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NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE AT UC SAN DIEGO: LARGE HIGH PERFORMANCE OUTDOOR SHAKE TABLE FACILITY

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Abstract

The Natural Hazards Engineering Research Infrastructure (NHERI) Experimental Facility at the University of California, San Diego, a National Science Foundation (NSF) sponsored facility, provides a large, high performance, outdoor shake table (LHPOST) to support research in structural and geotechnical earthquake engineering. Earthquakes have had considerable destructive effects on society in terms of human casualties, property and infrastructure damage, and economic losses. Building a multi-hazard, disaster-resilient, and sustainable environment requires the understanding and ability to predict more reliably the system-level response of buildings, critical facilities, lifelines, and other civil infrastructure systems to these extreme events. Research experiments performed at this facility will: i) enable large-scale investigations of the performance of structural, geotechnical and soil-foundation-structural systems under earthquake hazards, ii) generate landmark experimental data essential to advancing predictive seismic performance tools at the system level, iii) educate undergraduate, graduate, and K-12 students, as well as the general public, about natural disasters and iii) contribute towards the national need to develop effective technologies and policies to prevent natural hazards from becoming societal disasters.

The LHPOST, with a steel platen that is 12.2 meters long by 7.6 meters wide, has performance characteristics that allow the accurate reproduction of near- and far-field earthquake ground motions. The facility will support seismic testing, under near real-world conditions, of large structural, nonstructural, geotechnical, and geostructural systems, as well as soil-foundation-structural systems, up to a weight of 20 MN. Two large soil boxes can be used in combination with the shake table to investigate the seismic behavior of soil-foundation-structural systems. Software and hardware are available to support hybrid shake table testing of structural and soil-foundation-structural systems. Systems tested at the facility can utilize extensive data acquisition and instrumentation capabilities, including a broad array of state-of-the-art and advanced analog sensors and high-definition video cameras, to support detailed monitoring, through hundreds of data channels, of the system response. The landmark system-level tests performed using this facility will provide fundamental knowledge and data to support the development, calibration, and validation of high-fidelity, physics-based computational models of structural, geotechnical, and 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. These simulation tools will directly benefit the full realization of performance-based design to evaluate and reduce the risks of the built environment to natural hazards. This shake table facility can provide the validation tests for retrofit methods, protective systems, and the use of new materials, components, systems, and construction methods for disaster-resilient and sustainable civil infrastructure.

This paper presents the technical and performance characteristics of the LHPOST. Some past landmark experiments performed at this facility will be presented as well as the impact of the research enabled through this facility on the next generation of seismic design codes and earthquake protective systems, and the earthquake engineering profession in general. The paper also discusses key research questions that can be addressed using the LHPOST and lead to potential breakthroughs in earthquake engineering.

Keywords: Large outdoor shake table, Large-scale shake table tests, Large soil boxes

1. Introduction

The NHERI Experimental Facility (EF) at the University of California at San Diego (NHERI@UCSD) provides large-scale, high-performance, experimental research infrastructure to enable research that advances the science and practice of earthquake engineering. Research conducted at NHERI@UCSD leads to improved design codes and construction standards, validated high-fidelity computational simulation models, and accurate decision-making tools necessary to build and maintain sustainable and earthquake-resilient communities. Moreover, it supports the advancement of new and innovative materials, structural detailing, and construction methods. Although the U.S. possesses a very sophisticated societal infrastructure, it remains notably vulnerable to geophysical natural hazards such as earthquakes. A 2000 HAZUS study estimates a $4.4 billion annualized earthquake loss associated with buildings in the U.S. [1], which is likely to be higher with today's building inventory [2]. Scenario studies of large earthquakes in the U.S. suggest losses on par or higher than those caused by Hurricane Katrina in 2005, with $100 to $200 billion in economic losses and damaged buildings displacing hundreds of thousands of residents and thousands of businesses ([3] and [4]). Recent estimates by USGS for a rarer, though not improbable, magnitude 7.8 earthquake in Los Angeles indicate 1800 casualties, 50,000 injuries, and $200 billion in damage [4], which is five times greater than for the Northridge event in 1994 [5]. Indirect losses associated with business interruption would more than double this amount. According to this scenario, more than 600,000 structures would be damaged. Experiments conducted at the NHERI@UCSD experimental facility will help accelerate the earthquake engineering research devoted to ameliorate these losses and mitigate societal disasters caused by earthquakes.

Experimental programs utilizing the Large High Performance Outdoor Shake Table (LHPOST) at NHERI@UCSD provide experimental data that is essential to understanding the system-level performance of buildings, critical facilities, and bridges, including soil-foundation-structure (SFS) systems and non-structural systems during earthquakes. Such system-level data is scarce but crucial for the development, calibration, and validation of design provisions, damage-mitigation and life-protection strategies, and high-fidelity computational simulation models needed for design, performance assessment, and rational decision-making. High-fidelity computational predictive models and reliable, experimentally validated, fragility functions are essential for the full realization of performance-based design.

