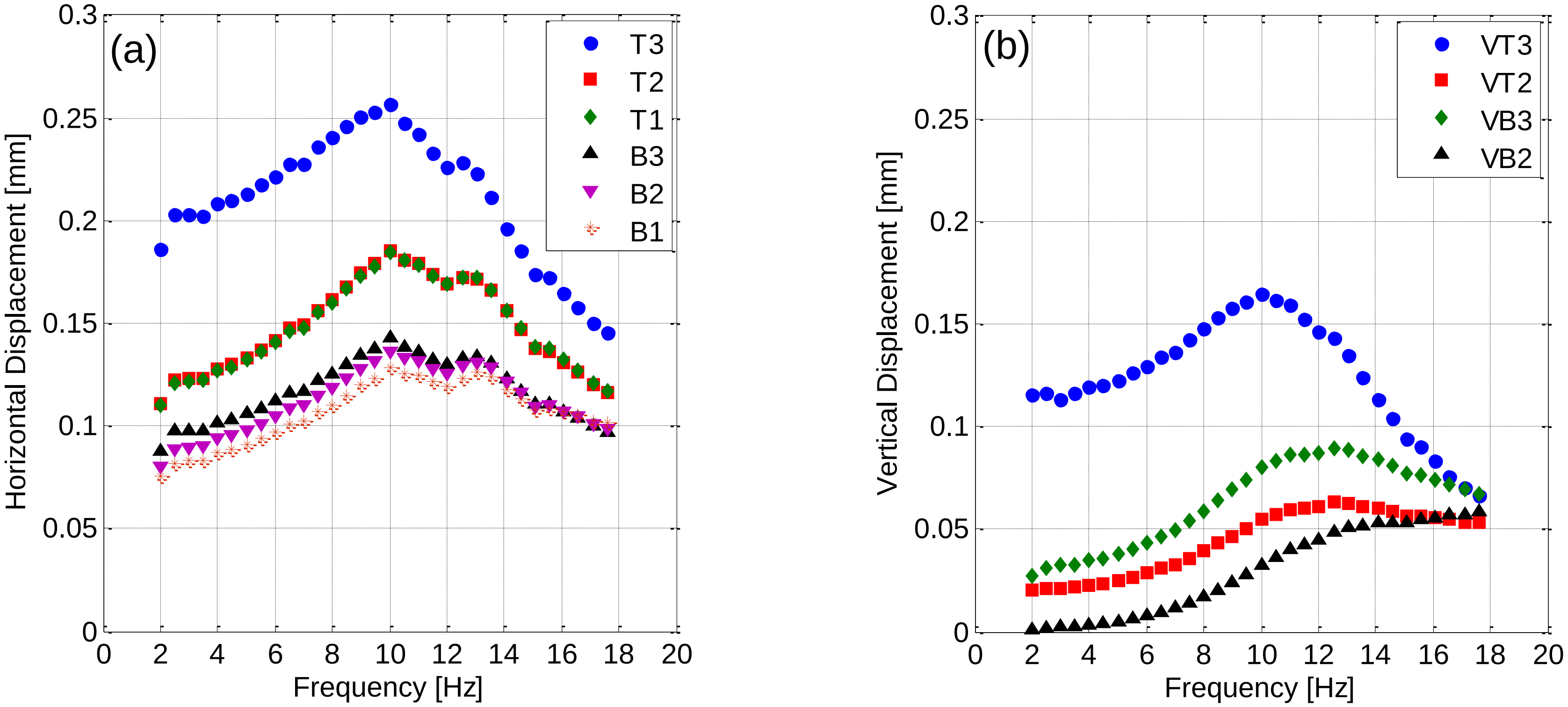
Forced Vibration Characterization Tests of the Reaction Mass/Block (2003)



Instrument locations on Reaction Block and adjacent foundations

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.

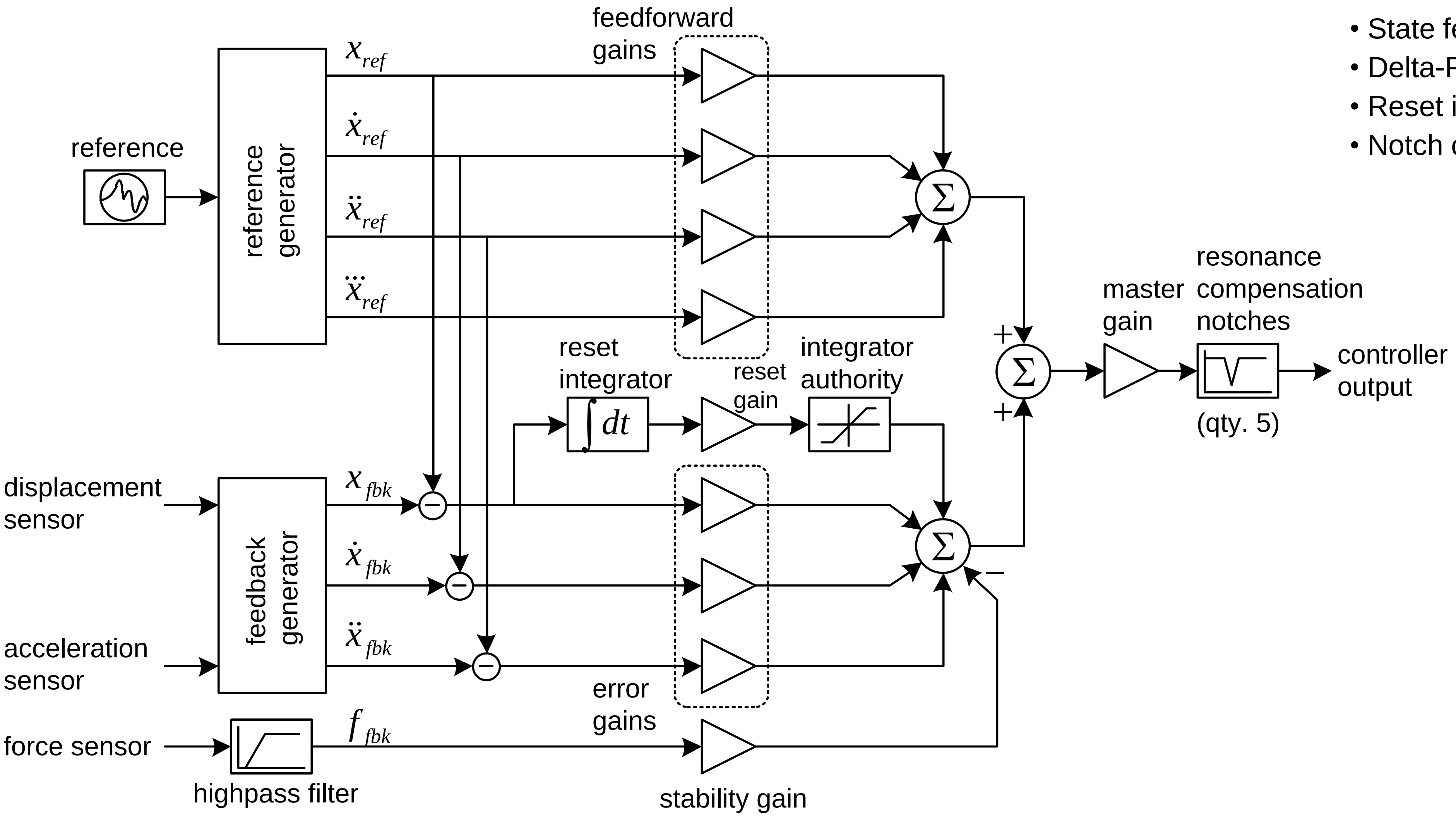
MTS Three-Variable Controller (TVC)

- **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

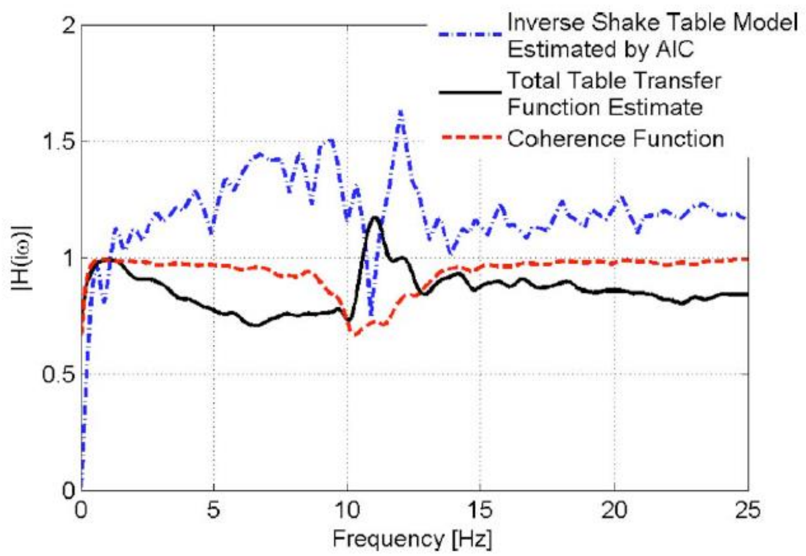
Tuning of LHPOST Controller (MTS 469D)

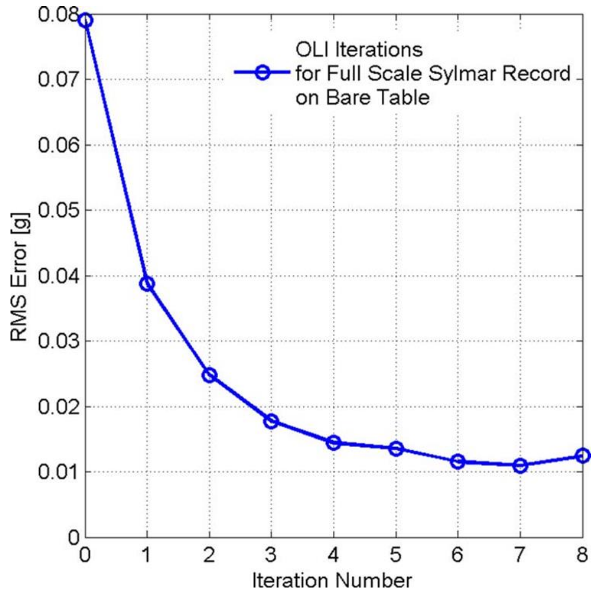
Tuning: Process of adjusting multiple control parameters (e.g., feedback and feedforward gains) and of preconditioning the input motion (through OLI) to optimize signal reproduction (tracking) capability of the shake table system.

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.

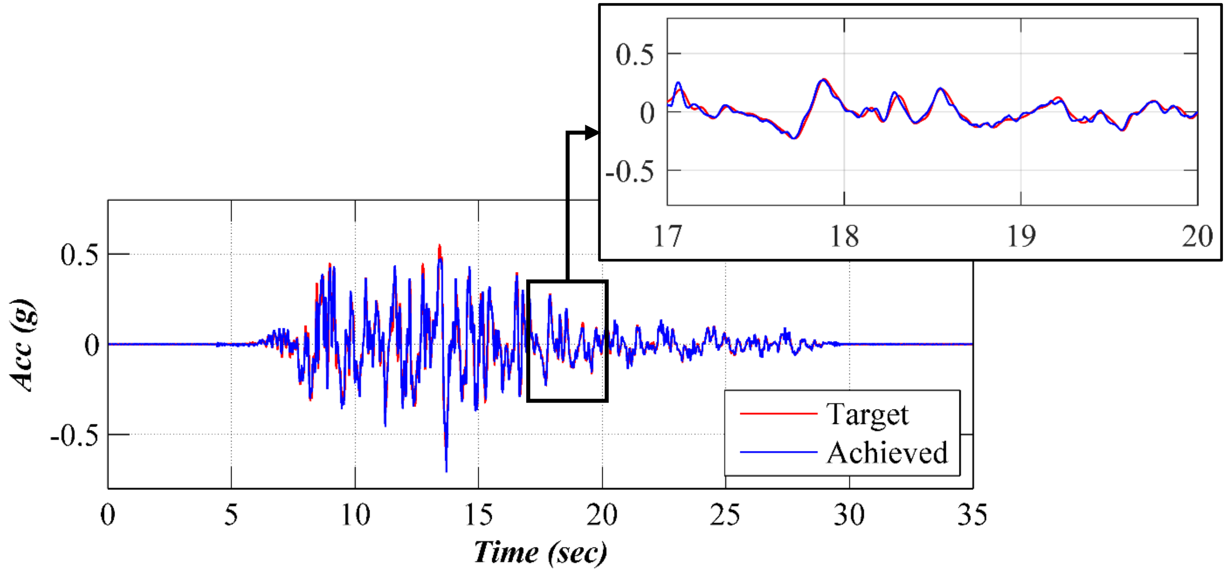
Step 2: Estimation of the inverse model of the plant using the adaptive inverse controller (AIC) technique.

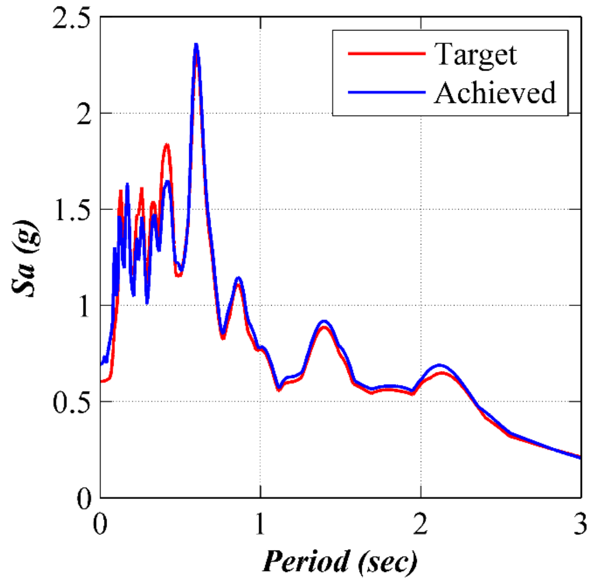
Step 3: Application of iterative time history matching technique called online iteration (OLI). The command input to the shake table controller (drive file) is repeatedly modified to optimize the match between the actual table motion and the desired/target motion (or reference signal).

