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DEVELOPMENT OF THE GEORGE E. BROWN JR. NETWORK FOR EARTHQUAKE ENGINEERING SIMULATION (NEES) LARGE HIGH PERFORMANCE OUTDOOR SHAKE TABLE AT THE UNIVERSITY OF CALIFORNIA, SAN DIEGO

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SUMMARY

In October 2002, through the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program, the National Science Foundation (NSF) awarded the University of California, San Diego (UCSD) $5.9 Million to provide the NEES portfolio with a Large High Performance Outdoor Shake Table (LHPOST). The LHPOST will be the first outdoor and largest (12.2 m x 7.6 m) shake table in the United States. A large soil pit funded by the California Department of Transportation (Caltrans) has been strategically located adjacent to the LHPOST for Soil-Foundation-Structure Interaction (SFSI) testing. The facilities will be used to conduct large- and full-scale testing to investigate structural and geotechnical seismic performance issues that cannot readily be extrapolated from testing at smaller scale, or under quasi-static or pseudo-dynamic conditions, including performance under near-field ground motions. Potential research that could be carried out on the LHPOST include (a) the effects of passive and semi-active energy dissipating systems on building response, (b) large-scale testing of kinematic soil-foundation-structure interaction, (c) seismic response of nuclear waste dry storage casks, including the soil-structure interaction and the kinematic interaction between casks, (d) loss estimation of buildings, including the interaction between their components, (e) seismic response of full-scale wood-frame construction including school buildings (f) response of building diaphragms, where the presence of a distributed mass constrains the testing to be performed solely under dynamic conditions, (g) assessment of liquefaction mitigation mechanisms, (g) optimization of shallow foundations to maximize kinematic soil-foundation interaction, and (h) the study of the complex interaction between interconnected components of electrical substations, such as high-voltage transformer-bushing systems. Such experiments will present unique opportunities to develop, calibrate, and validate predictive computational tools in earthquake engineering. The following paper summarizes design issues and specifications for the LHPOST.

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INTRODUCTION

The LHPOST, being constructed at UCSD as part of the NEES program, will be the first and largest outdoor shake table in the United States. The LHPOST is being developed at the Field Station at Camp Elliott, a site located 15 km East of the main UCSD campus. The shake table, acting in combination with equipment and facilities separately funded by the California Department of Transportation (Caltrans), which include a large laminar soil shear box and refillable soil pits, will result in a one-of-a-kind worldwide seismic testing facility (see Fig. 1). This unique facility will enable next generation seismic experiments to be conducted on very large- or full-scale systems. Moreover, the proximity of a soil pit to the LHPOST will allow hybrid shake table-soil pit experiments to be conducted. This innovative piece of NSF equipment in conjunction with the Caltrans SFSI facility will add unique testing capabilities to NEES and consolidate the leadership of the NEES collaboratory as the leading earthquake research consortium in the world.

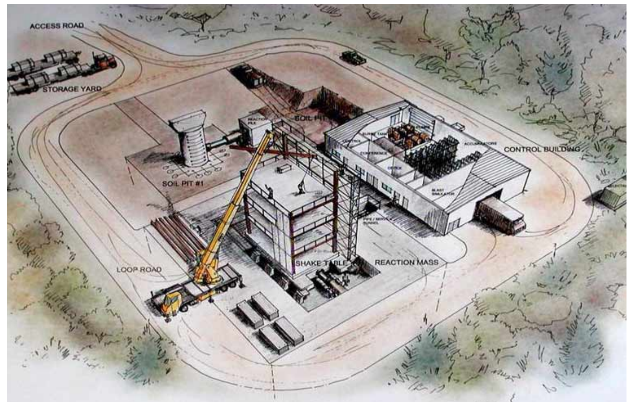


Fig. 1: Camp Elliott Field Station

Existing shake table systems in the United States are typically limited by payload (base shear and/or overturning moment), hydraulic power supply, stroke, and overhead room to construct and test tall structural systems. The LHPOST has been designed with performance characteristics that will allow for the accurate reproduction of far- and near-field ground motions for the seismic testing of structural systems. The primary research objective of these one-of-a-kind large-scale, system level experiments lies in the validation and calibration of analytical simulation tools to predict systems and/or SFSI response. The benefits of the proposed activity consist of archived "landmark experiments" that are known for completeness, realistic scale, and realistic seismic input. The LHPOST facility will also provide unique archived experiments for outreach at all levels such as K-12, college, news media, policy makers, infrastructure owners, insurance, etc. Furthermore, practicing engineers will benefit greatly from the experiments conducted on the LHPOST that verify actual designs (at full-scale) for construction.

In its first phase of development, the LHPOST is being built as a single axis (horizontal) shake table. However, the LHPOST has been designed for easy upgrade to six degrees-of-freedom. The specifications for the uniaxial configuration are a stroke of ± 0.75 m, a peak horizontal velocity of 1.8 m/s, a horizontal force capacity of 6.8 MN, a vertical payload capacity of 20 MN, and an overturning moment capacity of 50 MN-m due to an effective specimen mass of 200 tons at an effective height of 10 m accounting for a dynamic amplification of 2.5. The operational frequency bandwidth of the system is 0-20 Hz.

Fig. 2 provides a schematic rendering of the key components of the LHPOST. Component 1 shows the steel platen having overall dimensions 12.2 m (length), 7.6 m (width) and 2.2 m (depth). The platen consists of a welded steel structure with a torsionally stiff shell and internal stiffening honeycomb. Component 2 is the reinforced concrete reaction mass, including a service underground tunnel from the hydraulic power supply system located in the auxiliary building to the test pit, which facilitates the placement of the hydraulic piping and provides access. Holes for vertical tie-downs are also provided around the test pit for future installation of reaction frames or walls to be used in real-time hybrid testing. The hydraulic and mechanical systems for the LHPOST, designed by MTS Systems Corporation, consist of two servo-controlled dynamic horizontal actuators (component 3), a platen sliding system consisting of six vertical hydrostatic pressure balance bearings (component 4), an overturning moment restraint system consisting of discrete vertical hold-down struts (component 5), a yaw restraint system (consisting of pairs hydrostatic pressure balance bearings per longitudinal side) to prevent the platen from undesirable out-of-plane motions in the uniaxial configuration (component 6), and a weatherproofing system consisting of removable concrete planks (component 7). MTS Systems Corporation also designed the real-time multi-variable controller and the hydraulic power supply, which is being housed in the auxiliary building and consists of two pumps, a blow-down system, accumulator banks, and a surge tank. The LHPOST will be connected to the NEESgrid network and will provide tele-participation capabilities including high-resolution digital video and imaging capabilities. These components and their individual performance specifications are described in more detail in the subsequent sections.