Research activities using the NHERI@UCSD experimental facility train next-generation researchers, educators, and practitioners to attain a fundamental and holistic understanding of the system-level behavior of structures in order to address real world problems and advance the science and technology in natural disaster mitigation and prevention, to prevent natural hazard events from becoming societal disasters, and to be contributors and future leaders in world-wide natural disaster prevention efforts. Collaborating with other NHERI efforts, including other experimental facilities, the Cyberinfrastructure (CI), the Computational Modeling and Simulation Center (SimCenter) and the Network Coordination Office (NCO), NHERI@UCSD will actively engage in education and community outreach efforts to inspire the interest of K-12, undergraduate, and graduate students, including those from under-represented and under-privileged groups, in science and engineering, as well as other disciplines that will contribute to the realization of sustainable and natural disaster-resilient communities. Large-scale experiments conducted at NHERI@UCSD are persuasive life-size demonstrations that raise natural disaster awareness and educate the general public on the urgency of the nation's and world's efforts to develop effective technologies and adequate policies to prevent societal disasters that could be caused by natural hazards. Through the NHERI CI, the unique data sets generated from past and future NSF funded experiments are made available to the hazard engineering community through the DataDepot (https://www.designsafe-ci.org/) to be used for further research advancements.

This paper presents the technical and performance characteristics of the LHPOST. It will discuss some past landmark experiments conducted at this facility as well as the impact of the research enabled through this facility on the next generation of seismic design codes and earthquake protective systems, and the natural hazards engineering profession in general.

2. NHERI@UCSD Outdoor Shake Table Experimental Facility

2.1 Englekirk Structural Engineering Center (ESEC)

The LHPOST was built under the *George* E. *Brown*, Jr. *Network for Earthquake Engineering Simulation* (NEES) NSF program in response to the urgent need in the U.S. for a large shake-table facility ([6] - [10]). It is the largest outdoor shake table in the world and the second largest overall with the largest being the E-Defense table in Japan [11]. The LHPOST is part of the Englekirk Structural Engineering Center (ESEC) of UC San Diego, located at approximately 16 km east of the UC San Diego main campus at the Camp Elliott Field Station (Figs. 1 and 2). The site was dedicated in 2002 and has been fully and continuously operational since 2004. The ESEC is an outdoor large-scale structural laboratory complex that comprises (i) the LHPOST, (ii) the blast simulator (BS), built through the Technical Support Working Group of the U.S. Federal Government and used to replicate the effects of blasts on structural components, (iii) two soil pits separated by a strong reaction wall with one built through funding from the California Department of Transportation and the second by the Port of Los Angeles Authority, and (iv) a full-scale rail test bed built through funding from the Federal Railroad Administration. The NHERI@UCSD experimental facility consists of the LHPOST shown in Figs. 1 and 2. The LHPOST and BS share a common hydraulic power supply unit located in the Hydraulic Power System Building to the south of the LHPOST. The soil pits are Caltrans supported facilities and are available to NHERI researchers when not used by Caltrans projects. One soil pit is 21.4 m square by 7.1 m deep (north) and the other is 13.4 m square by 7 m deep (south), separated by a 6 m high reaction wall with a horizontal force capacity of 235 tons when applied at a height of 5 m. In 2009, the ESEC met the requirements of the International Accreditation Service accreditation criteria for Testing Laboratories, becoming the first large-scale structural testing laboratory in the U.S. to demonstrate compliance with International Standards Organization Standard ISO/IEC 17025 [12].

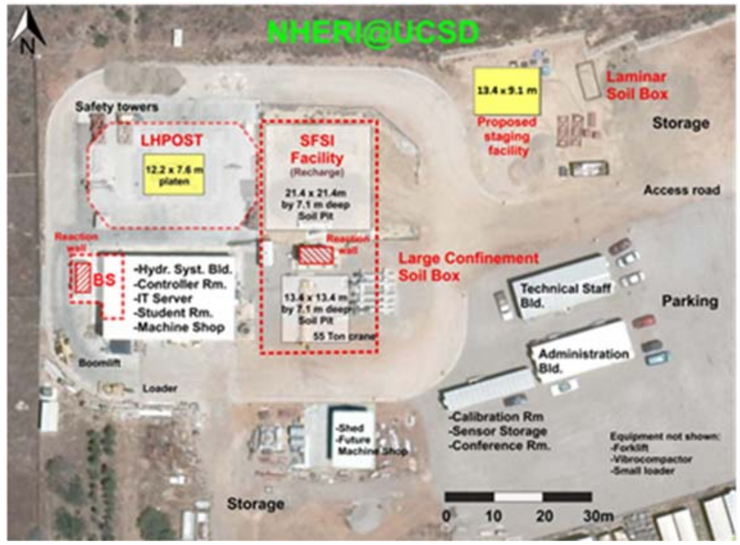
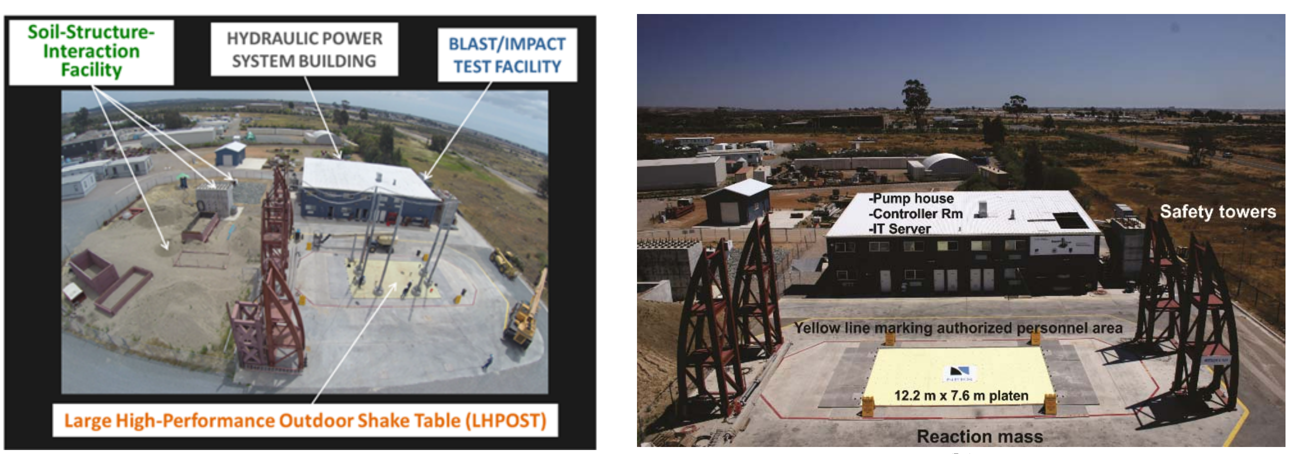