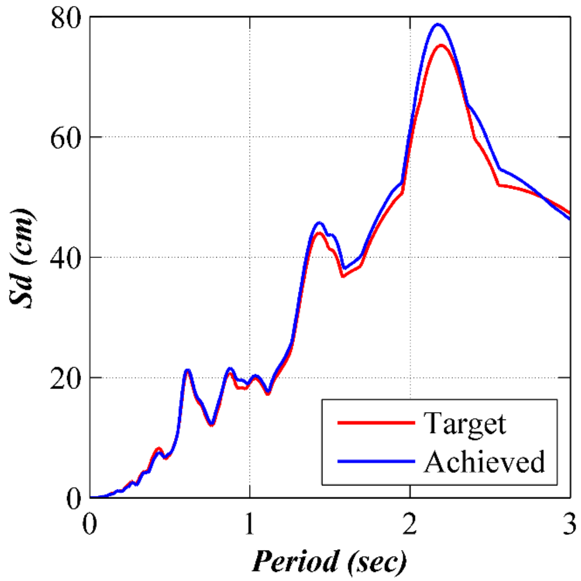




Tracking Performance of LHPOST (1-DOF)







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

Instrumentation of 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**
  - DJI Phantom 4 Pro Drone, 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 Shake Table Tests Performed on the LHPOST (1-DOF)

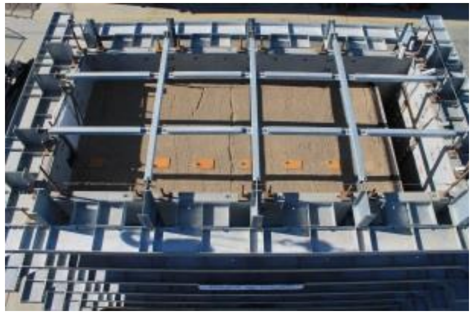
Select Set of Specimens Tested on the LHPOST (1-DOF)









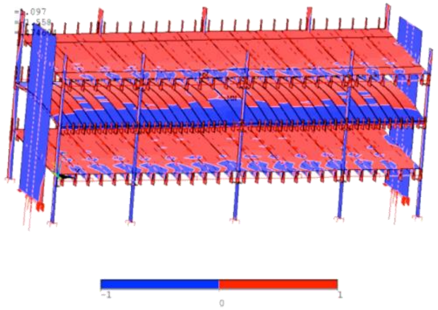




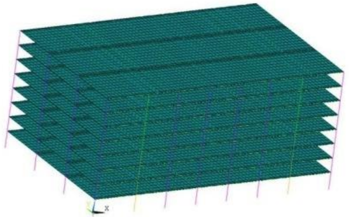
Integrated Experimental-Analytical Approach

Experimental Research
- Materials
- Structural components
- Structural systems

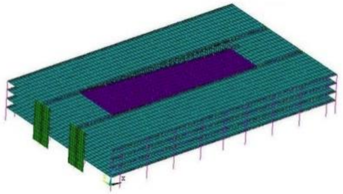
Computational Simulation
- Model development
- Model calibration
- Model validation



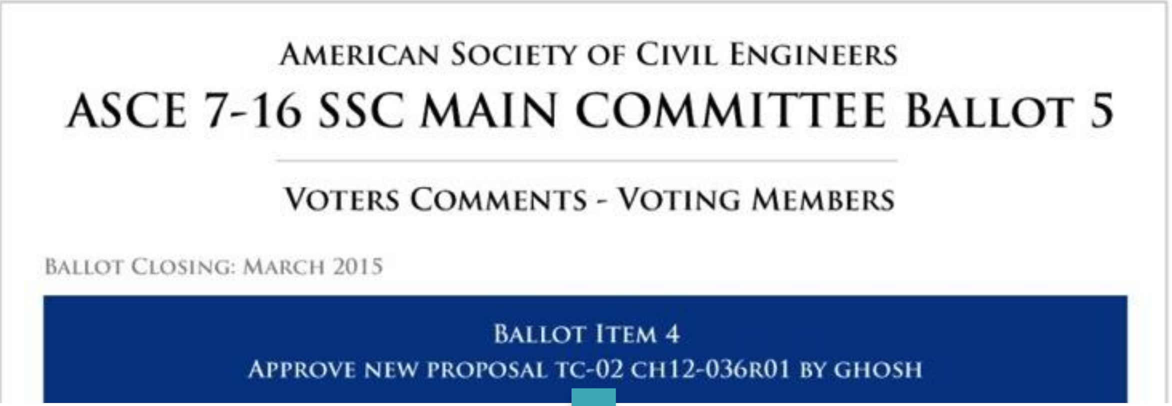
Design Provisions and Assessment Methods
- Development
- Verification through numerical simulation



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

SEISMIC RESILIENT BUILT ENVIRONMENT

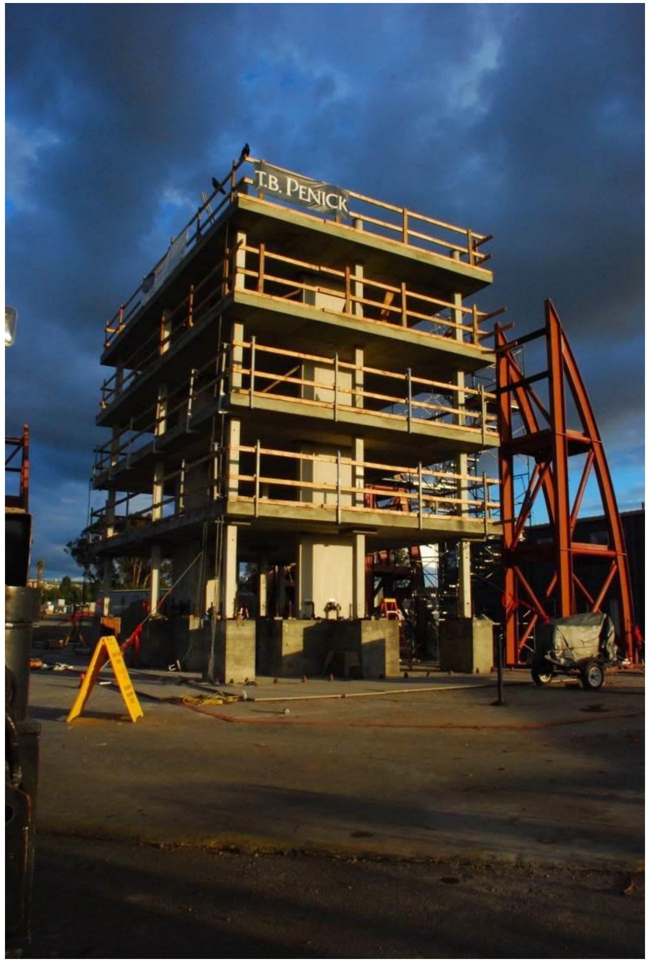
Development of a Seismic Design Methodology for Precast Building Diaphragms

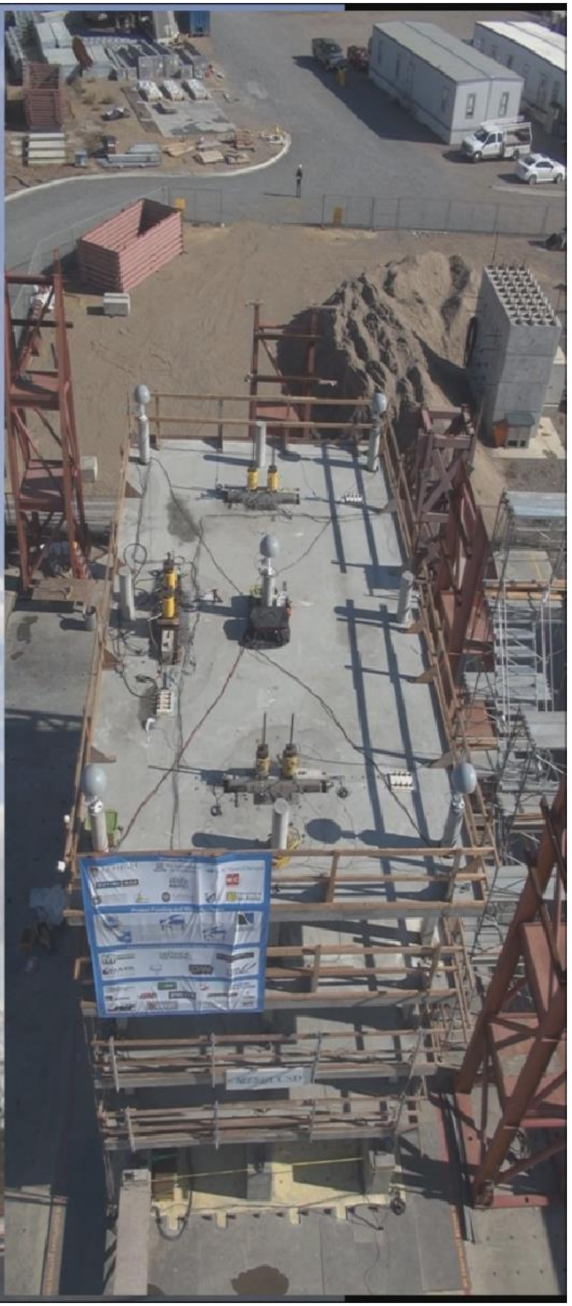
PI – Prof. Robert B. Fleischman, University of Arizona

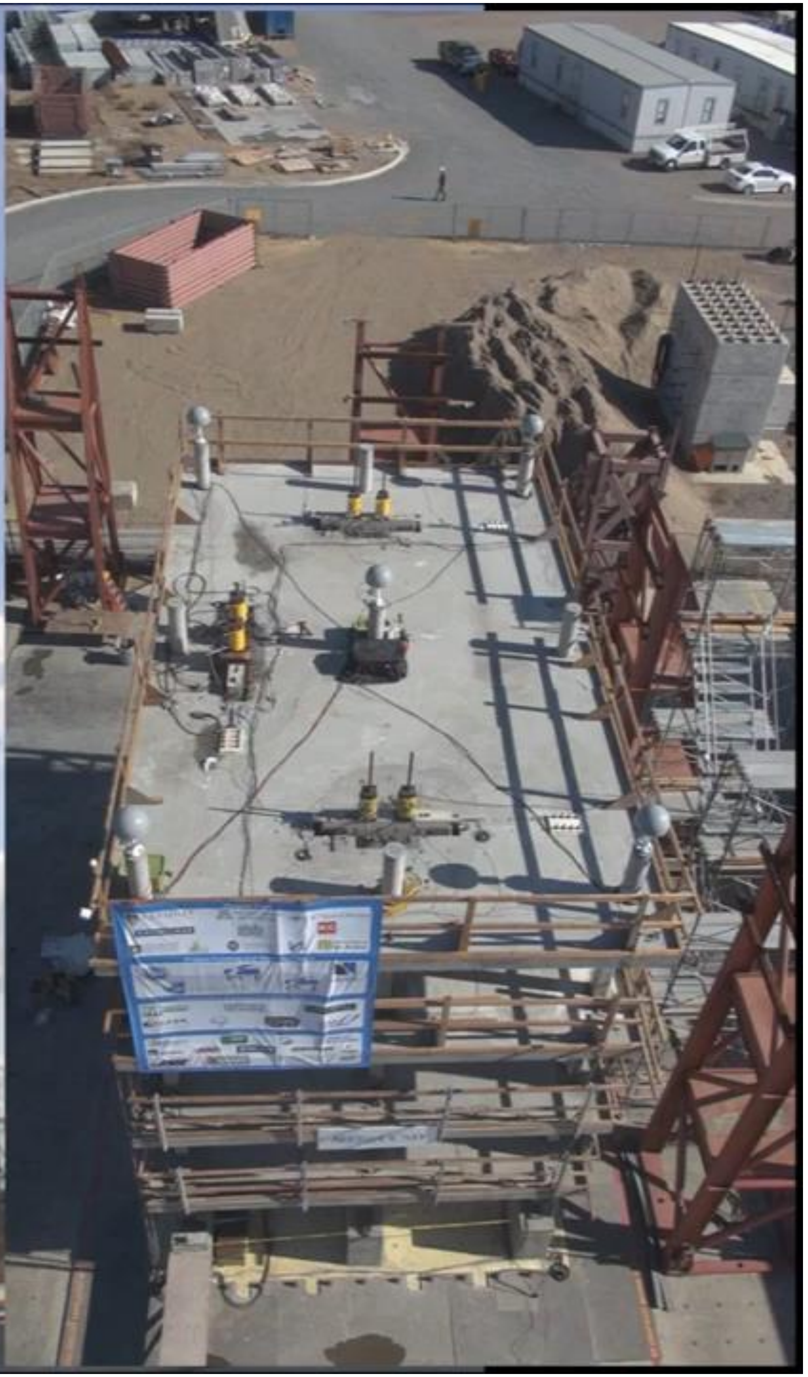

NEES

Inertial Force – Limiting Anchorage Systems for Seismic Resistant Building Structures