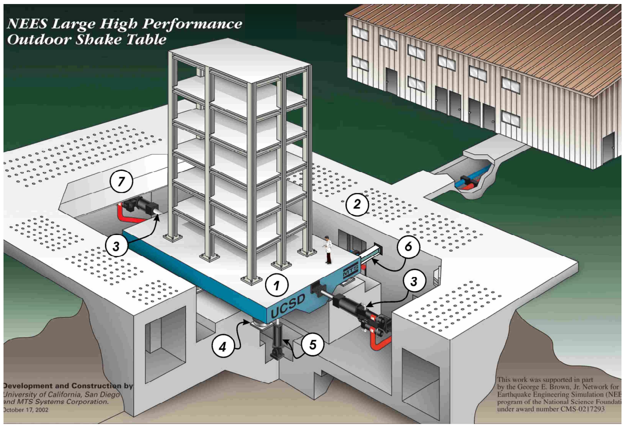


Fig. 2: LHPOST Components

DESIGN BASIS

The design criteria and main specifications of the LHPOST system, and in particular the base shear and overturning moment criteria, were dictated by consideration of a number of target research application examples consisting of several large- or full-scale shake table case-studies covering a number of critical areas of interest (i.e., large-scale modeling of kinematic and inertial SFSI, seismic response of nuclear waste storage casks, and evaluation of supplemental energy dissipating systems for multi-story buildings under near-field ground motions). The selection of the three main table parameters, namely peak displacement (stroke), peak velocity (controlled by hydraulic power flow), and peak force (controlled by hydraulic pressure and actuator size) was based on a range of large historical far- and near-field ground motions that have been recorded worldwide during real seismic events. Non-linear time history dynamic analyses were performed on a number of case-study structural systems to determine the performance specifications for the actuator stroke, velocity and force capacities, frequency bandwidth, and hydraulic power supply and volume.

Near-field, fault normal, ground motion records with forward directivity effects (Doppler effects) are characterized by a large velocity pulse, while near-field, fault parallel, ground motion records are characterized by a fling step (i.e., large step function in the ground displacement record). Since for many sites, the seismic hazard of the built environment is controlled by near-field ground motions at long return period hazard (e.g., 2% probability of exceedence in 50 years), it was essential that the LHPOST be able to accurately reproduce near-fault ground motion effects. For the reproduction of far-field ground motions (Table 1), the method proposed in the NEHRP Provisions for the seismic rehabilitation of buildings [1] was followed. A 5% damped design elastic acceleration response spectrum for a seismic zone 4 and a soil type C or D was constructed and used as the target spectrum. Each of the 20 earthquake records in Table 1 was then scaled to minimize the square of the error between its 5% damped response spectrum and the target NEHRP spectrum at the period values: T =0.1; 0.25; 0.5; 1.0 and 2.0 sec. The resulting scaling factors are listed in Table 1. It was determined that a maximum horizontal peak ground and peak table acceleration of 1g is required, corresponding to an upper bound to the vast majority of recorded ground motion records. Consideration of a suite of desired large- or full-scale specimens for shake table experiments, together with the mass of the table/platen, which at the time of design was estimated at 2.25 MN, and accounting for elastic and inelastic dynamic amplification effects (for the base shear), the effective height of the specimen, as well as dynamic similitude requirements, led to a maximum force of

6.8 MN to be imparted by the shake table actuators and a maximum overturning moment of 50 MN-m to be accommodated by the table/platen and its support mechanism. In determining the peak platen velocity and displacement requirements for reproducing far-field earthquake records, well known empirical relationships between peak ground acceleration, peak ground velocity, and peak ground displacement were used [2, 3]. The reproduction capability of near-field ground motions by the shake table system is controlled by the peak table velocity parameter.

Table 1: Set of Representative Far Field Earthquake Records

ID	Earthquake	Station	Mag	Dist. (km)	TSD (m)*	Scale	Scaled PGA (g)	Scaled PGV (m/s)	Scaled PGD (m)
Sup1	Superstition Hills, 1987	Brawley	6.7	18.2	1.83	2.7	0.313	0.464	0.230
Sup2	Superstition Hills, 1987	El Centro Imp. Co.	6.7	13.9	4.46	1.9	0.49	0.777	0.382
Sup3	Superstition Hills, 1987	Plaster City	6.7	21.0	1.62	2.2	0.409	0.453	0.118
Nor2	Northridge, 1994	Bev.Hills, 14145 Mul.	6.7	19.6	1.64	0.9	0.374	0.531	0.118
Nor3	Northridge, 1994	Topanga Cyn	6.7	15.8	1.71	1.2	0.427	0.385	0.109
Nor4	Northridge, 1994	Glendale, Las Palmas	6.7	25.4	0.5	1.1	0.393	0.135	0.021
Nor5	Northridge, 1994	LA, Hollywood Stor	6.7	25.5	1.98	1.9	0.439	0.348	0.091
Nor6	Northridge, 1994	LA. N. Faring Rd.	6.7	23.9	1.27	2.2	***0.601***	0.348	0.072
Nor9	Northridge, 1994	Cold Water Car.	6.7	14.6	2.21	1.7	0.461	0.377	0.196
Nor10	Northridge, 1994	Mt. Gleason Ave.	6.7	17.7	1.88	2.2	0.345	0.319	0.096
Lp1	Loma Prieta, 1989	Capitolia	6.9	14.5	1.74	0.9	0.476	0.329	0.082
Lp2	Loma Prieta, 1989	Gilroy Array #3	6.9	14.4	0.82	0.7	0.386	0.249	0.058
Lp3	Loma Prieta, 1989	Gilroy Array #4	6.9	16.1	1.84	1.3	0.542	0.504	0.092
Lp4	Loma Prieta, 1989	Gilroy Array #7	6.9	24.2	1.05	2.0	0.452	0.328	0.051
Lp5	Loma Prieta, 1989	Hollister Diff. Array	6.9	25.8	2.96	1.3	0.363	0.463	0.170
Lp6	Loma Prieta, 1989	W. Valley Coll.	6.9	13.7	3.68	1.4	0.465	0.861	0.508
Cm1	Cape Mendocino, 1992	Fortuna Blvd.	7.1	23.6	***6.48***	3.8	0.441	***1.14***	***1.045***
Cm2	Cape Mendocino, 1992	Rio Dell Overpass	7.1	18.5	1.62	1.2	0.462	0.527	0.260
Lan1	Landers, 1992	Desert Hot Springs	7.3	23.3	4.52	2.7	0.416	0.564	0.201
Lan2	Landers, 1992	Yermo Fire Sta.	7.3	24.9	4.01	2.2	0.334	0.653	0.542

* TSD = Total Swept Displacement (or cumulative displacement), defined as the integral of the absolute value of the ground velocity record over the record duration

The peak displacement or stroke specification for the LHPOST represents a compromise between the expected peak ground displacement according to Mohraz [3] for far-field ground motions having a peak ground acceleration of 1g, and the expected degradation of shake table performance with increasing actuator stroke. The significant frequency content of actual earthquake horizontal ground acceleration records lies in the range between 0 and 15 Hz, while the significant frequency components of horizontal ground velocity and ground displacement records lie in an increasingly lower frequency range than that of the ground acceleration. A frequency bandwidth of 20 Hz for accurate reproduction of actual full-scale ground acceleration records by the table was desired, thus allowing for a time compression of up to 33% for test specimens scaled down to 56% (assuming "same material and same acceleration" similitude).