Fig. 1 – Plan view of the Englekirk Structural Engineering Center (ESEC).

At the ESEC, there are three fully equipped trailers with offices for faculty, students and visiting researchers, including a conference room with complete AV capabilities and a 40 person seating capacity. The ESEC has a 10 Gbps Internet2 connection (via fiber connection to the San Diego Supercomputer Center – SDSC) to the outside world. Moreover, the offices at ESEC have internet access rates of 1 Gbps. Both connections are full duplex, which means 10 Gbps and 1 Gbps, respectively, send and receive simultaneously. The ESEC network resides behind a firewall and is password protected. A wireless network, available to visiting users is also firewall and password protected. Access to the 10 Gbps network is by permission only. For specimen construction, researchers can make use of a 50 ton crane, a bobcat with a 1.3 m bucket, a Caterpillar F-103 forklift with 44 kN lifting capacity, a backhoe model 460 4x4, a Genie S-80 man-lift with a maximum height reach of 24.4 m, and a welding MIG, a



(a) (b)

Fig. 2 – (a) Overall view of the Englekirk Structural Engineering Center, (b) overall view of the NHERI@UCSD Large High-Performance Outdoor Shake Table (LHPOST).

portable welding machine MIG and Stick, to be used on a recharge basis together with a certified staff. The site has a small workshop where various small jobs can be accomplished. For larger jobs, UC San Diego has a complete machine shop that can be used on a recharge basis. All utilities at the site have been designed for future upgrades. Electrical power service at the main transformer is rated 480V 100KVA.

2.2 Large High Performance Outdoor Shake Table (LHPOST)

The LHPOST is a unique outdoor shake table facility that in the past decade, with funding from the NSF NEES program (2004-2014), enabled a series of landmark experiments on large- or full-scale systems. The LHPOST was designed in 2001-2002, built in 2002-2004, and commissioned on October 1, 2004, in a joint effort between UC San Diego and MTS Systems Corporation to exhibit performance characteristics that allow the accurate reproduction of far- and near-field ground motions for the seismic testing of large structural, geotechnical or geostructural systems, or soil-foundation-structural (SFS) systems, up to a weight of 20 MN. The main research objectives of these one-of-a-kind large-scale, system level experiments have been: (i) validation and calibration of analytical simulation tools to predict the seismic response of these systems, and (ii) validation of the seismic performance of systems and components (including non-structural components). The LHPOST was designed as a six-DOF table, but built with a single-degree-of-freedom (SDOF) capability due to budget constraint. Upgrade to four or six degrees of freedom (DOFs) will not require any major modification to the infrastructure, but will require the acquisition and installation of additional hydraulic power supply, servo-hydraulic (i.e., servovalves and actuators) and piping systems as well as the modification of the existing hydraulic piping system. A partial upgrade has already been implemented by replacing the six initial pressure-balanced vertical sliding bearings by six vertical actuators with a stroke of ±0.125 m, which in the current state act as active sliding bearings. Plans are underway to raise funds to acquire servo-valves and actuators and upgrade the hydraulic power system to complete the upgrade of the LHPOST shake table to six degrees of freedom. The design basis and resulting specifications of the structural, mechanical, hydraulic, servo-hydraulic, and control components of the LHPOST are presented in [6].

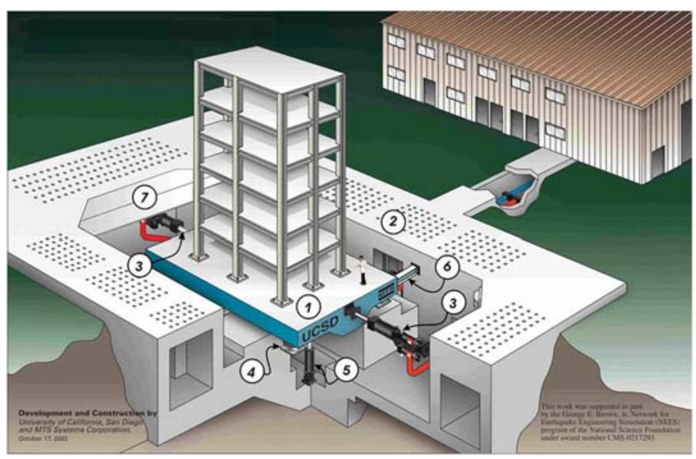


Fig. 3 – Schematic representation of the NHERI@UCSD Shake Table.