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

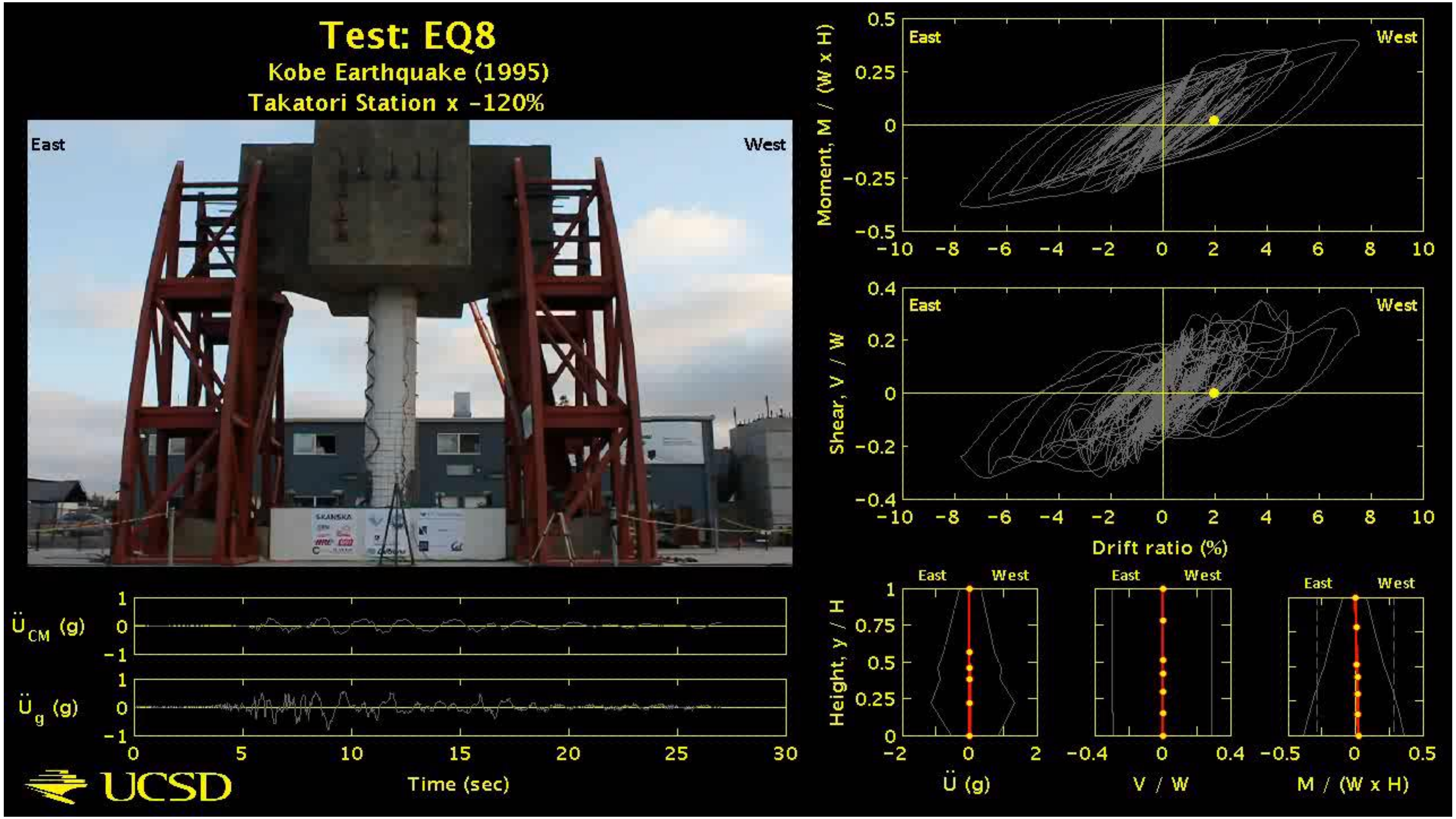


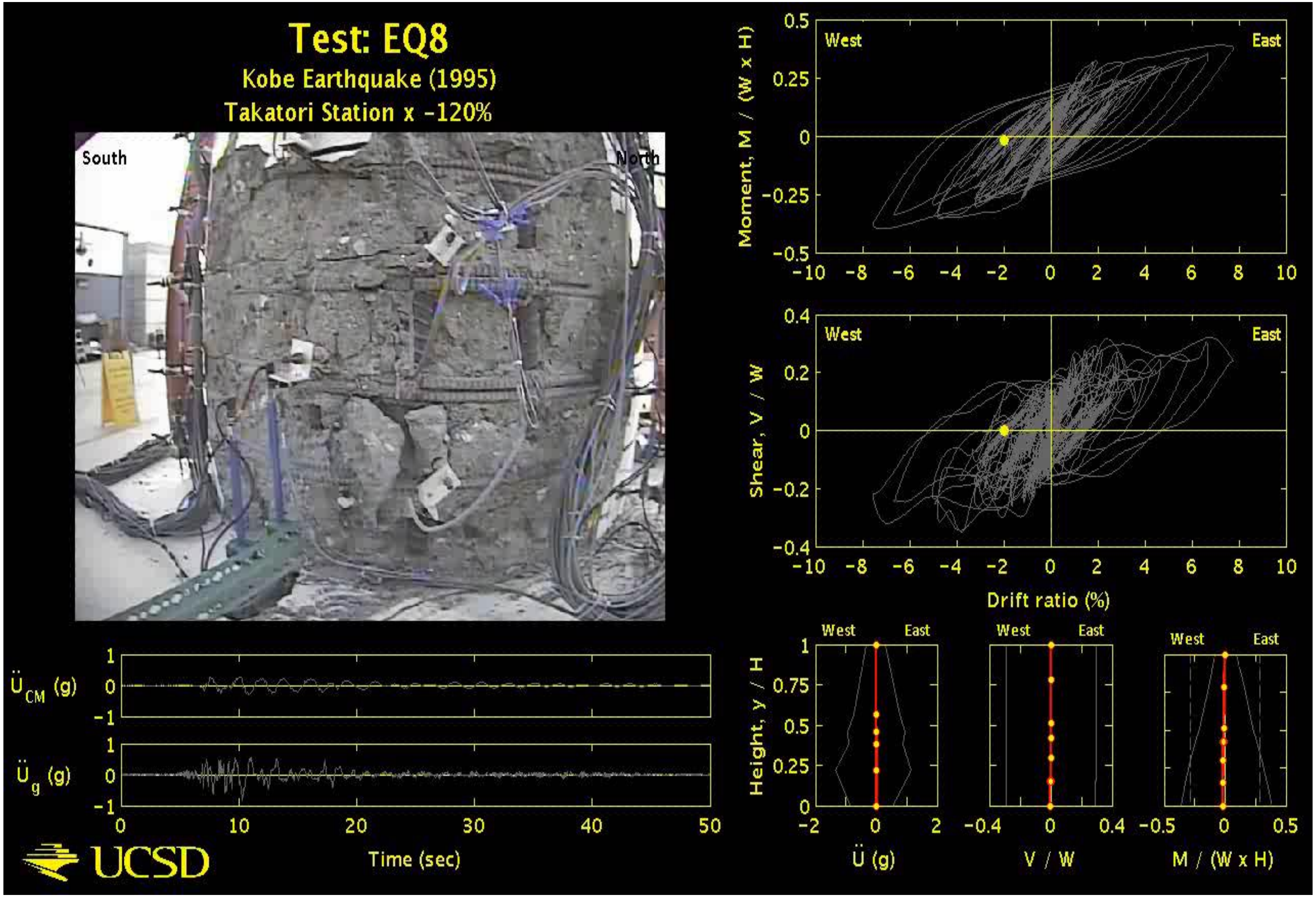



Large Scale Validation of Seismic Performance of Bridge Columns

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




Test: EQ8
Kobe Earthquake (1995)
Takatori Station x -120%
South
North
West
East
Moment, M / (W x H)
0.5
0.25
0
-0.25
-0.5
-10 -8 -6 -4 -2 0 2 4 6 8 10
Shear, V / W
0.4
0.2
-0.2
-0.4
Drift ratio (%)
Ü_CM (g)
Ü_g (g)
1
-1
0 10 20 30 40 50
Time (sec)
UCSD
Height, y / H
1
0.75
0.5
0.25
Ü (g)
-2 0 2
V / W
-0.4 0 0.4
M / (W x H)
-0.5 0 0.5

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

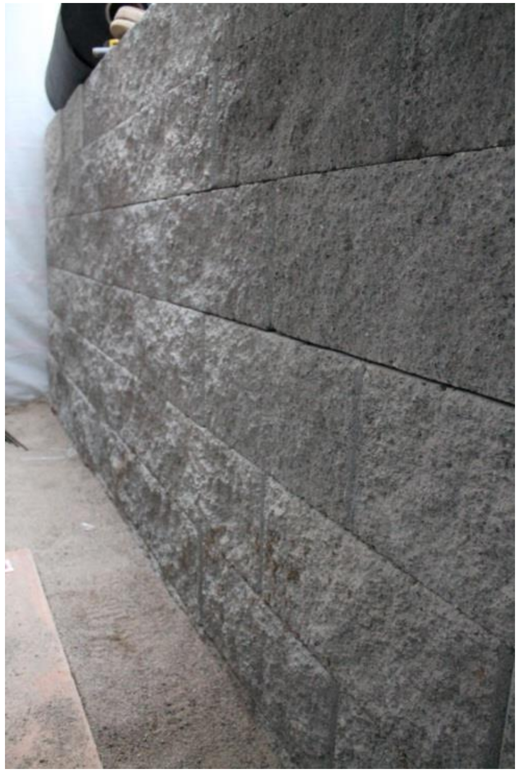
Liquefaction-Induced Lateral Spread Displacements and Soil-Pile Interaction in Multi-Layer Soil Strata