A peak table velocity of 1.8 m/s was selected by considering the set of representative (unscaled) near-field records given in Table 2, which are used extensively in numerical earthquake engineering research [4]. The selection of a peak velocity of 1.8 m/sec for the LHPOST was based on available near-fault seismological data and a compromise between technical performance and budgetary constraints.

Table 2: Set of Representative Near-Field Earthquake Records

ID	Earthquake	Station	Mag	Dist. (km)	TSD (m)	PGA (g)	PGV (m/s)	PGD (m)
NR94rrs	Northridge, 1994	Rinaldi	6.7	7.5	2.33	***0.84***	***1.66***	0.29
NR94newh	Northridge, 1994	Newhall	6.7	7.1	2.73	0.59	0.97	0.38
NR94scs	Northridge, 1994	Sylmar Converter Station FF	6.7	6.2	2.71	0.83	1.18	0.34
NR94syl	Northridge, 1994	Sylmar Olive View FF	6.7	6.4	2.4	0.84	1.30	0.32
KB95kobj	Kobe, 1995	KJMA	6.9	0.6	2.54	0.82	0.81	0.18
KB95tato	Kobe, 1995	Takatori	6.9	1.5	5.61	0.62	1.27	0.36
MH84cyld	Morgan Hill, 1984	Coyote L D	6.2	0.1	1.1	1.3	0.81	0.10
TAB-TR_AT2	Tabas, Iran, 1978	Tabas	7.4		7.25	0.85	1.21	***0.95***
H-E05230.AT2	Imperial Valley, 1979	El Centro Diff. Array #5	7.0		3.44	0.38	0.91	0.63
LCN275.AT2	Landers, 1992	Lucerne Valley	7.3		4.35	0.72	0.98	0.70

To date, the largest near-source peak ground velocity observed in the United States is 1.66 m/sec from the Rinaldi record during the Northridge 1994 (M_W=6.7) earthquake [5]. Strong motion records from the recent Chi-Chi, Taiwan earthquake in 1999 (available from the PEER Strong Motion Database, http://peer.berkeley.edu) indicate that the peak ground velocity ranged from 1.66 m/sec up to 2.63 m/sec. Based on ongoing research, it is understood that the Taiwan earthquake experienced a fling or large displacement step, which is essentially a large velocity pulse in one direction. Except for special structures (e.g. base isolated), the fling portion of a near-field record is generally not critical to the structural response (being at lower frequencies) and can be ignored in most situations. Removal of this fling from the record results in approximations for peak ground velocity levels close to 1.8 m/sec [6]. From these observations and keeping in mind budgetary constraints, the design team felt that a peak velocity of 1.8 m/sec was more than appropriate to envelope extreme near-field ground motions recorded to date. It must also be recognized that 1.8 m/sec represents the peak platen velocity. When the Caltrans laminar shear box is used, additional amplification would take place within the soil box and the peak velocity on the soil surface could exceed 1.8 m/sec.

The total actuator tensile and compressive force requirement of 6.8 MN results in a total actuator piston effective area of 0.34 m^2 assuming an effective fluid pressure at the piston under dynamic conditions equal to 94% of the nominal fluid pressure of 21 MPa to account for various pressure losses in the system. This effective piston area, when multiplied by the peak table velocity of 1.8 m/s, yields a peak oil flow into the actuator chambers of 36,000 liter/min, which becomes the main design requirement for the actuator servo-valves. An important quantity controlling the design of the accumulator bank is the total volume of oil swept through the servo-valve/actuator system during the reproduction of an earthquake record. The swept fluid volume is simply given by the product of the total actuator piston effective area and the integral of the absolute value of the ground velocity record over the duration of the earthquake record, the latter being called the total swept displacement (TSD in Tables 1 and 2). The total swept displacement was computed for each of the 20 far-field earthquake records scaled to 1g of peak ground acceleration (Table 1), and the 10 unscaled near-field records (Table 2). Based on the results obtained, a total swept displacement of 4 m was selected for the design of the accumulator bank, since a majority of the earthquake records considered do not exceed this value of swept displacement. The selected design criterion for the accumulator bank is that its capacity allows the reproduction of the same earthquake record twice back-to-back in the context of the On-line Iterative Reproduction (OIR) test compensation method needed for reducing nonlinear system distortions (e.g., friction effects) during earthquake time history testing. Consequently, an accumulator bank with a capacity exceeding 2,720 liter at or above the nominal pressure of 21 MPa was required.

LHPOST SPECIFICATIONS

The design methodology described above led to the development of the high performance system specifications for the LHPOST listed in Table 3.

Table 3: LHPOST Performance Specifications

Size	7.6 m x 12.2 m
Peak horizontal velocity	1.8 m/s
Stroke	± 0.75 m
Maximum gravity (vertical) payload	20 MN
Horizontal force capacity	6.8 MN
Maximum overturning moment (bare table, 6.8 MN specimen, 20 MN specimen)	25MN-m, 50MN-m, 50MN-m
Frequency bandwidth	0 - 20 Hz

Performance Envelopes of LHPOST

Based on the specifications of the servo-hydraulic components described in the previous sections, the performance envelopes of the LHPOST in a tripartite plot are shown in Fig. 3. Table performance envelopes for a bare table condition with 2 MN (200 Metric ton) moving mass, a table loaded with a 4 MN (400 Metric ton) rigid payload (equivalent to a 2 MN (200 Metric ton) flexible payload with a dynamic amplification of two), and a table loaded with a 20 MN (2000 Metric ton) rigid payload are provided. These performance curves were generated based on the final design platen weight of 145 Metric ton (1.4 MN). Fig. 3 also shows that the maximum acceleration input of the LHPOST is a function of the vertical payload on the table. For a bare table the performance curve indicates an acceleration in excess of 4.2g, which reduces with increasing payload. For a 4 MN payload, the maximum acceleration is anticipated to be 1.28g, while for a maximum 20 MN payload it reduces to 0.3g.