Fig. 3 shows a schematic view of the LHPOST mechanical and servo-hydraulic components in its current state. Component 1 is the 12.2 m long by 7.6 m wide by 2.2 m deep honeycomb steel platen with a grid of multi-purpose, high-capacity, tie-down points spaced at 610 mm o.c. The platen has an effective weight of 1.45 MN. Component 2 is the reinforced concrete reaction mass and the service tunnel that connects to the Hydraulic Power System Building. The reaction mass is 33.12 m long, 19.61 m wide, and extends to a depth of 5.79 m. A smaller central area of the foundation housing the hold-down struts extends to a depth of 7.92 m. The reaction mass has a weight of 43.8 MN. The unconventional (low-weight) design of the NHERI@UCSD reaction mass took advantage of the natural conditions at the site in terms of high soil stiffness to build a lighter and considerably less costly foundation, which resulted in a high characteristic frequency (between 11.2 and 12.5 Hz) and a large effective (radiation) damping ratio (between 32% and 42%) [10] as opposed to the conventional design that relies on the use of massive foundations to achieve a low characteristic frequency (e.g. [11]). The reaction mass also has a grid of multi-purpose, high-capacity vertical tie-downs for the deployment of safety towers or measurement frames or for the deployment of reaction frames as needed for hybrid testing. Component 3 consists of the set of two ±750 mm stroke servo-controlled dynamic horizontal (longitudinal) single-ended actuators with a combined maximum force of 6.80 MN. Each actuator is equipped with two four-stage servo-valves (each rated for a flow of 10,000 liter/min @ 7 MPa pressure drop). Component 4 comprises the six vertical actuators, currently acting as active hydrostatic bearings, which support the shake table platen. Component 5 is a set of two nitrogen-filled hold-down struts that passively pre-compress the platen against the sliding bearings and, consequently, provide overturning moment resistance. Component 6 is a yaw restraint system (consisting of two pairs of transversal actuators, one at each end of the platen, with each pair consisting of two coupled actuators, one at each side of the platen) to prevent the platen from undesirable yaw in the current single axis configuration. Finally, Component 7 is a weatherproofing system consisting of removable concrete planks. The performance characteristics of the LHPOST in its current single axis configuration are shown in Table 1. The overturning moment capacity of 50 MN-m can resist an effective specimen mass of 200 tons with an acceleration of 2.5 g at an effective height of 10 m. Fig. 4 depicts the performance specifications of the LHPOST, for harmonic motion reproduction, in a classical tri-partite plot. The fundamental parameters of a simple mathematical model representing the mechanical sub-system of the LHPOST were identified [8]. These parameters include the effective horizontal mass, the effective horizontal stiffness, and the coefficient of the classical Coulomb friction and viscous damping elements representing the various dissipative forces in the system.

Table 1 – Specifications of LHPOST.

Platen size	7.6 m × 12.2 m
Maximum displacement	± 0.750 m
Peak velocity	1.8 m/s
Maximum acceleration (bare / 4 MN rigid payload)	4.7 g / 1.2 g
Horizontal force capacity	6.8 MN
Maximum gravity payload	20 MN
Overturning moment capacity	50 MN-m
Frequency bandwidth	0-33 Hz

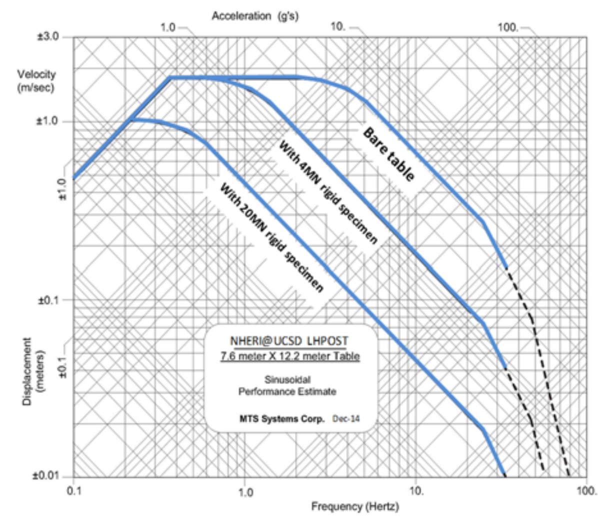


Fig. 4 – LHPOST performance specifications

2.2.1 Hydraulic Power System and Controller

The hydraulic power system consists of two MTS hydraulic power units or pumps (each with a flow capacity of 720 liter/min at 21 MPa, and 430 liter/min at 35 MPa), an accumulator bank (of volume 9.5 m^3 and maximum pressure of 35 MPa), a blow-down system (with peak flow capacity of 38 m^3/min), a 20 m^3 capacity surge tank, a cooling tower and a 1.23 MW electrical power substation. During a shake table test, the hydraulic power is supplied to the actuators by the accumulator bank (charged up at 35 MPa prior to the test) through a blow-down valve (Fig. 5), which converts the high-pressure oil from the accumulators (35 MPa) to a constant system pressure of 21 MPa for controlling the actuators. Two standard MTS Hydraulic Power Units (with a combined electric power of 250 KW) are provided to pump oil into the accumulator bank. Return flow is directed to an auxiliary reservoir or surge tank (Fig. 6).