PI – Prof. Ahmed Elgamal, UC San Diego

Seismic Performance Tests of Full-Scale Retaining Walls

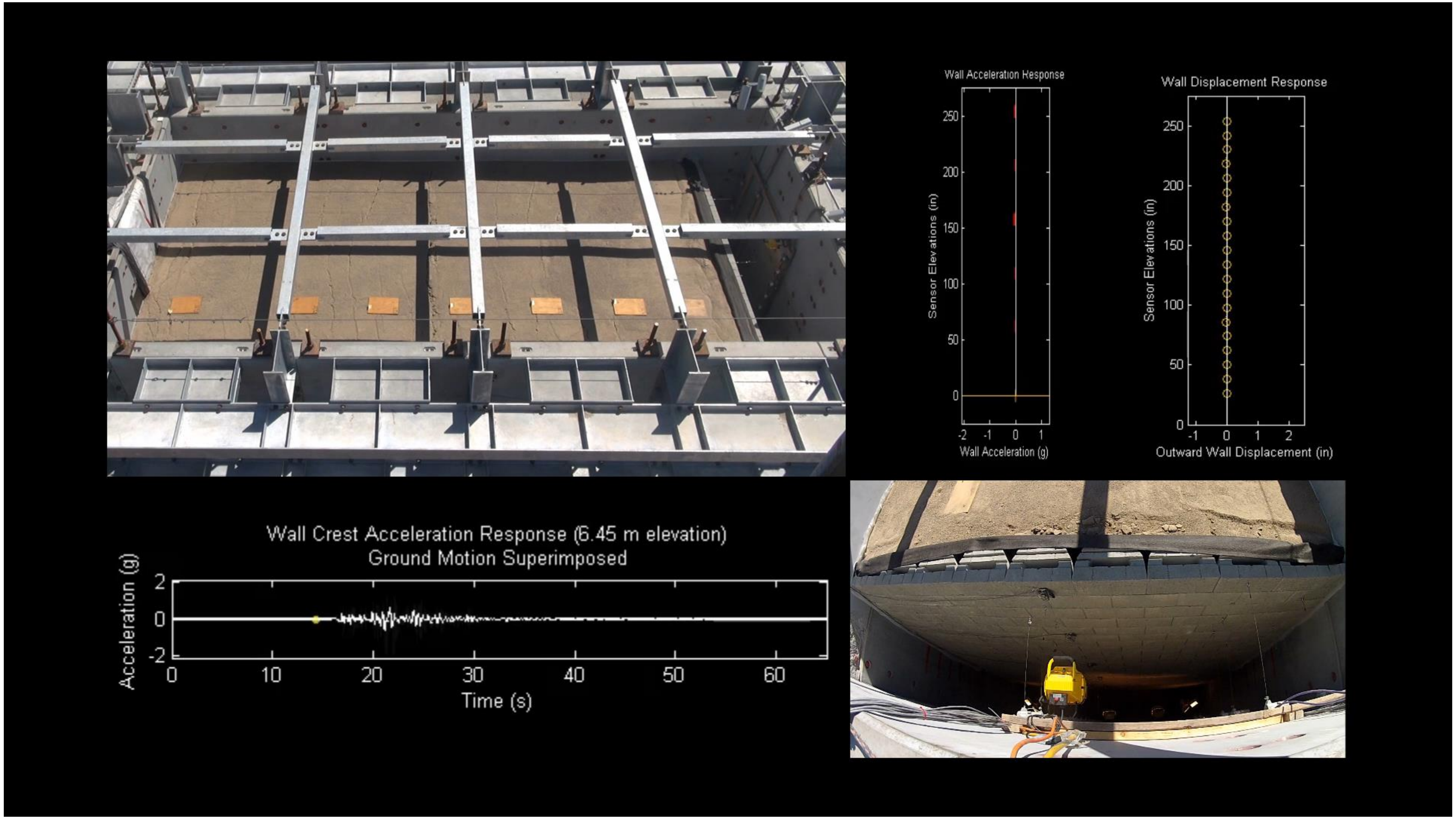
PI – Prof. Patrick Fox, UC San Diego

22 ft Above Table Elevation



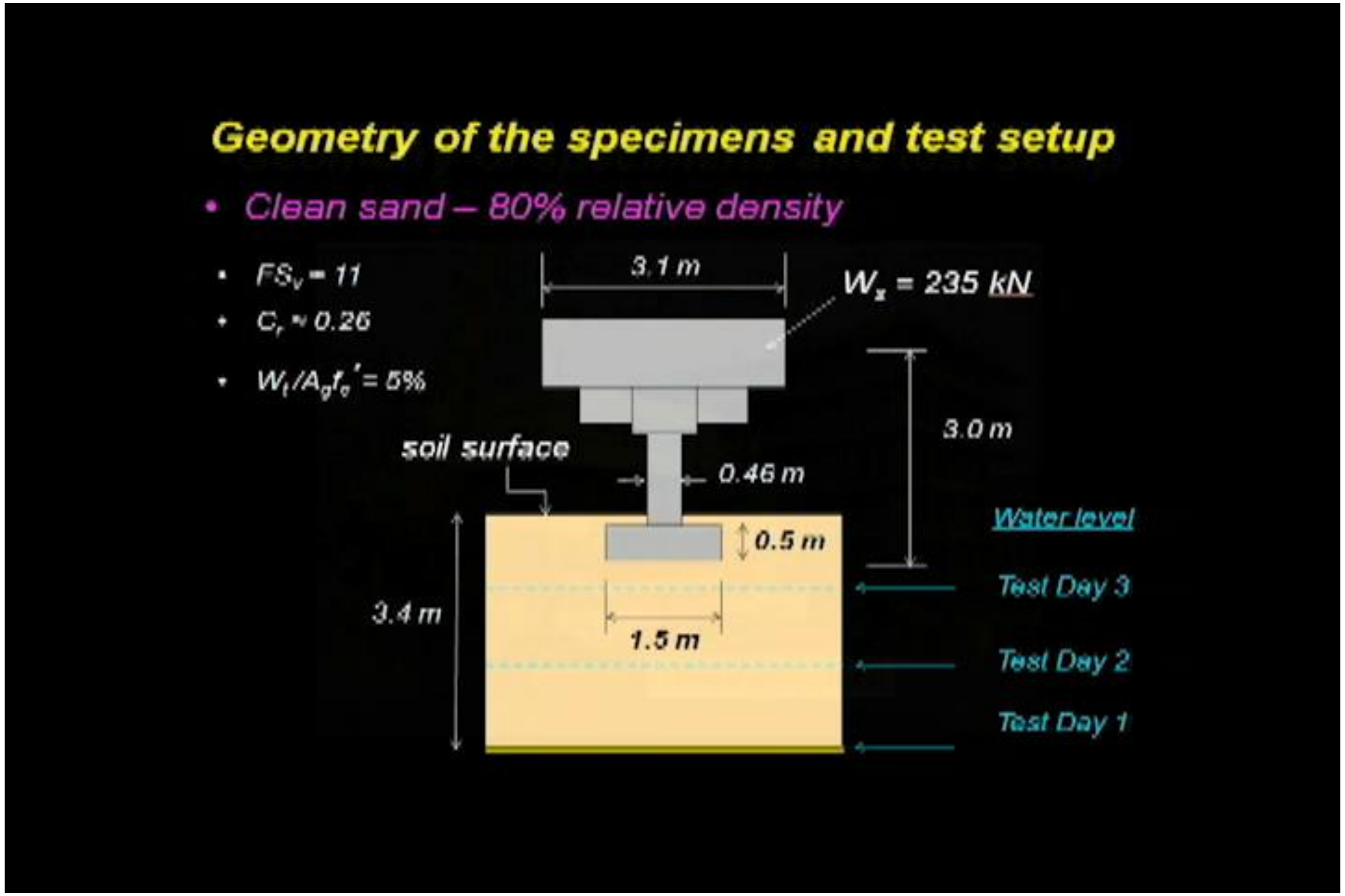
Seismic Performance Tests of Full-Scale Retaining Walls

PI – Prof. Patrick Fox, UC San Diego



Soil-Foundation-Structure Interaction Test

PI – Prof. Marios Panagiotou, UC Berkeley



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

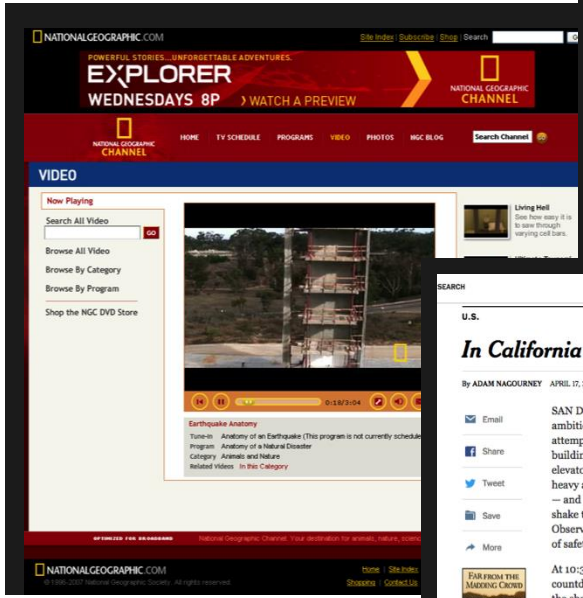
Tres desafíos

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.

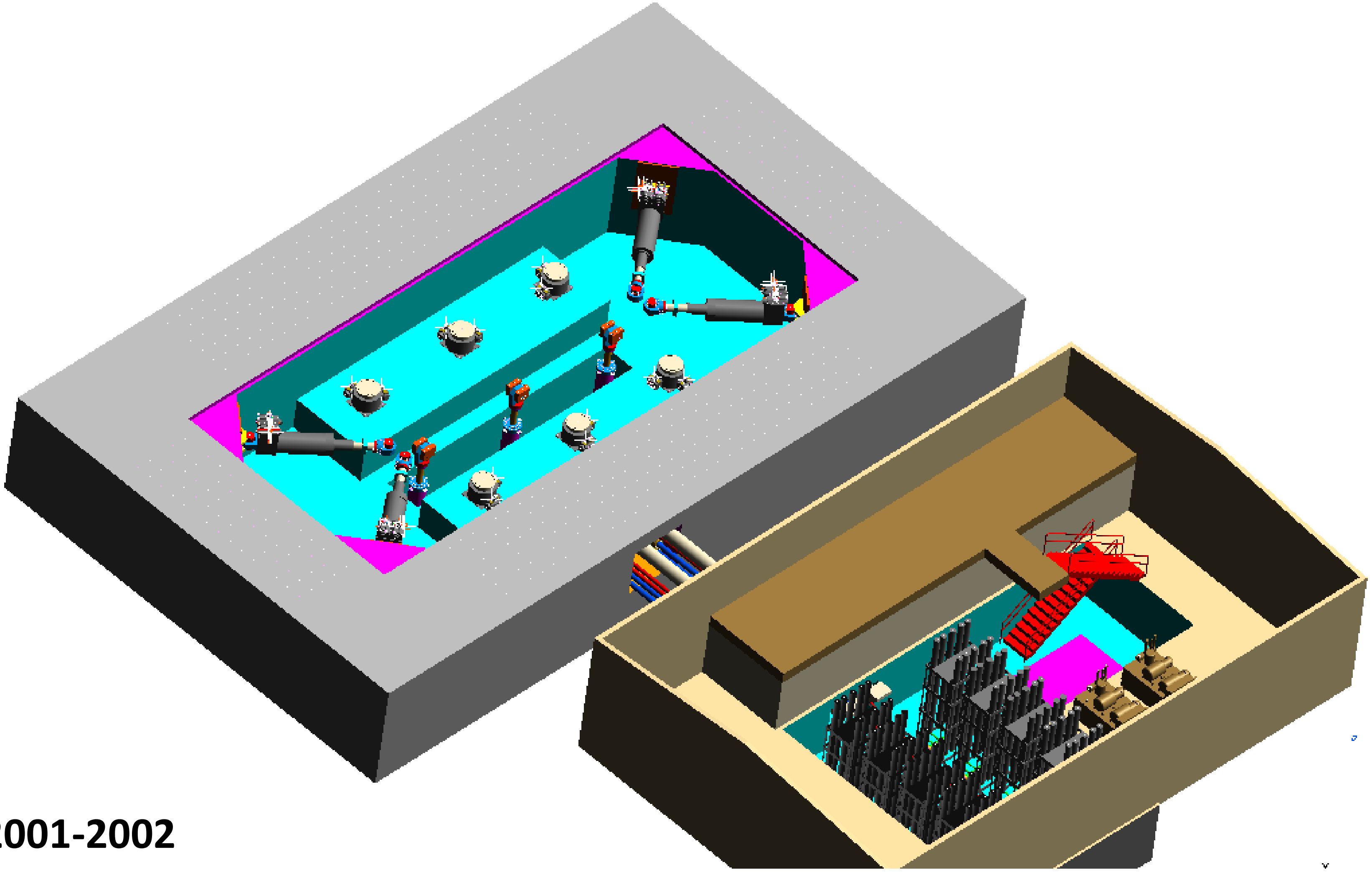
At 10:30 a.m. Tuesday, after an ominous countdown and as red warning lights whirled, the shake table unleashed the mechanical equivalent of a one-minute earthquake that replicated the 6.7-magnitude Northridge temblor that rolled through Los Angeles in 1994. It was the first of two earthquake re-enactments

Researchers conducted two earthquake simulations in San Diego on Tuesday.

Sam Hodgson for The New York Times

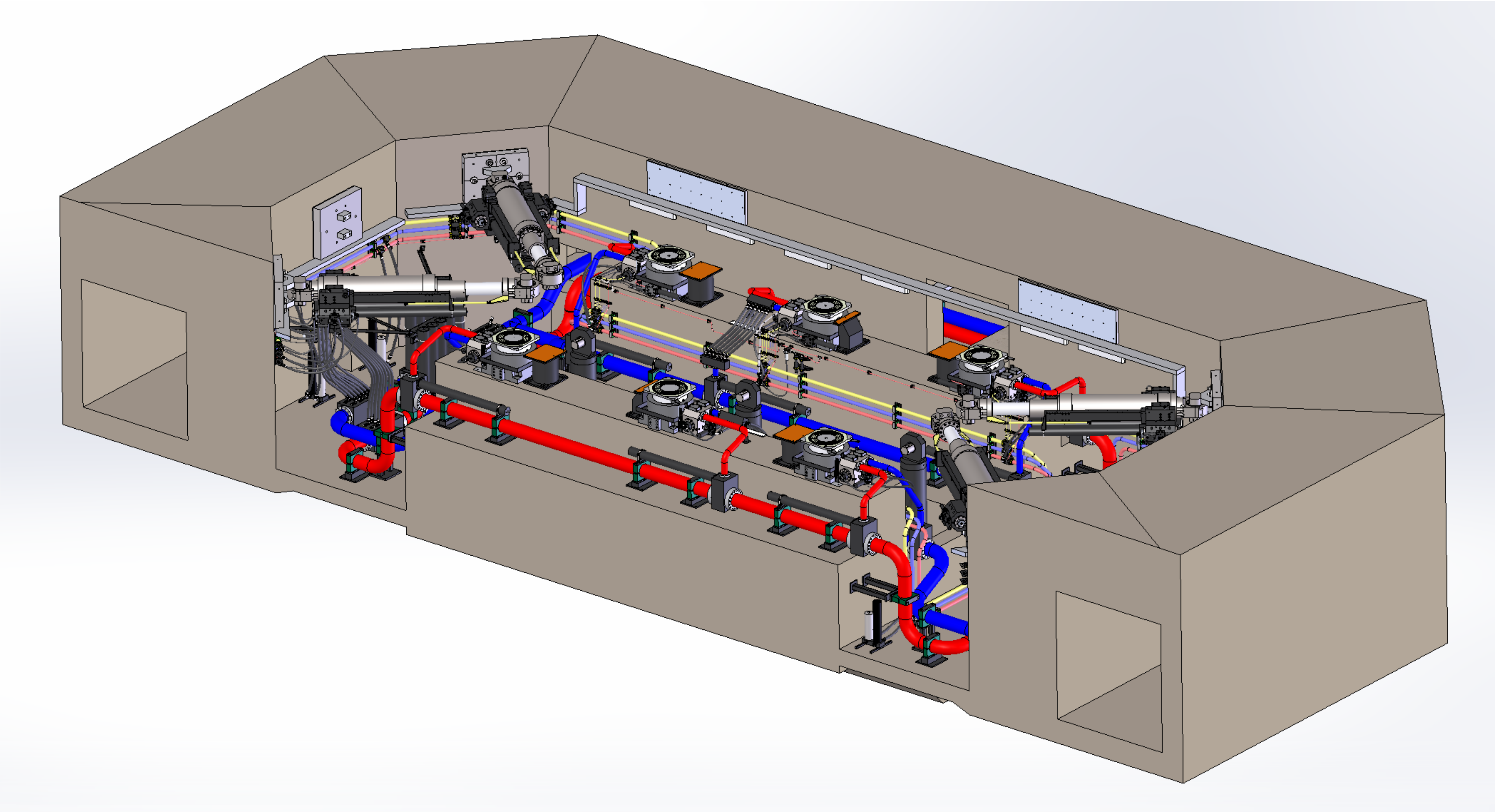
Six Degree-of-Freedom (6-DOF) Upgrade of LHPOST into LHPOST6