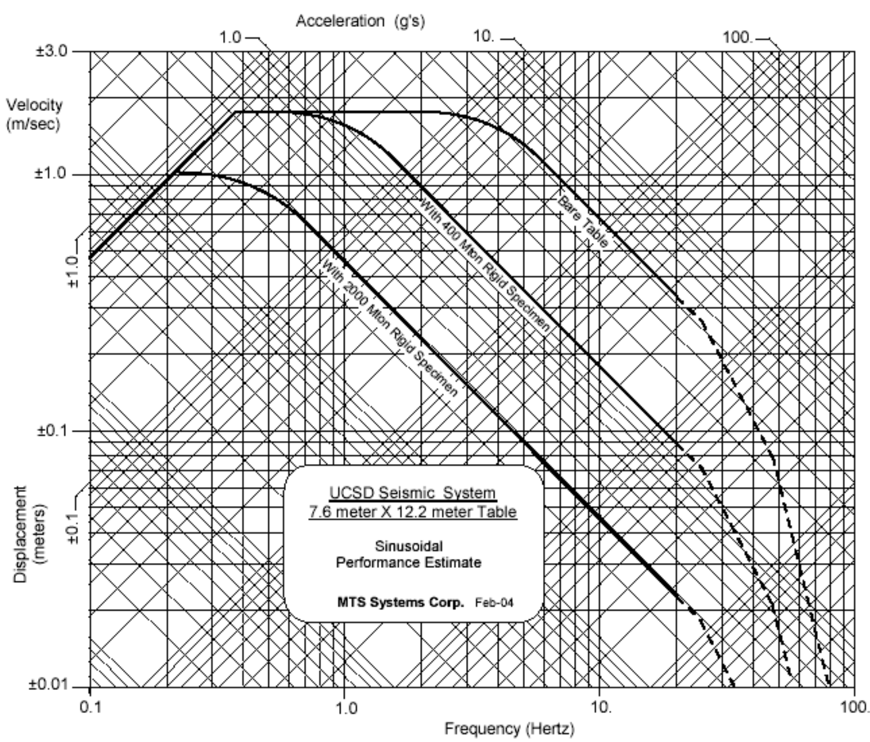


Fig. 3: Performance Envelopes of LHPOST

The overturning moment-specimen weight interaction diagram is shown in Fig. 4. An overturning moment of 20 MN-m can be resisted by the system with the bare platen. Such moment of resistance is mainly due to the presence of the two vertical hold-down struts in the current uniaxial shake table configuration (for the six degree-of-freedom upgrade, a third vertical hold-down strut will be added). As gravity load is increased by placing a specimen on the platen, the overturning moment capacity is increased to a maximum of 50 MN-m. Weight in excess of 6.5 MN will not result in an increase in the overturning moment of resistance since the outermost pressure balance hydrostatic bearings will reach their allowable compressive capacity.

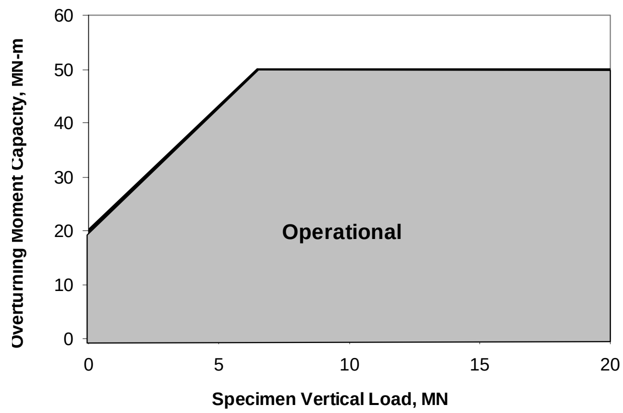


Fig. 4: Specimen Vertical Load – Overturning Moment Interaction Diagram

COMPONENT SPECIFICATIONS

The design of the LHPOST, based on the requirements presented above, consists of a variety of mechanical, structural, hydraulic, control, and weatherproofing components. These components are described in detail in the following sections.

Mechanical Components

The mechanical subsystem for the LHPOST consists of two horizontal actuators, six vertical pressure balance bearings, and two vertical hold-down struts (Fig. 5).

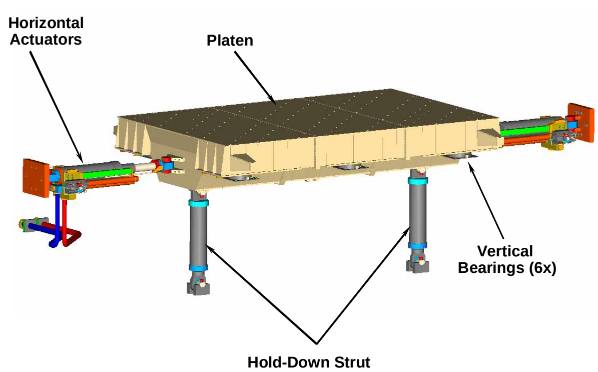


Fig. 5: Mechanical Subsystem Overview

Horizontal Actuators

In the current uniaxial LHPOST configuration, two MTS Model 243 servo-controlled dynamic horizontal actuators (Fig. 6) equipped with high flow servo-valves (Fig. 7) will power the shake table. The actuators are single ended actuators ported to allow flows over 20,000 liter/min. For the future upgrade to six degrees of freedom, the actuators are capable of accepting additional swivel ends. Dual 10,000 liter/min servo-valves are mounted to each actuator. The technical specifications for the actuator consist of a maximum compression and tension force of 4.2 MN and 2.6 MN, respectively, resulting in a combined force of ± 6.8 MN on the table. The pilot stage rated flow capacity of the servo-valves is 19 liter/min @ 7 MPa servo-valve pressure drop. At the intermediate stage, the rated flow is 630 liter/min @ 7 MPa servo-valve pressure drop, and at main stage the rated flow is 15,000 liter/min @ 16 MPa servo-valve pressure drop and 10,000 liter/min @ 7 MPa servo-valve pressure drop.

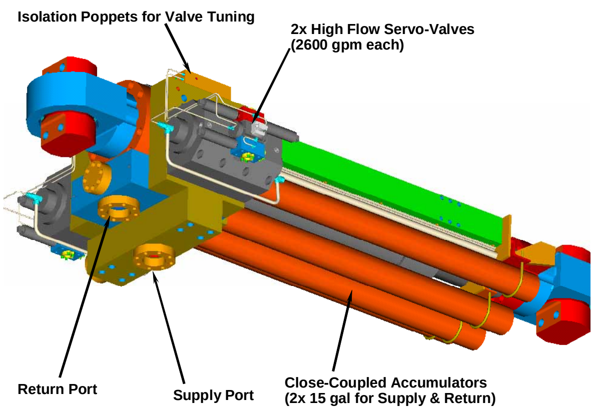


Fig. 6: Horizontal Actuator

Fig. 7: MTS 10,000 liter/min High Performance Servo-valve

Hydrostatic Pressure Balance Bearings

For the platen sliding system, the LHPOST requires six MTS Model 270 Style vertical pressure balance bearings to react against the vertical forces imposed by the platen, the specimen, the discrete prestressing overturning moment system hold-down force, additional gravity loads, and the overturning moments from test specimens. These pressure balance bearings are very efficient at high capacities. The high-pressure capability allows minimum size. The seals minimize leakage and zero power is required for flow. The bearings are self-aligning up to 2 degrees, low in friction, can operate at high velocities and high strokes, use servo-control, which allows height adjustment to provide alignment, and can also function as actuators. The bearings have a force capacity of 9.4 MN and a stroke of ± 13 mm. Fig. 8 shows the hydrostatic bearing being used in the LHPOST system.