The LHPOST is controlled via the MTS digital Three Variable Controller (TVC) referred to as Model 469DU located on the first floor of the Hydraulic Power System building. The Operator Control Room resides on the second floor of the same building and houses a PC workstation directly connected to the 469D that functions as

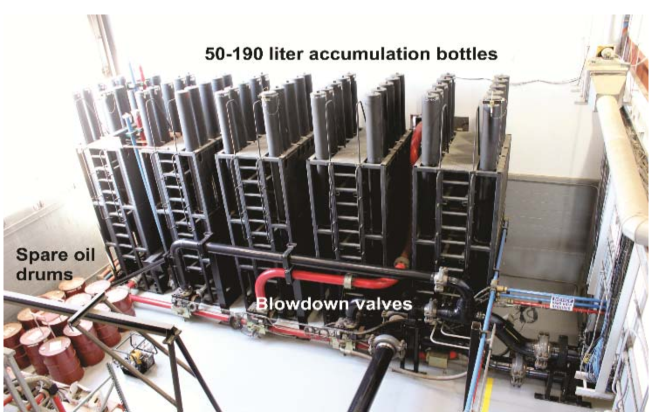


Fig. 5 – View of accumulator bank and blowdown valve

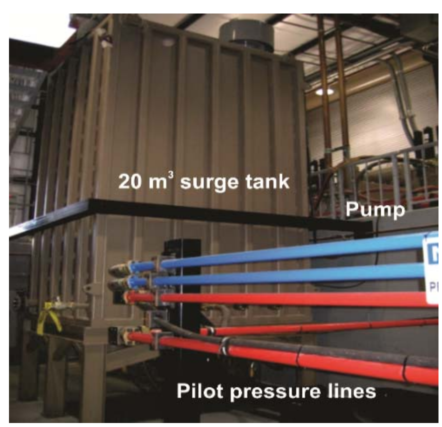


Fig. 6 – Oil surge tank and pilot pressure lines

the main user interface for operations and control of the LHPOST. A second workstation serves as the Data Acquisition Central Communication Computer to interface with the National Instruments DAQ nodes. The 469DU shake table controller is a linear state variable controller. It has additional special features to compensate for linear and nonlinear system distortions for both harmonic and broadband command signals (e.g., amplitude/phase control, adaptive harmonic cancellation, adaptive inverse control, on-line iteration, and notch filters). The three state variables controlled by the TVC are displacement, velocity, and acceleration. The controller can be set to run under displacement, velocity or acceleration control mode. Depending on the control mode, only one state variable becomes the primary control variable with the others serving only as compensation (feed-forward and/or feedback) signals to improve damping and stability of the system. A conceptual representation of the controller is given in Fig. 7 [7]. The tracking (signal reproduction) capability of the LHPOST was investigated and quantitative relations between different measures of the signal reproduction error and the amplitude of the reference excitation used to tune the shake table controller were obtained [9].

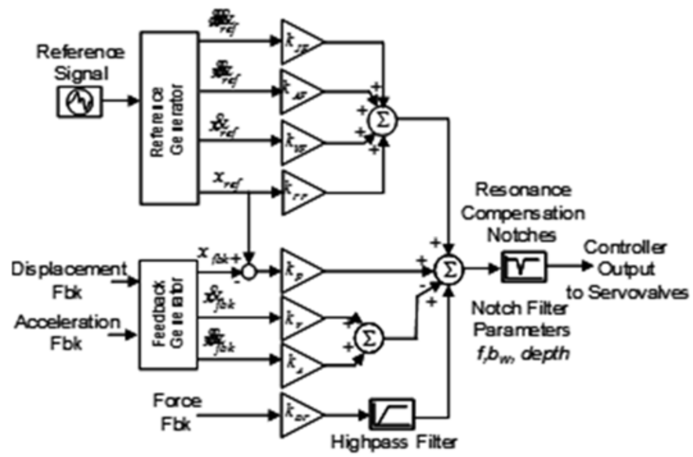


Fig. 7 – Conceptual representation of MTS TVC controller.

2.2.2 Sensors and Data Acquisition System

LHPOST Data Acquisition (DAQ) and Instrumentation available to users consists of 12 64-channel DAQ National Instruments Chassis Model NI-PXI-1052 nodes, of which 9 nodes are available to the users. One node is dedicated for in-house sensor calibration and the other 2 nodes are used to log in-line sensors attached to the hydraulic power supply system and to the reaction mass. Each node has (i) a PC Controller to run the DAQ software and to store data, (ii) an A/D Card (Model NI-PXI-6251), (iii) 8 signal conditioner cards (Model NI-SCXI-152) with 8 channels, with 100 programmable gain settings, and (iv) 8 connection boards (Model NI-SCXI-1314) with 8 channels that provide different connection configuration depending of the type of sensor connected to the channel. The data-acquisition software was written in-house using LabVIEW and, per ISO 17025, the software is locked and changes and updates are tracked and logged. The current instrumentation inventory for the LHPOST consists of: (i) one hundred thirty MEMS Measurement Specialties Model 4001A accelerometers (±10 g, 96 dB, DC-200 Hz), (ii) one hundred twenty five Penny & Giles LVDTs with strokes ranging from 50 mm to 350 mm, (iii) one hundred fifty three Celesco string potentiometer displacement transducers with strokes ranging from 50 mm to 1500 mm, (iv) four Enerpac 2 MN load flat jacks, (v) twenty-two PELCO HD video cameras (NTSC Color, 30 Hz) and fifteen GoPro HD video cameras (1080P, 30 Hz), and (vii) one GPS system with RTD_NET software by Geodetics and a network of three NAVCOM ANT-2004T antennae (two mobile and one reference) which provides dynamic displacement monitoring in three coordinates. A dedicated standalone computer allows continuous monitoring via three NAVCOM NCT2030M receivers operating at 50 Hz. The site is in the process of acquiring soil pressure sensors. NHERI@UCSD, being part of ESEC, is an ISO/IEC 17025 accredited laboratory. Hence, all calibrations performed on servo-hydraulic equipment, equipment control sensors, data acquisition and instrumentation are NIST traceable [13].