Upgrade to 6-DOF Capability Planned from the Start

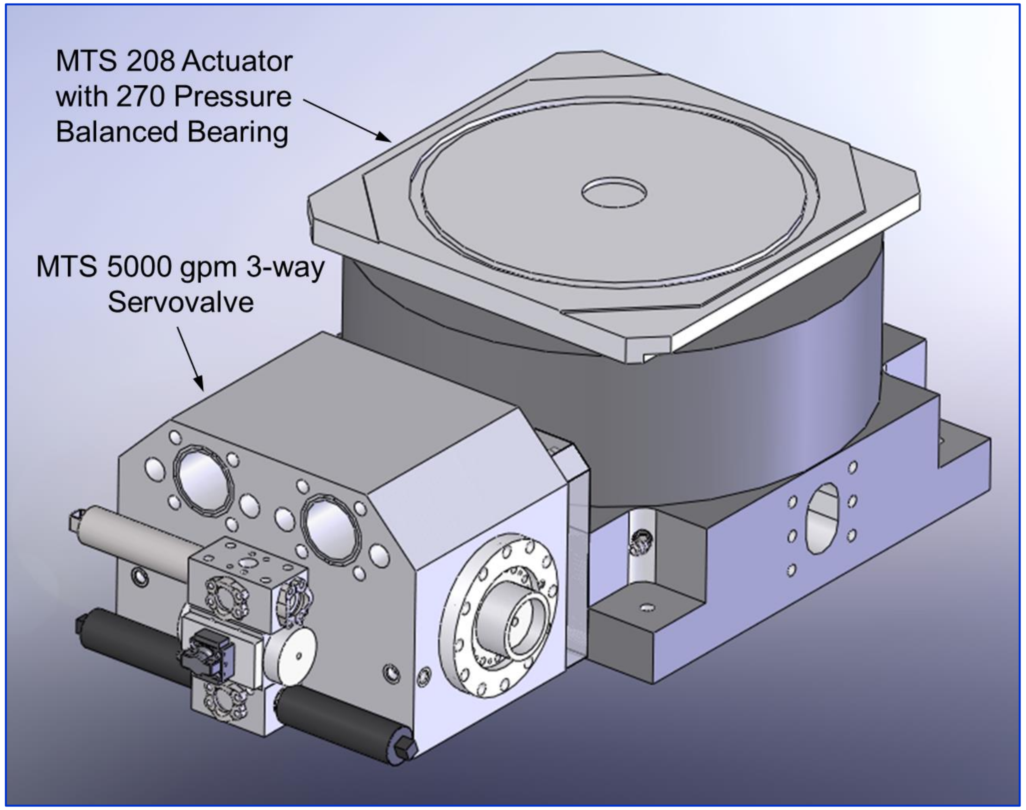


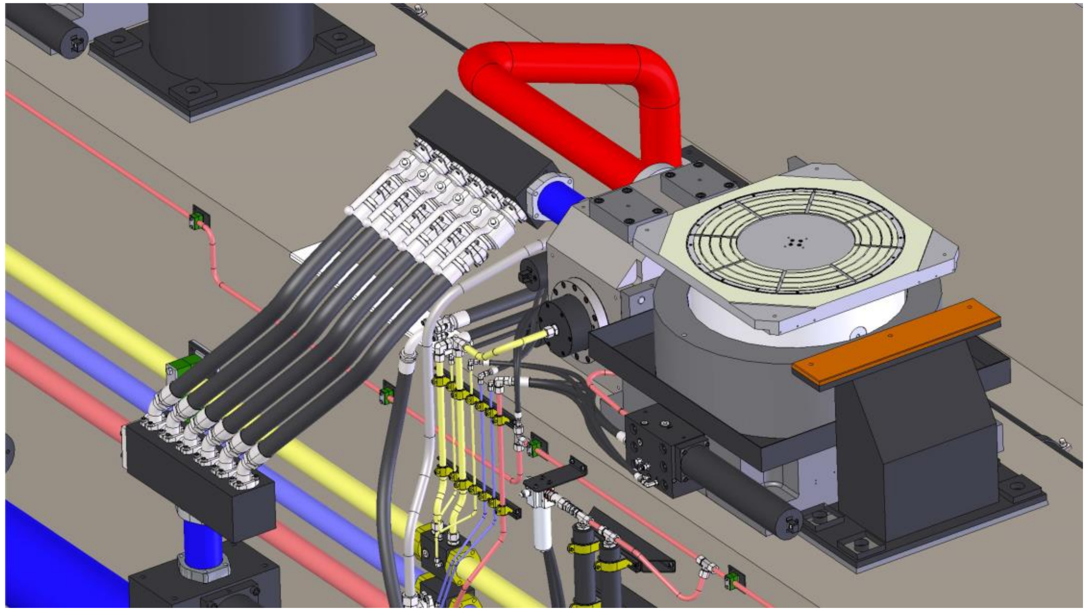
Rendering from 2001-2002

Horizontal and Vertical Actuators of LHPOST6

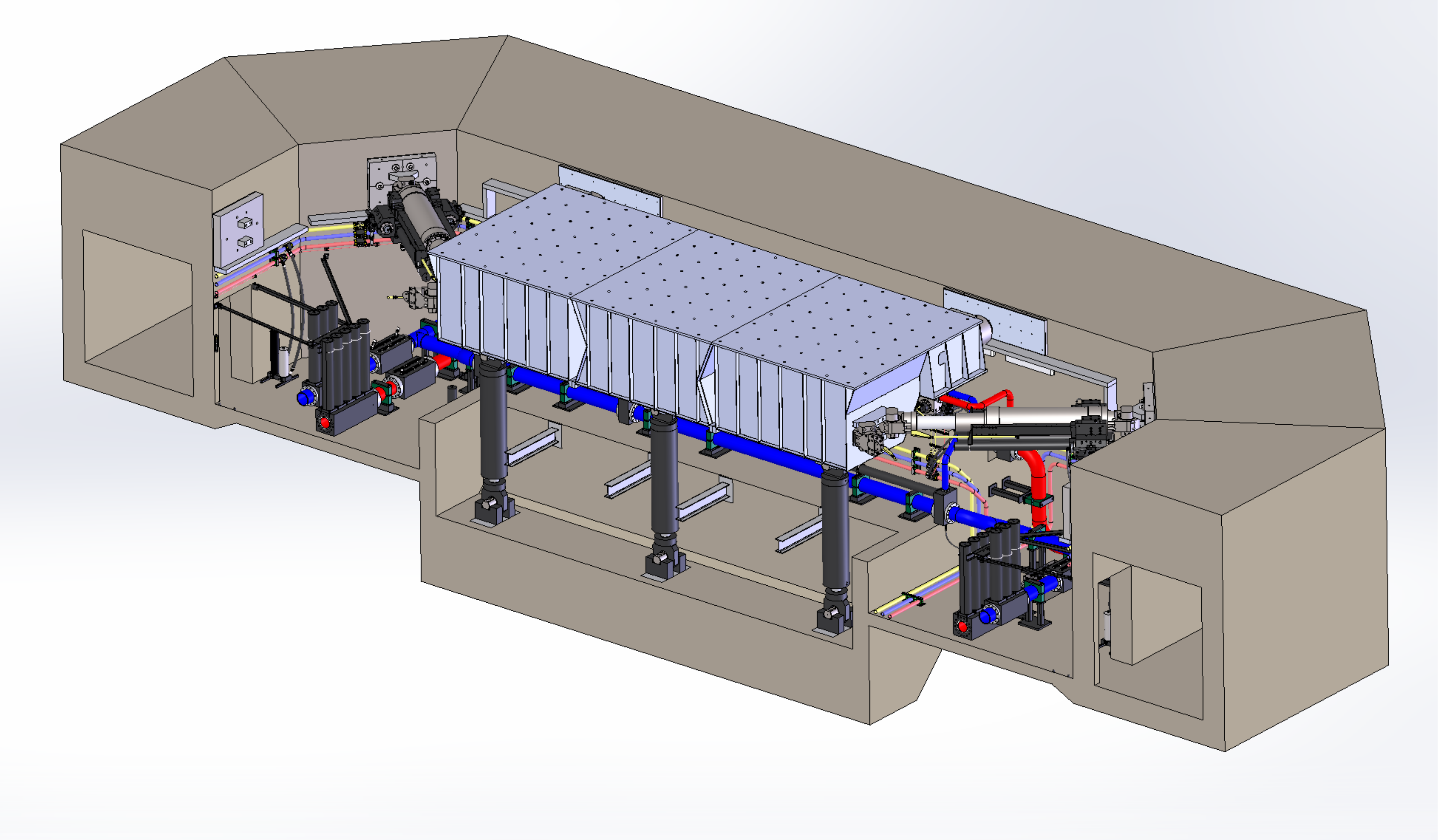


High-Flow Servovalves for Vertical Actuators

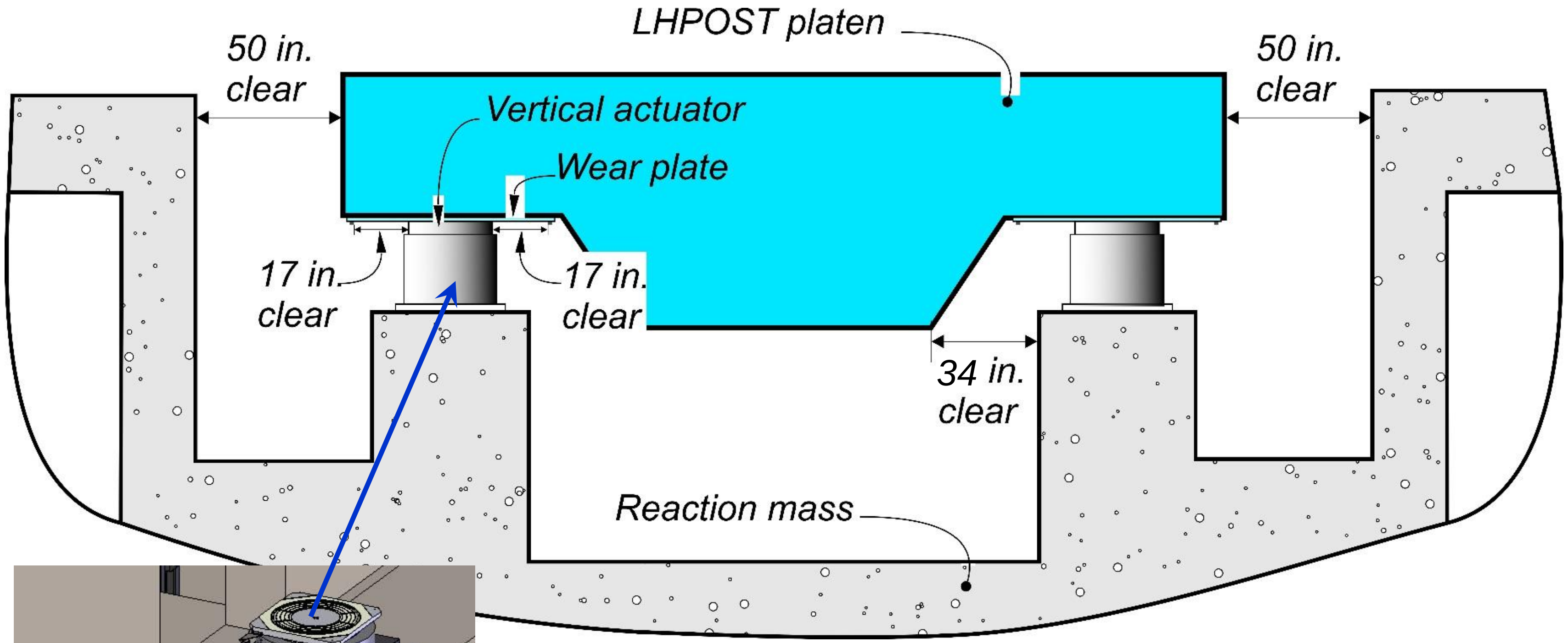


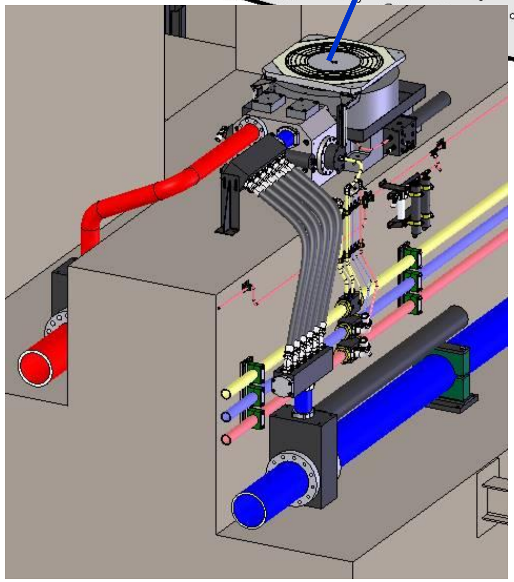


Third Nitrogen-filled Hold-down Strut



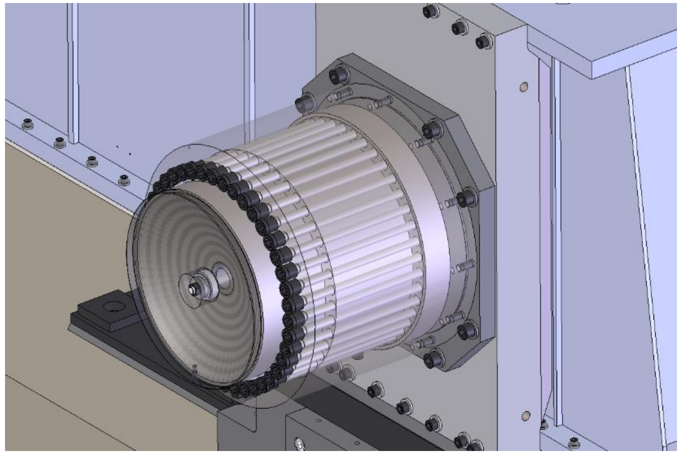
Displacement Limit in the Transverse (N-S) Direction

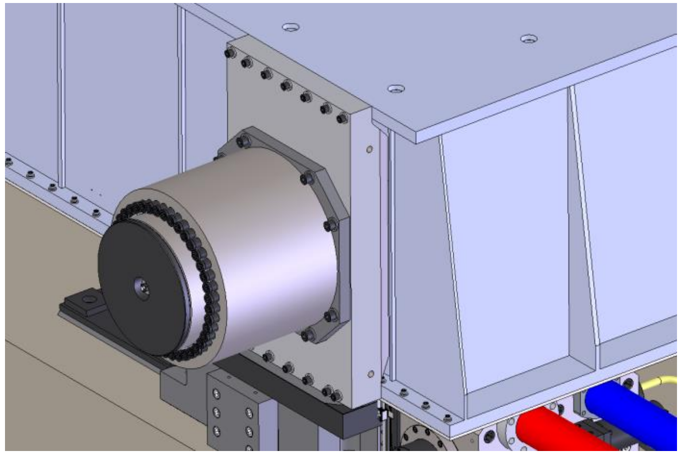


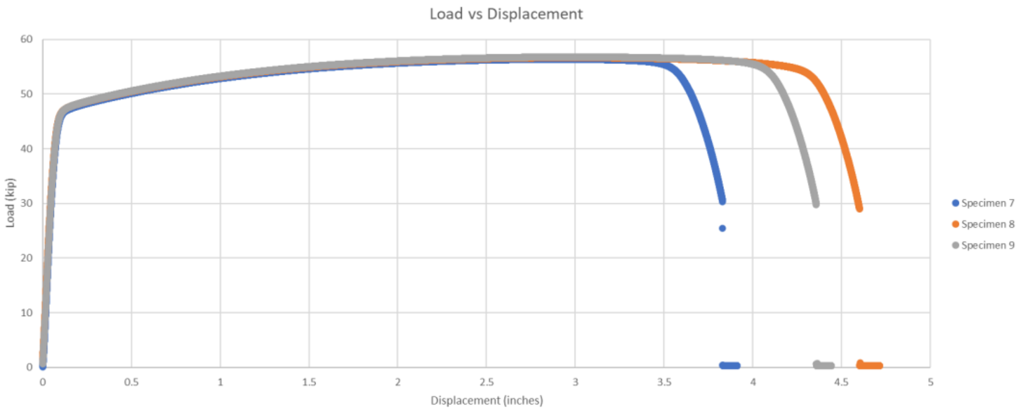


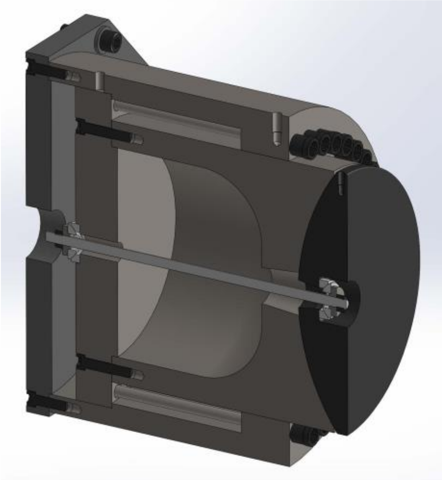
- Three lines of defense against potential impact:
  - Software limit detectors (interlocks)
  - Physical limit switches (LVDT’s)
  - Collision/crash protection devices (last resort)