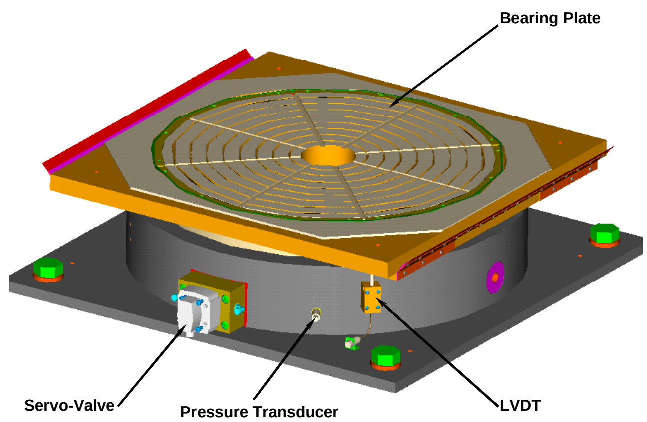


Fig. 8: Hydrostatic Bearing

Vertical Hold-Down Struts

The overturning moment resistance in the LHPOST is provided by a combination of gravity loading (test specimen plus platen) and a pair of low-stiffness vertical nitrogen-gas cylinders or hold-down struts. These cylinders work with a nitrogen pressure of 20.7 MPa, have a uniaxial stroke of 0.083 m, and a maximum hold-down force capacity of 3.1 MN. The design of a vertical hold-down strut is depicted in the rendering in Fig. 9.

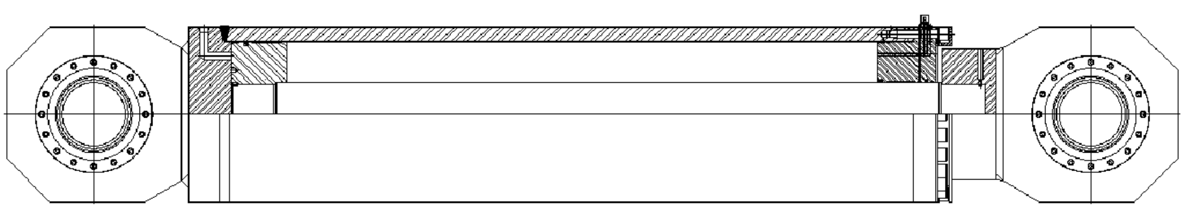


Fig. 9: Vertical Hold-down Strut

Structural Components

Platen

The platen consists of a closed steel box structure constructed in three separate pieces with an overall dimension of 7.6 m x 12.2 m x 2.2 m (Fig. 10). The platen is supported on six hydrostatic bearings, three along each longitudinal side, located 0.9 m from the edge of the table on center. Through holes are provided on a grid of 0.61 m on center to accommodate 44 mm Dywidag tie-rods with tie-down capacity of 890 kN per bar for affixing specimens to the platen. Detailed platen specifications are provided in Table 4. A controlling design criterion for the platen is that the fundamental structural (dish mode) natural frequencies of the table must be several times (3 to 5 times) the highest frequency of operation of the table (20 Hz). This minimizes coupled dynamics phenomena between resonant modes of the table and inherent dynamic characteristics of other mechanical, hydraulic, and electronic components of the shake table system. Coupled dynamics negatively affects the dynamic tracking performance of the system, especially in determining the trade-off decisions between system stability and accuracy [7]. Therefore, to satisfy stiffness requirements, the fundamental mode of vibration of the platen was specified to be greater than 65 Hz. It should be noted that although the oil column natural frequency of the system was determined to be approximately 8 Hz, the availability of notch filtering in the control system allows for the correction of dynamic distortions around oil column resonance.

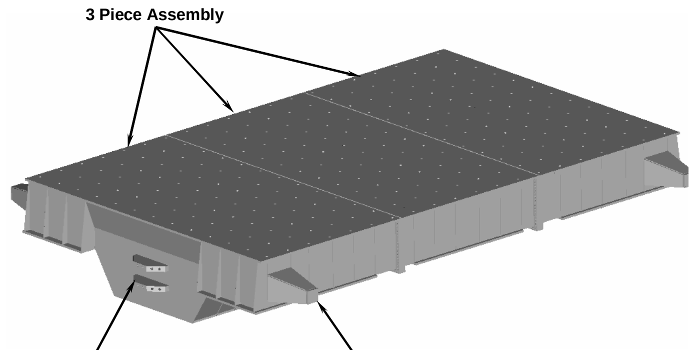


Fig. 10: Steel Platen

Table 4: Platen Specifications

Description	Metric Units
Platen Footprint	7.6 m x 12.2 m x 2.4 m
Platen Weight	1.128 MN
Specimen Payload	20 MN
Specimen CG	10 m
Maximum Overturning Moment	50 MN-m
Unloaded Mode 1	74 Hz
Loaded Mode 1	44 Hz
Top plate thickness	50 mm
Bottom plate thickness	20 mm
Side plate thickness	12 mm
Ribs	10 mm & 20 mm

The platen is stiffened transversally with 10 mm and 20 mm plates. To satisfy strength requirements throughout the entire operation of the LHPOST facility, the platen was designed to remain elastic with localized yielding only permitted upon impact of a collapsing body and extensive yielding allowed only upon unanticipated loss of control of the LHPOST. The latter requirement is to protect the reaction mass from irreparable damage. With respect to stability requirements, that platen was designed for a factor of safety of 3.0 against wall stability, even for the case when a specimen that extends across the entire width of the table is post-tensioned to the table at 890 kN/tie-down.

Reaction Mass

The design of the reaction mass for the LHPOST departed considerably from conventional design of reaction masses for systems subjected to large impact/dynamic loading where fidelity of the intended response is paramount. Such reaction masses are typically conceived with a characteristic fundamental frequency at the lower end of the frequency range of operation and essentially react the impact loads by inertia. The typical result is an extremely massive and costly foundation. The approach taken for the LHPOST took advantage of the extremely stiff natural soil conditions at the site and resulted in a considerably lighter and less costly foundation. The geometry and mass distribution of the reaction mass was aimed at maximizing radiation damping and, in this way, controlling the amplitude of the response.