2.2.3 Large Soil Boxes

The LHPOST can be used in combination with either a 3 m wide by 6.7 m long by 4.7 m high large laminar soil box (Fig. 8), funded by Caltrans, or a 4.6 m or 5.8 m wide by 10 m long by 7.6 m high large soil confinement box (Fig. 9), funded by NSF [14]. Both soil boxes are modular and can be configured to a given height. The soil confinement box can be configured in two different widths. These large soil boxes enable large-scale seismic experiments on geotechnical and SFS systems.

Fig. 8 – Large laminar soil box installed atop of the shake table platen

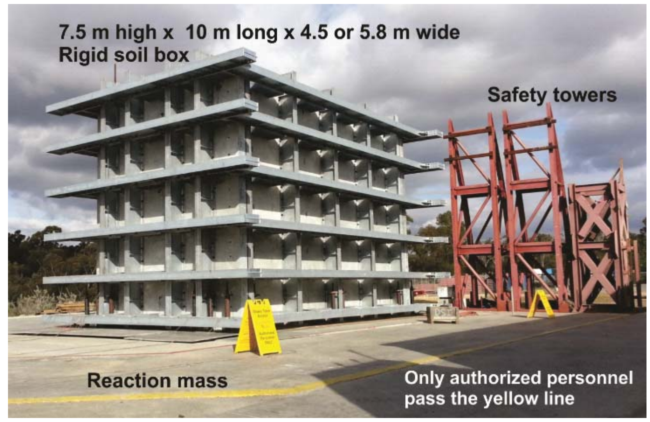


Fig. 9 – Large soil confinement box installed atop of the shake table platen, safety towers and safe area.

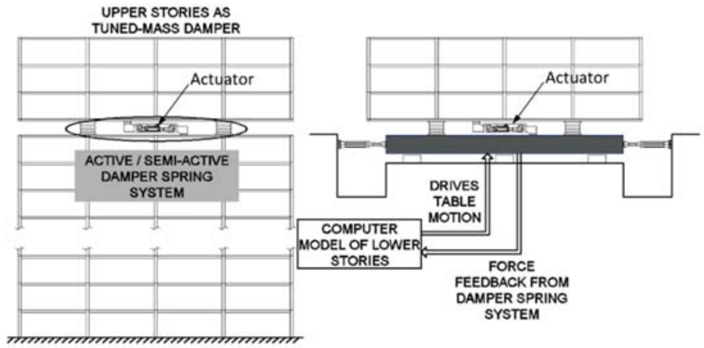
2.2.4. Basic Infrastructure for Hybrid Shake Table Testing

The real-time hybrid simulation capability using the LHPOST is user ready in that a basic hardware and software platform is in place to perform real-time computation and real-time closed-loop control of the shake table and a 500-kN dynamic actuator (MTS model 244.41S), which has a stroke of ±200 mm and three-stage servo-valve rated at 950 liter/min. The actuator can be powered through a portable hydraulic power system consisting of a 35 MPa accumulator bank (475 liter capacity) chargeable by a small diesel engine driven pump. The shake table and the actuator can be configured and controlled to exert different combinations of force/displacement/acceleration boundary conditions on experimental substructures. With this platform, computational models can be programmed in the Simulink environment and then compiled to run on the Mathworks xPC real-time Operation System (OS). The MTS 469DU shake-table controller, the MTS FlexTest that controls the dynamic actuator(s), and the computer running xPC are networked via a SCRAMNet ring that allows for real-time digital communication and synchronization of data flow between all three computers with update rates on the order of a microsecond. The FlexTest controller can control up to 4 dynamic actuators if additional actuators become available in the future or are borrowed through recharge from the UC San Diego Powell structural labs or other labs.

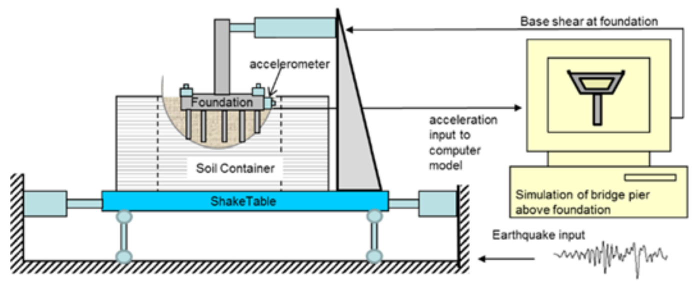
However, it should be noted that hybrid simulation may require customized software to support each unique research application. Users need to provide the custom software and computational model that can be run in real time. The simplest way to do this is for users to program their models in Simulink, and compile them to run on the xPC in real-time. Users may also be required to include compensation algorithms to minimize actuator response delay in a test. A base Simulink model that provides connectivity to the input and output channels of the MTS 469D and FlexTest controllers is available for users interested in hybrid simulation. Alternatively, computational software for structural analysis, such as OpenSees/OpenFresco [15], can be run in a real-time OS in another PC, and integrated with the xPC via Ethernet or an additional SCRAMNet card.