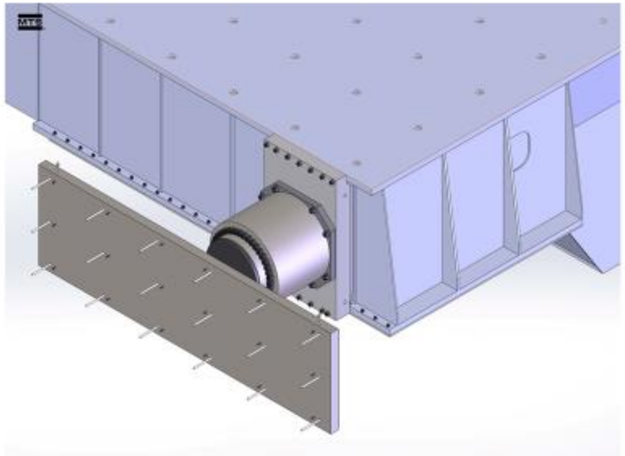
Crash Protection System

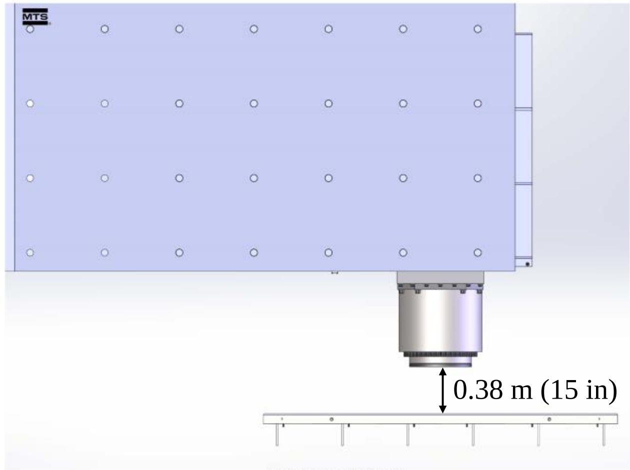




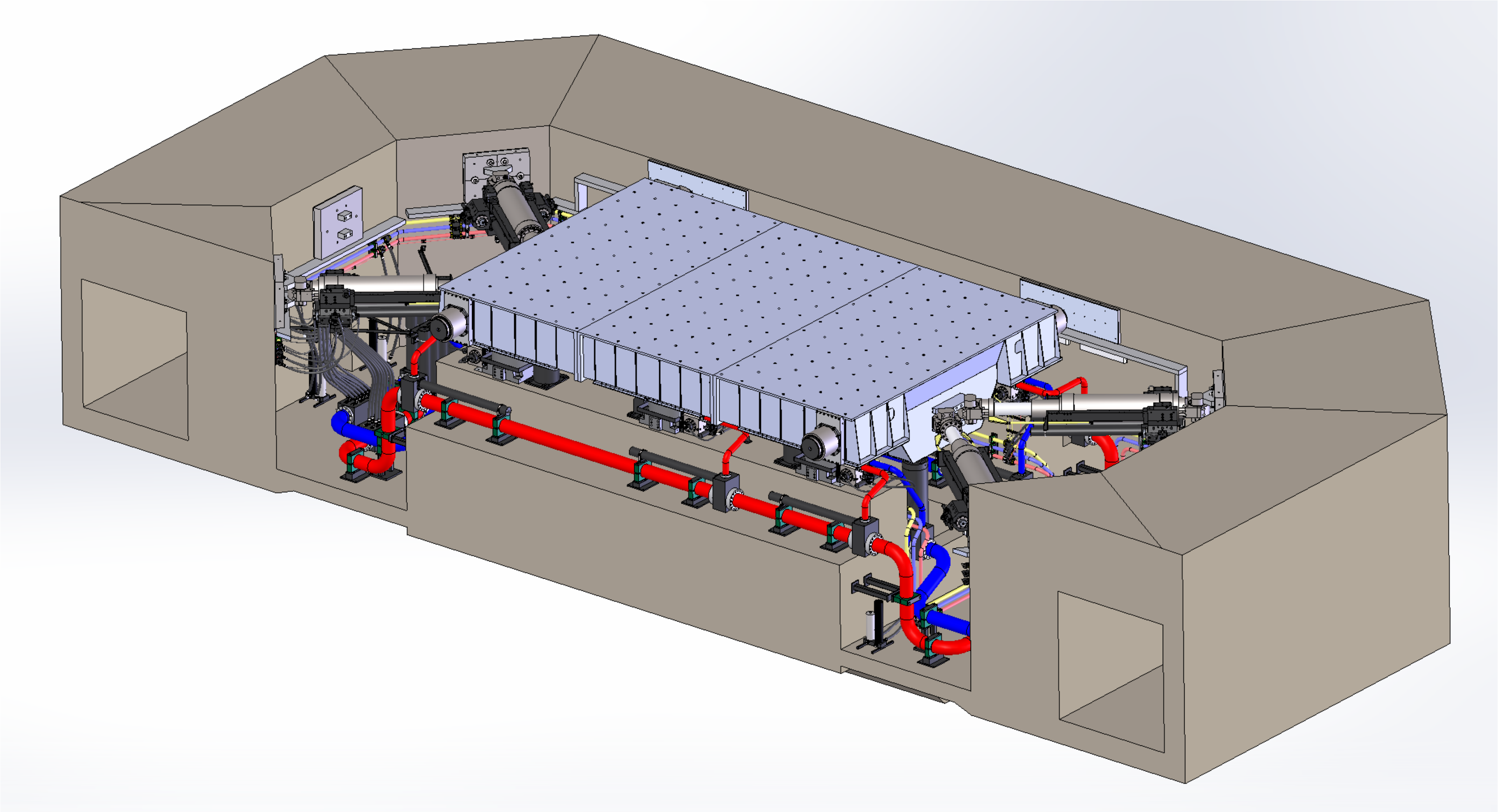




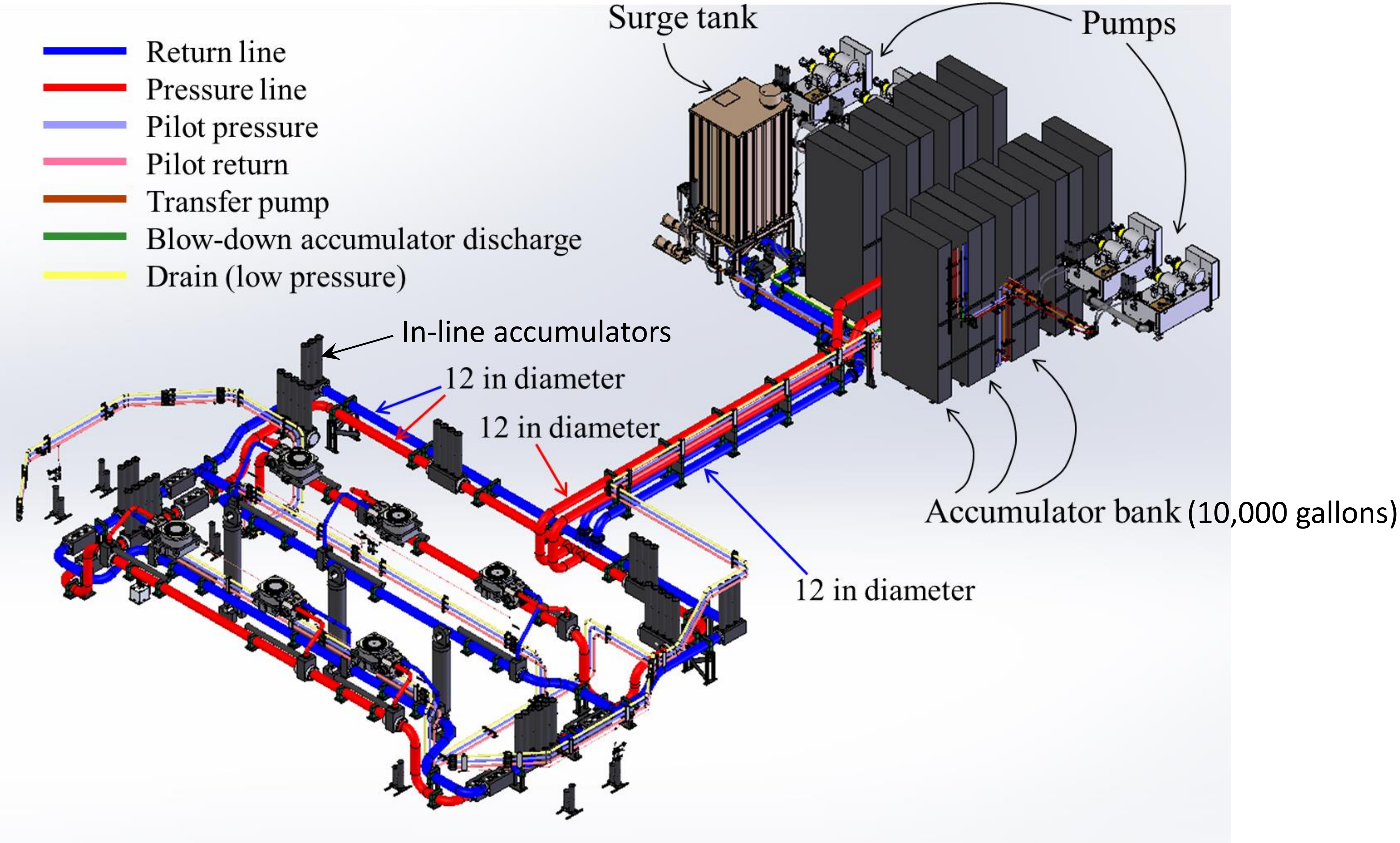




LHPOST6



Hydraulic Power System for LHPOST6



Accumulator Bank of LHPOST6

August 2020

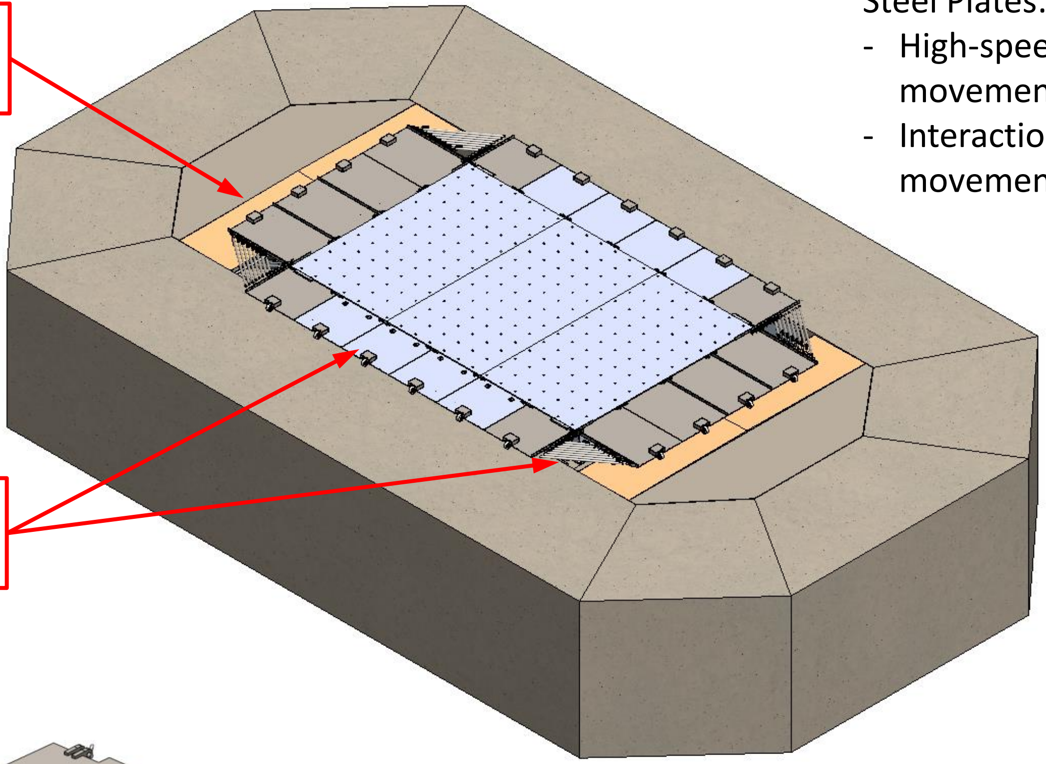
Prediction of Oil Column Frequencies and Modes of LHPOST6

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

- As for the 1-DOF LHPOST, the resonant peaks of the oil column modes will be damped out numerically by the shake table controller using the delta-pressure feedback gains and notch filters, if necessary.