Geotechnical studies of the Camp Elliott site including small-diameter borings extending to depths varying from 2 to 22 m indicate that below a 1 m thick layer of topsoil there is a layer of Quaternary soils (Linda Vista Formation) extending to a depth of about 4 m. This layer is characterized by very dense, clayey sands with gravel and cobble, with a shear wave velocity varying in the range from 183 to 305 m/sec. Underneath the Linda Vista Formation, Tertiary soils of the Stadium Conglomerate are found. These soils extend to a depth of at least 22 m, and are characterized as very dense silty sand to sandy, cobbly gravel with a shear wave velocity of 760 m/sec.

The initial design of the reaction mass contemplated a foundation with dimensions of 19.6 m by 35.2 m in plan and a depth of 4.3 m. The characteristic natural frequencies for the horizontal and rocking modes of vibration of the reaction mass in the longitudinal direction were calculated to be 23 and 31 Hz, respectively. The corresponding effective damping ratios for these modes exceeded 100%, and consequently no amplification of propagating waves was expected. Final adjustments, including the need for a deeper central region to accommodate the hold down struts, resulted in a reaction mass 19.6 m wide, and 33.1 m long extending to a depth of 5.8 m over most of the area. In a small central area the reaction mass tapers to a depth of 7.9 m to anchor the hold down struts (refer to Fig. 2). Furthermore, the corners of the reaction mass were truncated. These modifications resulted in a reduction of the calculated horizontal and rocking characteristic natural frequencies to 18.4 and 20.7 Hz, respectively, when the adjacent soil pit was full of soil. The corresponding calculated effective damping ratios are 87 and 54%, respectively, still resulting in very small amplification.

An upper bound estimate to the peak velocity of the reaction mass when subjected to the full actuator force (6.8 MN) acting at the characteristic frequency amounted to 0.8 cm/sec which is in the range troublesome to humans (> 0.25 cm/sec) but is below the limit considered appropriate for machinery (2.5 cm/sec) (Fig. 11). Given the strong attenuation of the ground motion with distance, which amounts at the site to a factor of approximately 50 for a distance of approximately 200 m to the reaction mass (Fig. 12), it is expected that the vibrations of the ground will not affect people beyond the immediate vicinity of the table [8].

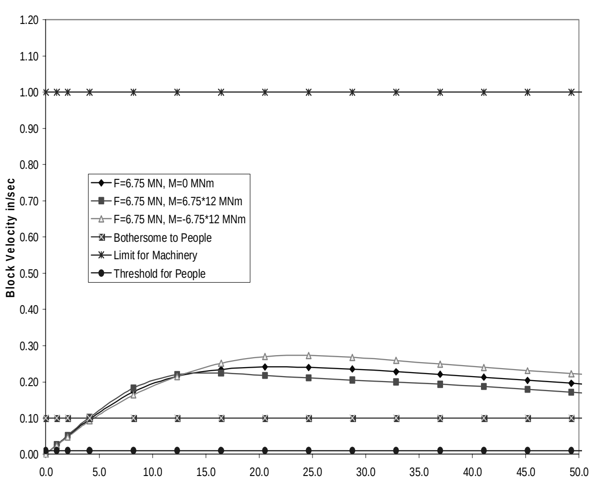


Fig. 11: Frequency Response Curves for Velocity at Foundation of Table

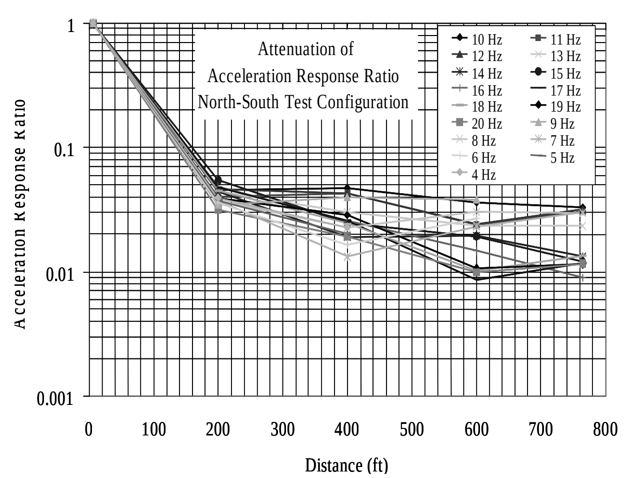
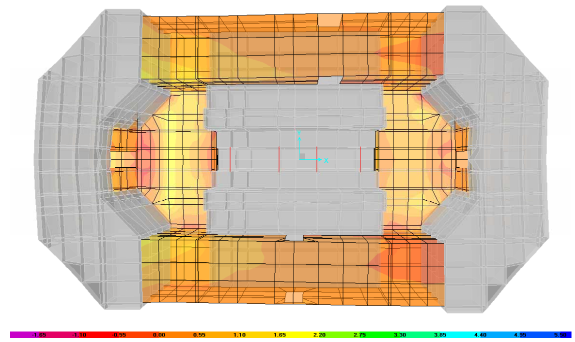
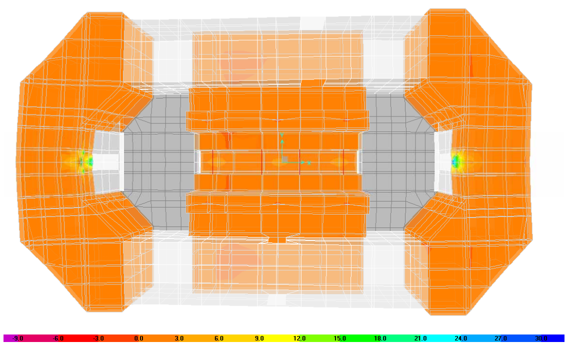


Fig. 12: Amplitude Decay Curves vs. Distance from Source

The reaction mass was built with concrete having a nominal compressive strength of 25 MPa at 28 days. The reaction mass is a tubular structure with a central dent. The tubes provide access for hydraulic lines and future developments. The reaction mass was designed for two performance-limit states. The first was normal operation conditions under maximum design loads. The second was an ultimate limit state associated with the impact loading caused by the horizontal actuators hitting the safety cushions and impacting against the reaction mass. Under service load conditions, tensile stresses in the concrete of the reaction mass would be less than 2.5 MPa, except at some specific locations. The structural design of the reaction mass involved extensive use of strut-and-tie modeling for the ultimate limit state and finite element model validation for determining principal stress-states at the service and ultimate limit states. Fig. 13 shows the principal tensile stresses for horizontal actuator impact loading at the ultimate limit state.



(a) Shell elements



(b) Solid elements

Fig. 13: Reaction Mass Principal Tensile Stress Contours for the Ultimate Limit State

Hydraulic Power Supply

The hydraulic power is supplied to the actuators by an accumulator bank through a blow-down valve. The accumulator bank provides the high flow needed to simulate a transient earthquake signal, and the blow-down valve 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 (HPUs) are provided to pump oil into the accumulator bank. These HPUs include filters, heat exchangers, and all necessary valves and controls needed for operation. Return flow is directed to an auxiliary reservoir or surge tank. Because of the targeted future upgrade to six degrees-of-freedom, the hydraulic power system construction allows for increasing the flow in the future. The technical specifications for the hydraulic power supply are summarized in Table 5.