Two potential applications of hybrid simulations using the shake table and the 500-kN actuator are illustrated in the Fig. 10. In the first example of a multi-story building, the effectiveness of using the upper stories as a passive, active, or semi-active mass damper is examined. To study active or semi-active mass dampers, the motion of the upper stories with respect to the lower stories is driven by the 500-kN dynamic actuator. Different control algorithms can be developed and implemented to control the actuator. The lower stories are numerically modeled while the remaining upper stories including the dynamic actuator are physically tested on the shake table. The shake table excites the physical substructure using the input acceleration obtained from the response at the top level of the numerical substructure. The numerical substructure takes the measured story shear at the base of the physical substructure (essentially the actuator force) as the feedback force.

A second potential application examines the simulation of a bridge pier including soil-structure interaction effects. In this case, the physical model consists of the foundation slab supported on piles embedded in soil within the laminar soil box installed on top of the shake table. The computer model is a bridge pier and the tributary mass of the bridge deck. The ground motion is applied as input to the shake table to excite the soil. The forces transferred by the bridge pier to the foundation are applied via the external actuator. Assuming the numerical model is a SDOF system, the single actuator at the height of the effective mass can apply the correct shear force and moment to the foundation. The input to the computer model consists of the acceleration of the foundation including the soil-structure interaction effect with potential rocking of the foundation slab. One advantage of this approach is that the mass of the bridge deck does not need to be physically included in the test setup, allowing for larger-scale tests to be conducted.



(a) Multistory building with active or semi-active mass dampers



(b) Bridge pier including soil-structure-interaction effects

Fig. 10 – Hybrid simulation examples

3. Past Achievements and Impact of Research

Since its commissioning on October 1, 2004, 26 landmark structural, nonstructural and soil-foundation-structural system tests were performed successfully at the LHPOST. The large- or full-scale specimens tested include reinforced concrete buildings, a bridge pier, a bridge abutment, a precast concrete building (parking) structure, unreinforced and reinforced masonry building structures, metal building structures, a wind turbine, earth retaining walls, columns supported on rocking shallow foundations, woodframe buildings, 500kV bus support structure (electrical poles and transmission lines), a cut-and-cover shallow tunnel, a spillway embedded in soil, and helical pile foundations ([16]-[25]). Some of these specimens are depicted in Fig. 11. Three of the tests performed on the LHPOST (7-story building, wind turbine, and BNCS) could not have been carried out at the E-Defense shake table facility because the height of the test specimens exceeded the 22 m height limit of their laboratory.

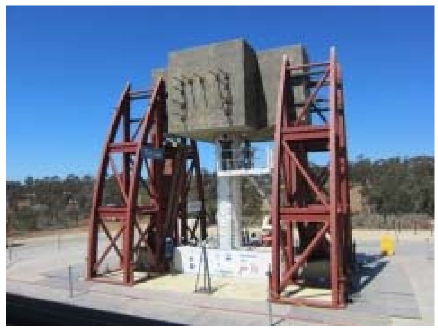
Results from the 7-story (Fig. 11a), Precast concrete (Fig. 11b) and BNCS (Fig. 11g) buildings have supported the development of prescriptive requirements for the design of building diaphragms in ASCE 7-16 loadings standard, which will be published late in 2016. Results from the tests on the precast concrete building (Fig. 11b) resulted in: the development and validation of nonlinear finite element modeling and analysis techniques, extrapolation of the models developed for the analysis of testbed structures, distillation of the results, and importantly the development of a comprehensive design framework and prescriptive code requirements [26]. The success of this project relied heavily on the valuable industry oversight in the planning, execution, and technology transfer stages of the project. In this project, a three-story diaphragm sensitive structure was built at half scale and tested on the LHPOST. The slender diaphragm design required a width of the building that was over twice the width of the LHPOST platen, which required a special mechanism to be engineered for this landmark test. In another NEES project led by Prof. J. Van de Lindt [27], shake table tests were conducted on a full-scale 4-story woodframe soft-story building with various retrofits and without retrofit (Fig. 11i), which eventually collapsed when tested without retrofit. This project demonstrated the performance of retrofits following recommendations in FEMA P-807. References [16]-[25] provide a selected set of research publications resulting from the landmark tests performed at the LHPOST. The research performed at the LHPOST has impacted future design codes in the following areas, among others: (i) design of floor diaphragms for all building types, especially for precast concrete structures, (ii) improvement of design methods for masonry structures (e.g., specification of attachment of masonry veneer to woodframe structures, evaluation via displacement-based design methods), (iii) assessment of RC frames with masonry infills, (iv) repair/retrofit techniques of masonry structures using engineered cementitious composite materials, (v) attachment of facades to building structural frames, and (vi) detailing considerations in the construction methods for elevators. Also, low-damage systems such as base isolation and rocking walls have been validated at the LHPOST as perhaps the best way to provide seismic resiliency, namely through avoiding damage.

(a) 7-story RC building (2006)
(scale: 1:1)

(b) Precast concrete building (2008)
(scale: 1:2.5)

(c) Wind turbine (2010)
(scale: 1:1)

(d) Metal building (2010)
(scale: 1:1)



(e) Bridge pier (2010)
(scale: 1:1)

(f) Reinforced masonry structure (2011)
(scale: 1:1)

(g) Base-isolated and fixed-base BNCS building (2012) (scale: 1:1)

(h) Reinforced soil wall (2013)
(scale: 1:1)

(i) Soft-story woodframe building (2013)
(scale: 1:1)

Fig. 11 – Examples of landmark tests performed at the LHPOST.