Cover Plate System

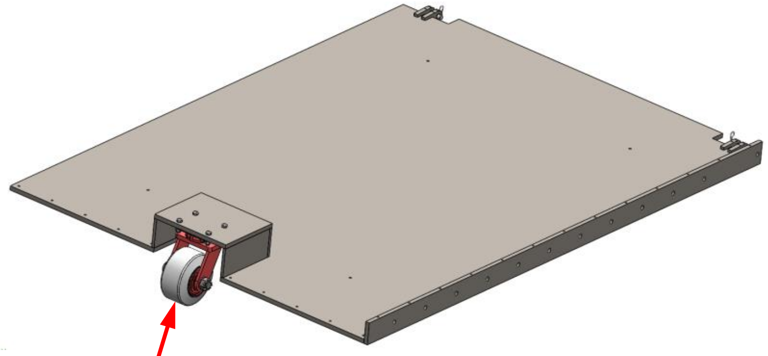
Re-design of concrete cover slab



Steel cover plates and corner tubes

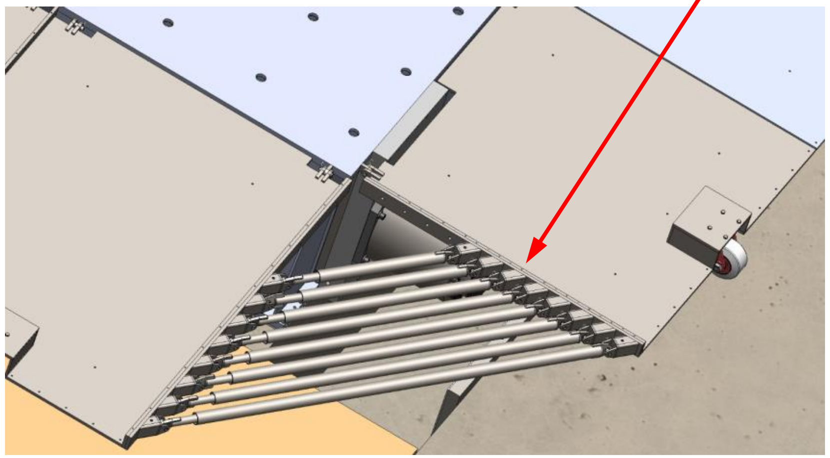
Steel Plates:

- High-speed castor wheels allows movement in any direction.
- Interaction with tubes allows free movement at the corner

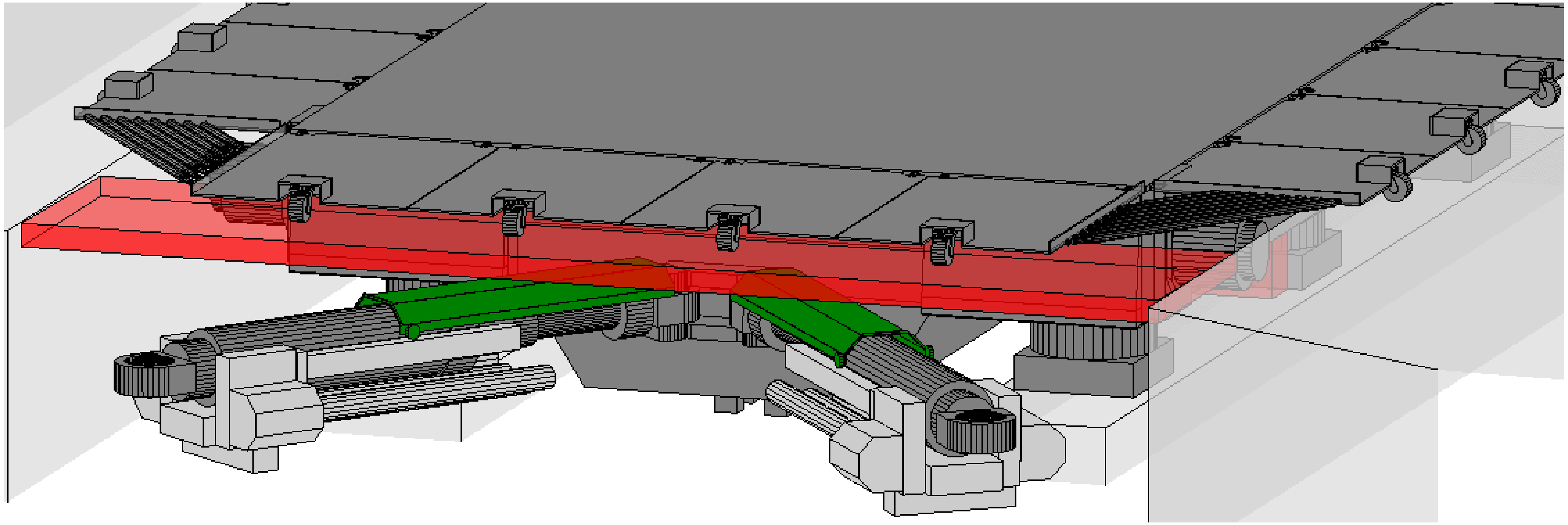


Castor wheel

Telescopic tubes elongate and pivot freely at ends to allow movement of the plates



Cover Plate System Kinematics



Performance Characteristics of LHPOST6

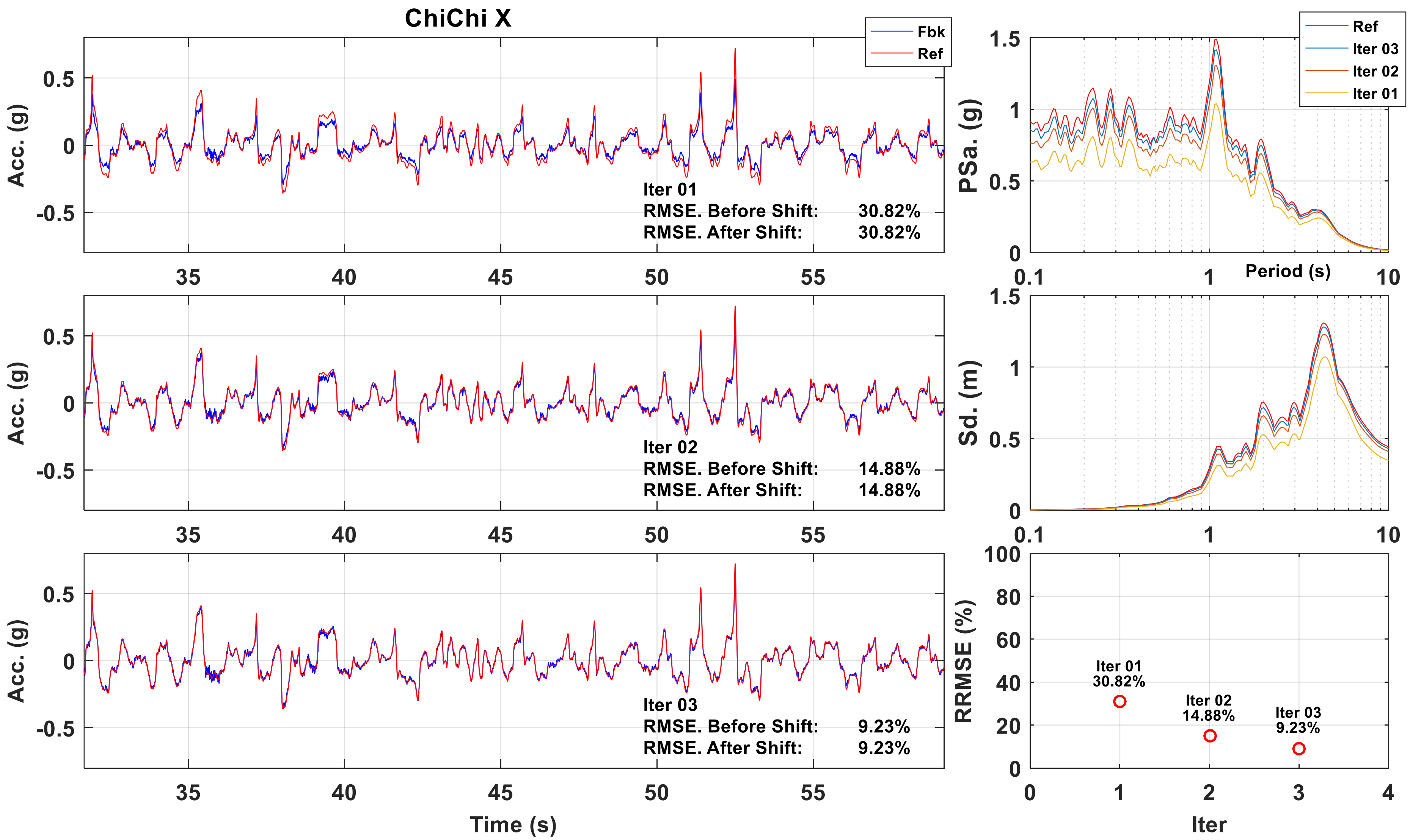
Platen size	12.2 m × 7.6 m (40 ft × 25 ft)		
Frequency Bandwidth	0 – 33 Hz		
Vertical Payload Capacity	20 MN (4,500 kip)		
	Horizontal X	Horizontal Y	Vertical Z
Peak Translational Displacement	±0.89 m (±35 in)	±0.38 m (±15 in)	±0.127 m (±5 in)
Peak Translational Velocity	2.5 m/sec (100 in/sec)	2.0 m/sec (80 in/sec)	0.6 m/sec (25 in/sec)
Peak Translational Force*	10.6 MN → 6.8MN (2,380 kip)	8.38 MN → 3.4MN (1,890 kip)	54.8 MN** (12,300 kip)
Peak Rotation*	2.2 deg	1.5 deg	4.0 deg → 3.8 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

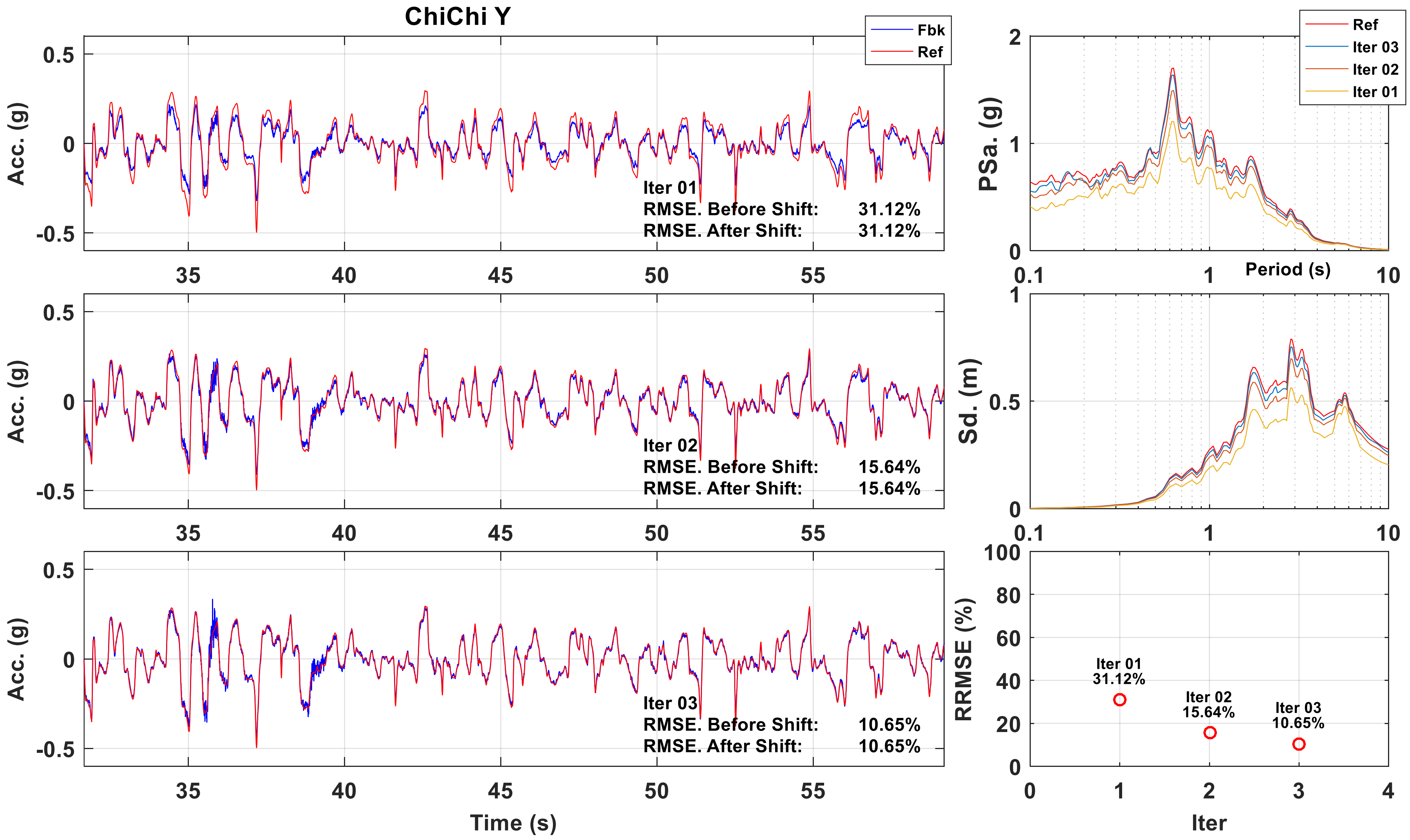
** peak compressive force in the compression-only vertical actuators