Table 5: Hydraulic Power Supply Specifications

Component	Specifications
Accumulator bank	Volume of 9,500 liters and pressure at 35MPa
Blow-down valve(s)	Peak flow of 38,000 liter/min
Hydraulic power units (2)	Flow of 720 liter/min each, main pressure at 35MPa, pilot pressure at 21MPa, and power at 450 kVA each
Surge Tank	Volume of 10,000 liter

For the accumulator bank and blow-down valve system, only about 1,900 liter of the 9,500 liter of the accumulator bank capacity are available at or above the nominal pressure of 21 MPa. Therefore, the accumulator bank, when supplemented with the two 720 liter/min hydraulic power units, satisfies the design requirement of providing 2,720 liter at 21 MPa or above in order to simulate the same earthquake record back-to-back during the on-line iterative (OLI) compensation method. Several experiments were conducted on the existing 3 m x 5 m uniaxial shake table at UCSD to verify that discontinuous iterations, necessary to allow the recharge of the accumulators, would still enable accurate and fast tuning of the

LHPOST. The results of these tests are depicted in Fig. 14. Using a clipped acceleration white noise between 0.25-25 Hz, it was determined that the combined pump and accumulator bank configuration of the hydraulic power supply is capable of providing sufficient flow for unlimited tuning time. The accumulator banks (without the pumps) provide a limited tuning time of 2.91 min.

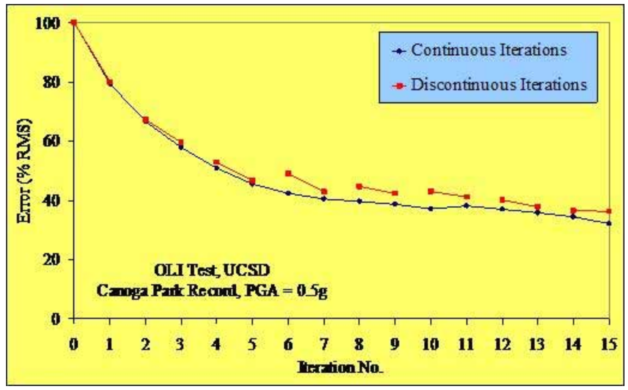


Fig. 14: Continuous vs. Discontinuous Iterations

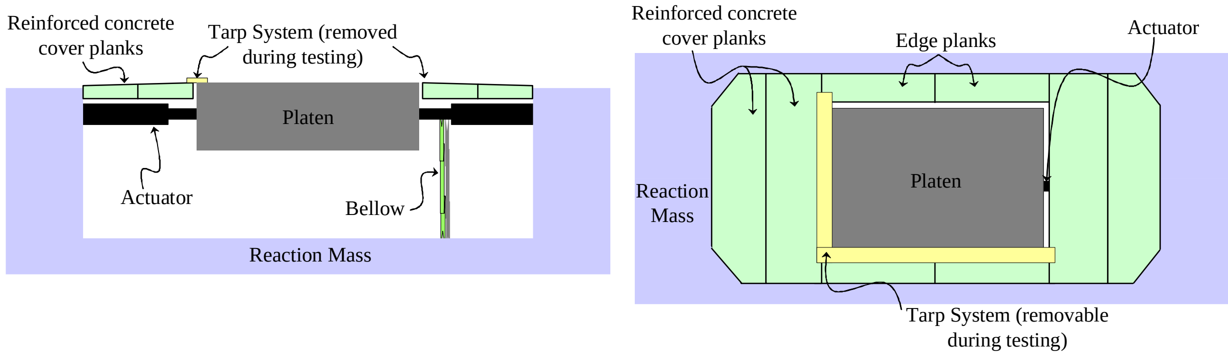
The blow-down valve flow capacity of 38,000 liter/min satisfies the peak flow requirement of 36,000 liter/min. One of the two hydraulic power units with a total continuous flow capacity of 720 liter/min at 21 MPa and 430 liter/min at 35 MPa will be used to charge up the blow-down accumulator bank. The recharge time will be approximately 5 min, which is very satisfactory, leaving the operator just enough time to verify the data acquisition and control system between tests.

Control System

The LHPOST will be controlled by the proven yet advanced technology digital control system MTS 469D, which is an integrated control solution including all computer hardware, software, transducers, data acquisition electronics, and cabling necessary for system operation. The system will provide for shake table tuning, system operation, and test execution in real time. The MTS Seismic Digital Control Software provides an advanced graphical user interface (GUI). Full functionality is provided through the GUI for system tuning, test set-up and operation, table data acquisition, and advanced high level adaptive control for high fidelity earthquake waveform reproduction. The control software includes a set of high-level fixed control techniques such as Three-Variable Control (TVC: displacement, velocity, and acceleration) for high fidelity reproduction across a wide bandwidth, Delta Pressure Stabilization (DPS) for effectively dampening oil column compliance to allow for higher gains settings across a wider bandwidth, Servo-valve Flow Linearization (SFL) for effectively removing the inherent non-linearities present in all servo-hydraulic systems, and Resonance Canceling Non-Linear Notch Filters for extended system response in the presence of significant specimen and system resonances. The MTS 469D control system also includes a set of adaptive control techniques such as Amplitude Phase Control (APC) for automatic correction of amplitude and phase errors during sine wave testing, Adaptive Harmonic Cancellation (AHC) for control and elimination of harmonic distortions during sine wave testing, Adaptive Inverse Control (AIC) for reducing linear distortions during random waveform testing, and On Line Iteration (OLI) for reducing the effects of non-linear distortion causes during random waveform testing when the highest levels of waveform fidelity are required.