4. Key Research Questions and Potential Technical Breakthroughs in Earthquake Engineering

The NHERI@UCSD shake table facility can be used to address the following key research questions, which will lead to high-impact technical breakthroughs in earthquake disaster prevention.

- How will existing older (wood, concrete, masonry, and steel) buildings, which were not designed and constructed according to current codes and construction practice perform in future earthquakes? Preservation of existing infrastructure systems is essential to attaining the disaster resilience and sustainability of the built environment. Past earthquake events in the U.S. and around the world repeatedly demonstrated that the vast majority of structural collapses in any seismic event have been associated with older structures. The development of adequate databases and reliable computational tools to evaluate the earthquake performance of these older structures so as to accurately identify the “killer” structures is of critical importance to ensuring life safety and disaster-resilient communities.

- How effective are new and existing seismic retrofit and mitigation techniques and post-earthquake repair methods for building structures and critical facilities? Identifying and improving the effectiveness of economical seismic retrofit methods will encourage building and facility owners to adopt such measures and upgrade deficient structures to meet current safety standards. The performance of a retrofitted structure is often governed by the interaction and connectivity of new and existing materials and components in the system. This often presents a challenge in computational modeling. Sometimes, localized retrofit or strengthening of structural elements produces unexpected behavioral outcomes at the system level. Hence, system-level testing provides the ultimate assurance of the effectiveness of these measures.
- How well do structural systems designed according to current code standards perform in earthquakes? Can their damage and failure mechanisms be reliably predicted? Do they have an acceptable margin of safety against collapse? Current seismic design provisions are largely based on experimental data from structural component and subassembly tests as well as field data from past earthquakes. The behavior of structural components in a system can be quite different from that observed in laboratory component tests. This may be due to varying boundary conditions and/or interaction with other structural or nonstructural components. The next-generation PBD code provisions will focus on the system-level performance as predicted by computational simulation models, which have to be calibrated with available experimental data. Testing large-scale structural and SFS systems will provide critically needed data to assess how existing code provisions measure up to new performance criteria and to calibrate computational simulation models.
- What are the effects of SFSI on the performance of structural systems? SFSI can be beneficial or detrimental to the performance of structures during earthquakes. Design guidelines considering these effects are mostly based on analytical models, computational simulations, small-scale shake-table experiments in centrifuges, large-scale field testing of pile and slab foundations, and field observations from past earthquake events. Large-scale field testing provides pertinent data to calibrate soil properties in analytical and computational models; however, it cannot conclusively validate how SFSI affects structural response during an earthquake, because these tests neglect the dynamics of soil response during earthquake shaking and the inertial interaction with the superstructure. Moreover, they are generally at amplitudes lower than design target earthquake demands. The scale of SFS specimens in centrifuge tests has to be necessarily very small. This means that detailing of superstructure elements and materials for these tests necessitates simplicity due to the small scale. Therefore, results of such tests will have limited accuracy regarding the behavior of the actual structure or foundation. Shake-table tests used in combination with large soil boxes and reasonable size foundation and structural models are needed to complement centrifuge tests to validate corresponding computational models. These types of tests can also be used to study the performance of underground structures, bridge abutments, earth retaining walls and slope stability in hillside construction.
- How successful are innovative structural systems, materials, construction methods, design concepts, and response modification devices at delivering their targeted system-level performance? Through years of research, current seismic design and construction standards more or less satisfy the life-safety design criterion. To move towards a sustainable and disaster-resilient community, methods and techniques to minimize structural and non-structural damage, post-earthquake downtime and repair cost, and the total economic loss in an earthquake event have received much attention. These include the development of sustainable and high-performance materials, innovative structural configurations, and effective earthquake protection technologies. There also exists tremendous potential to transform the construction process of building and other infrastructure types using modern fabrication technologies. For example, borrowed from the field of rapid prototyping, it is now possible to use 3-dimensional printing together with sustainable rapid-set cementitious materials to accelerate the construction process. System-level testing provides the ultimate evaluation of these concepts, which can lead to new breakthroughs in structural engineering and earthquake hazard protection.
- What are the impacts of nonstructural components on overall losses in earthquakes and how can such loss be minimized? Damage to architectural elements, mechanical/electrical/plumbing systems, and building contents, often collectively referred to as nonstructural components and systems (NCSs), can incur significant direct and indirect economic losses in the event of an earthquake. Repair and replacement costs can be significant and the temporary loss of functionality of critical facilities like hospitals is not only costly but also has direct and indirect impacts on life safety. Moreover, to support safe evacuation and post-event rescue, it is absolutely

essential that some of these systems, such as those supporting egress, remain operable following an earthquake. This has become an important consideration in the next-generation PBD methodology. Understanding how non-structural components respond and interact with the structural system and devising effective means to protect them from damage are essential. This requires system-level studies with realistic structures and realistic earthquake excitation on total structural systems (structures that house NCSs). Data from these studies can be used to derive fragility functions for PBD.

5. Conclusions

This paper provided a description of the present capabilities of the NHERI@UCSD shake table facility (LHPOST). Some past experimental research achievements obtained using this facility were presented as well as their impact in the field of earthquake engineering and future seismic design codes. Finally, the paper also discusses some key research questions that can be addressed effectively using the LHPOST and lead to high-impact technical breakthroughs in earthquake disaster prevention.

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