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

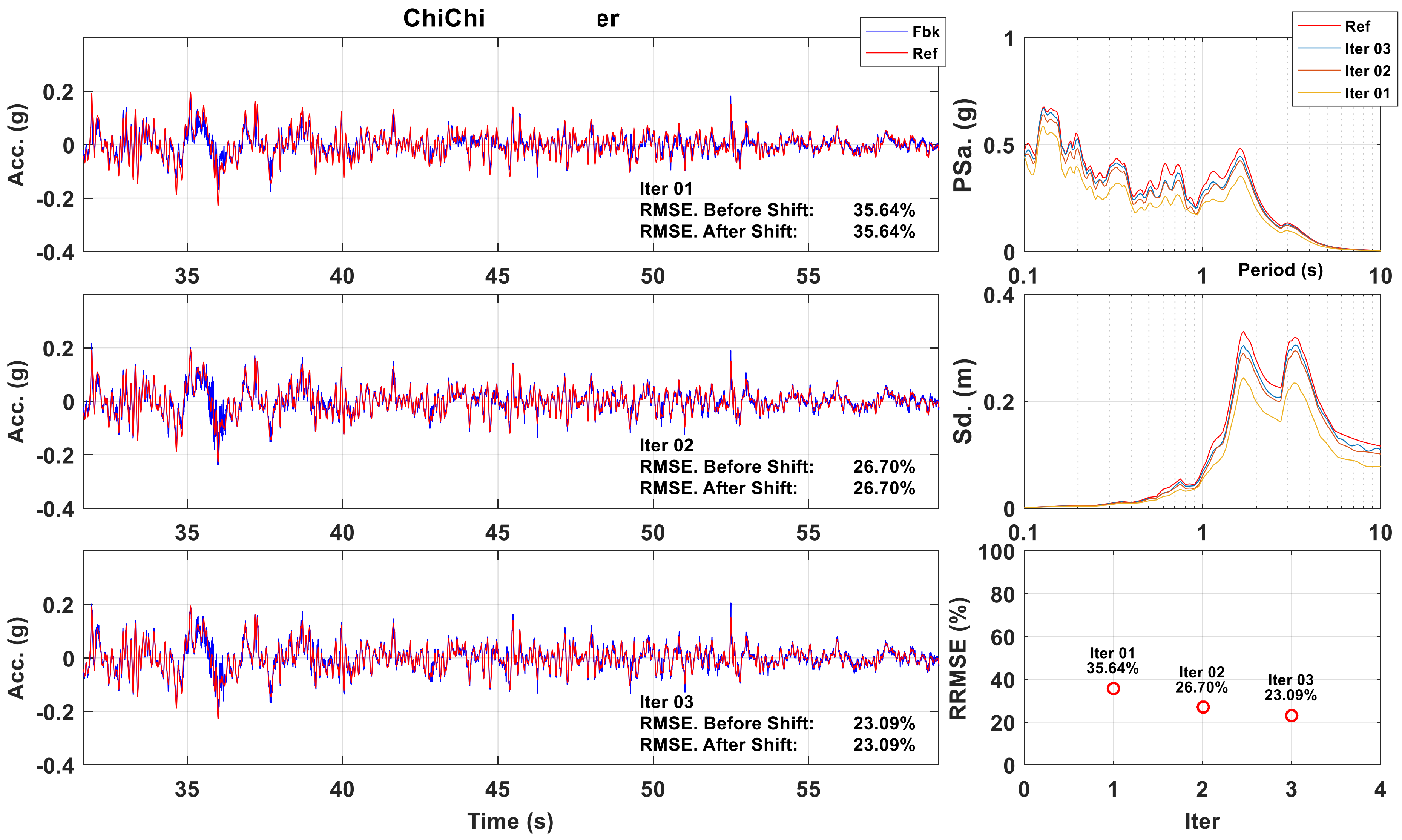
Target vs. Achieved Tri-Axial Ground Motion
1999 M7.6 Chi-Chi, Taiwan, TCU065 Station, X Component



Target vs. Achieved Tri-Axial Ground Motion
1999 M7.6 Chi-Chi, Taiwan, TCU065 Station, Y Component



Target vs. Achieved Tri-Axial Ground Motion
1999 M7.6 Chi-Chi, Taiwan, TCU065 Station, Z Component



LONGITUDINAL DOF

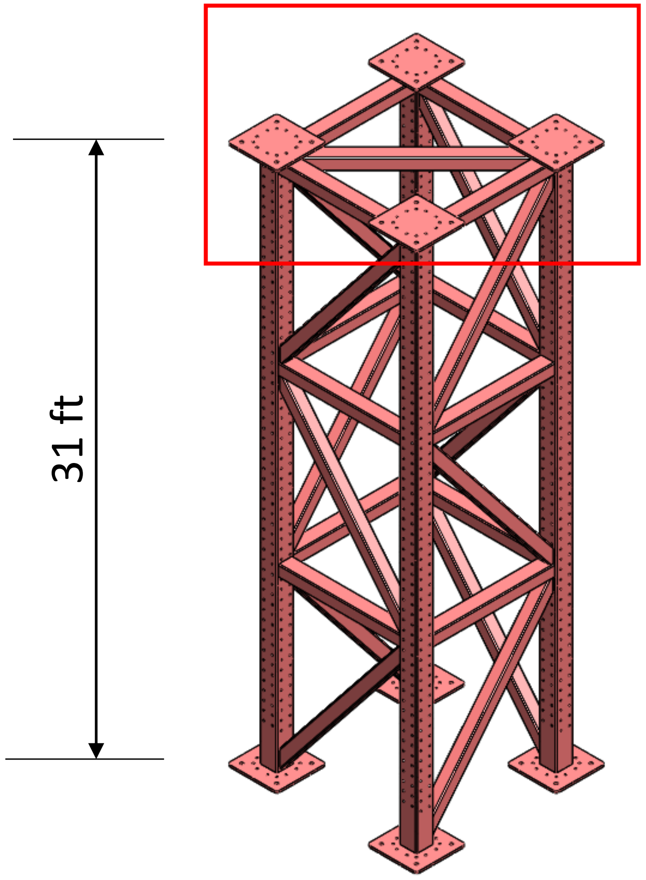
1978, M7.4 Tabas, Iran, Tri-Axial Ground Motion

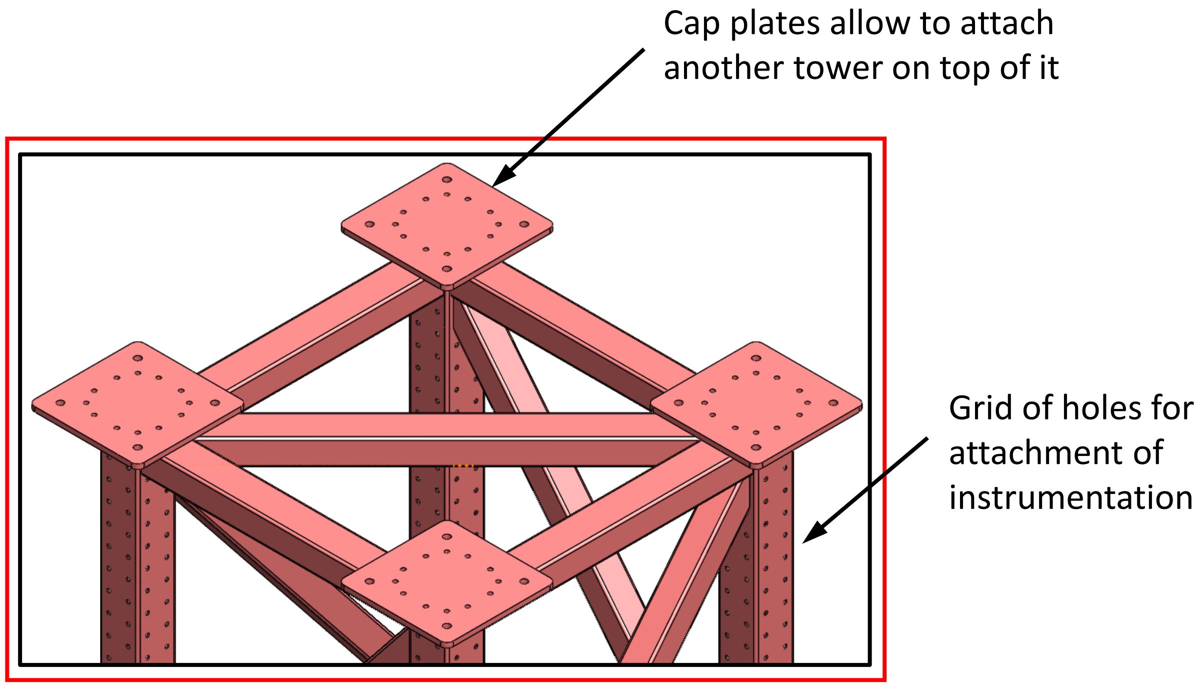
AC-156 Compatible Earthquake, Tri-Axial Ground Motion

Synthetic Six-Axial Ground Motion

Safety Towers

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



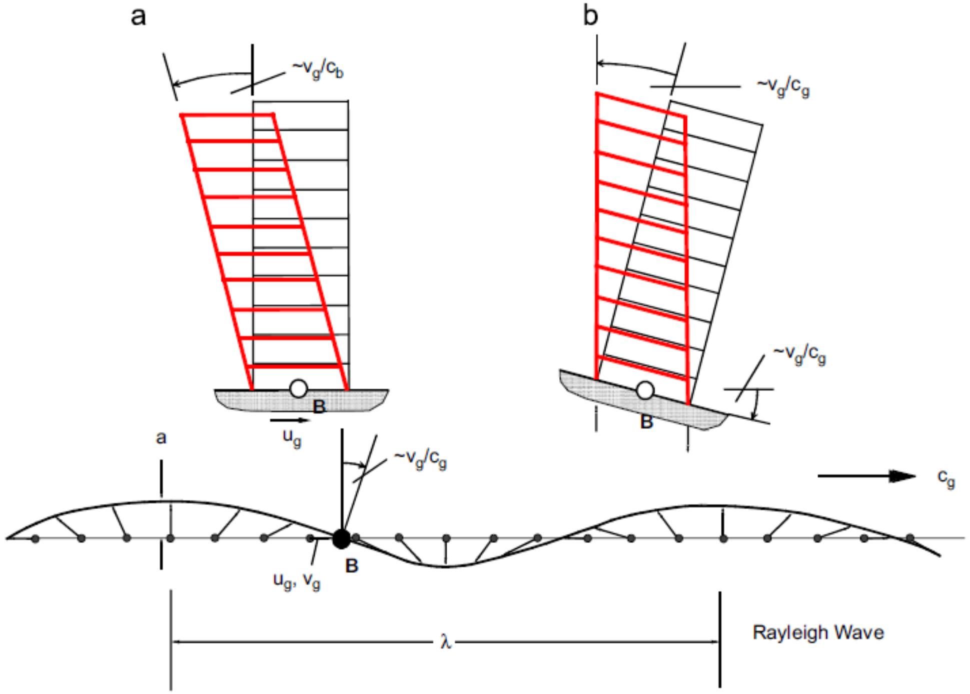


New Research Opportunities Made Possible by the LHPOST6

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 appropriate 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)

- **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.

- **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

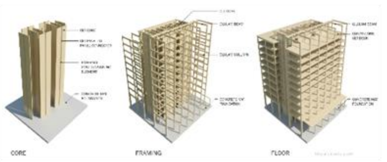
- **Non-structural components and systems (NSCs).**
  - Architectural, mechanical, electrical and plumbing, or building contents.
  - Improve our understanding of the seismic response of NCSs under multi-directional earthquake excitation.
  - Advance the development of a reliable, unified design methodology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

- **Low-damage, 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

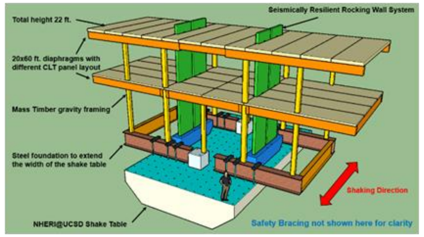
NHERI TallWood

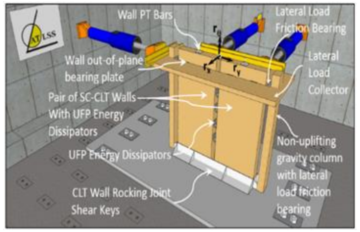
Nheritallwood.mines.edu spei@mines.edu



Define Tall Wood Archetypes

Investigative testing at system level



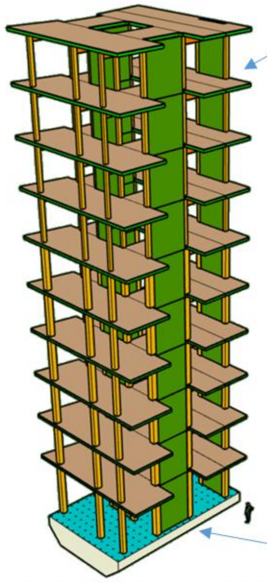


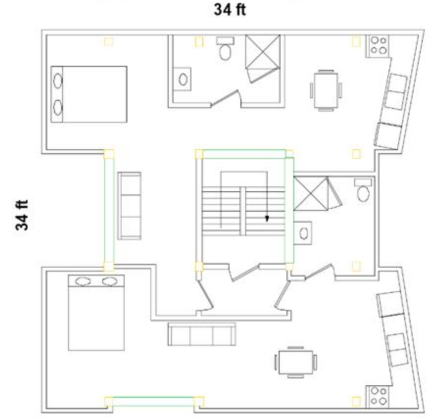
Two-story test at NHERI@UCSD 2017 Summer

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)

THANK YOU !

NHERI@
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.

Van Den Einde, L., Conte, J. P., Restrepo, J. I., Bustamante, R., Halvorson, M., Hutchinson, T. C., Lai, C.-T., Lotfizadeh, K., Luco, J. E., Morrison, M. L., Mosqueda, G., Nemeth, M., Ozcelik, O., Restrepo, S., Rodriguez, A., Shing, P. B., Thoen, B., and Tsampras, G., "NHERI@UC San Diego 6-DOF Large High-Performance Outdoor Shake Table Facility." *Frontiers in Built Environment* (2021): 181.

- https://ucsd.designsafe-ci.org
- Contact one of the NHERI@UC San Diego team member:
  - Joel Conte, jpconte@ucsd.edu
  - Tara Hutchinson, tara@ucsd.edu
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  - Jose Restrepo, jrestrepo@ucsd.edu
  - Koorosh Lotfizadeh, klotfiza@ucsd.edu

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NHERI

Natural Hazards Engineering Research Infrastructure