Weatherproofing System

Although being built in San Diego, which is known for its mild climate, all of the accessible portions of the LHPOST will be covered and pressurized with filtered, conditioned air running continuously. The cover consists of enclosing the space between the platen and the surrounding reaction mass with permanent concrete planks that can support the weight of equipment and foot/vehicle traffic necessary for the construction of test specimens. In addition to the planks, a tarp system will be provided to span the gap between the platen and the planks and provide the required sealed indoor environment in the reaction mass to protect the sensitive mechanical equipment. During operation of the table, these tarps will be removed temporarily and vertical bellows will be attached to protect components from dust and debris. Fig. 15 shows an elevation and plan view of the weatherproofing system. The planks will be used for weatherproofing the actuator pit and providing vehicular access to the shake table. For this reason they are designed to resist a 40-kip point load at midspan. A total of eight planks will cover the opening to the actuator pit, but the pit is symmetrical and only four different geometries are required. Two of these geometries will incorporate cast-in-place acrylic inserts or windows to provide light into the pit area but keep water and debris out.



a) Elevation b) Plan View

Fig. 15: Weatherproofing System Concept

NEES@UCSD Telepresence System

The NEES network, known as NEESgrid, connects the equipment sites and remote researchers together and provides telepresence capabilities, a curated data repository, a simulation tools archive, and collaborative tools for facilitating on-line planning, execution, and post-processing of experiments. NEESgrid is necessary to facilitate the proposed multi-disciplinary, geographically distributed NEES research projects. The key to successful collaboration across multiple sites and investigators is the management of the information needed to design the research program and the data and information created from the experimental and computational research. The NEES@UCSD Local Area Network (LAN) will be integrated to and will further enhance all NEESgrid specific tools for data discovery online collaboration through text chat, information sharing, the electronic laboratory notebook, and videoconferencing, and data and metadata viewing [9]. During the set-up, observation and monitoring of tests at NEES@UCSD, the scheduling of resources, design and construction of specimen, calibration and placement of instrumentation, and real-time monitoring of data will be achieved using the web-based tools such as the electronic laboratory notebook, the telepresence systems at each site, and the CHEF collaboration and data-viewing environment (consisting of data archive search, email archive, and visualization tools). Students and researchers will input data and metadata such as experimental notations, calibration data, data plots and sample data tables with the NEESgrid laboratory notebook.

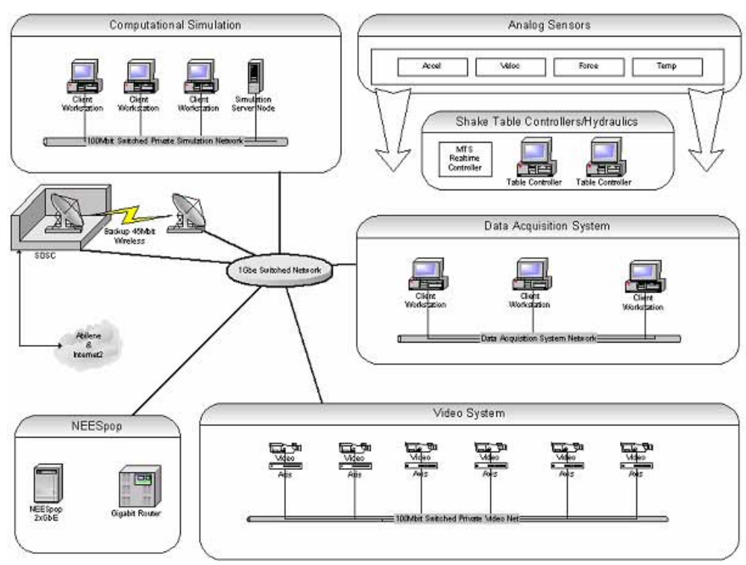


Fig. 16: UCSD LAN Configuration Diagram

The general NEES@UCSD LAN for the LHPOST is depicted in Fig. 16. Site specific tools to accommodate UCSD instrumentation, data acquisition equipment, and testing protocols have been developed. The NEES@UCSD LAN is structured around an integrated system for experimental data collection and simulation that directly interfaces with the LHPOST to enable telepresence and teleparticipation. The system will include a basic computational simulation module and a digital control/hydraulics module with parallel processing capabilities for real-time data processing and control. The data acquisition module receives experimental data through advanced sensors, including digital video cameras, point and remote measuring devices, distance/motion detectors, and from remote users and operators through the NEESgrid interface. Through the NEESpop, the integrated system takes advantage of digital video with compression and IP transmission, to actively involve remote users in operation, observation, and data processing. All of these modules feed directly via a high speed network connection to the San Diego Supercomputer Center (SDSC), which is connected directly to the UCSD campus backbone and Abilene and Internet 2.

GEOTECHNICAL INVESTIGATIONS

Extensive forced vibration tests were conducted at Camp Elliot under separate funding from the National Science Foundation. In the first set of tests, after excavation and prior to the construction of the reaction mass, the two large eccentric mass shakers (50 tons capacity each with operational frequency range from 0 to 25 Hz) available at the University of California in Los Angeles NEES node (NEES@UCLA) were mounted on small concrete pads embedded at the bottom of the excavation for the reaction mass, and the dynamic response at a large number of stations within the excavation and on the ground surface at distances of up to 350 m from the table location was recorded over a wide frequency range (0-25 Hz). In the second set of tests conducted when the adjacent soil pit was empty, the two NEES@UCLA shakers were mounted on the just completed reaction mass at locations close to the reaction points of the future actuators, and the motion at many stations within the reaction mass and on the ground surface was recorded for frequencies in the range from 1 to 22 Hz (Fig. 17). The results of these tests with maximum force levels of 50 ton per shaker are being used to identify the soil properties at the site, to study the motion and the deformation patterns of the reaction mass, and to validate analytical and computational models of the soil and reaction mass [10].

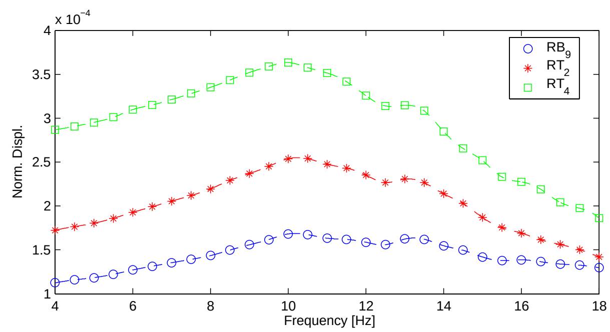


Fig. 17: Normalized Displacement Amplitudes for Constant Harmonic Shaker Force

CONCLUSIONS

This paper provided a brief summary of the design basis and performance specifications for the Large High Performance Outdoor Shake Table (LHPOST) being constructed at Camp Elliott at UCSD through the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program funded by the National Science Foundation (NSF) . The LHPOST will be the first outdoor and largest shake table in the United States and will allow for the unique testing of large- and full-scale structural and geotechnical systems under near-field ground motions. In its first phase of development, the LHPOST is being built as a single axis (horizontal) shake table. However, the LHPOST has been designed for easy upgrade to six degrees-of-freedom. To maximize performance within the available budget, the NEES@UCSD project team evaluated many application examples that have led to a design maximum payload capacity of 6.8

MN and a maximum overturning moment capacity 50 MN-m. Design of the hydraulic power supply system was based on the ability to reproduce numerous far- and near-field earthquake records resulting in very high performance capabilities consisting of a stroke of ± 0.75 m, a peak horizontal velocity of 1.8 m/s, and an acceleration capacity ranging from 0.3-4.2g depending on the payload. The LHPOST will be operational on October 1, 2004 when NEES comes online. It will be connected to the NEESgrid network and provide extensive telepresence capabilities.

ACKNOWLEDGEMENTS

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