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AN APPROACH FOR SHAKE TABLE PERFORMANCE EVALUATION DURING REPAIR AND RETROFIT ACTIONS

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ABSTRACT

Large-scale, servo-hydraulic shake tables are a central fixture of many earthquake engineering and structural dynamics laboratories. Wear and component failure from frequent use may lead to control problems resulting in reduced motion fidelity, necessitating repairs and replacement of major components. This paper presents a methodology to evaluate shake table performance pre- and post-repair, including the definition of important performance metrics. The strategy suggested is presented in the context of the rebuilding of a $4.9 \times 3.1\text{m}$, 350kN-capacity uniaxial shake table. The rebuild consisted of characterization of wear to table components, replacement of worn bearing surfaces, and replacement of hydraulic accumulators. To assess the effectiveness of the repair actions, sinusoidal and triangular waves, white noise, and earthquake histories were run on the table before and after the rebuild. The repair actions were successful in reducing the position- and velocity-dependence of friction, improving the ability of control algorithms to accurately reproduce earthquake motions. The maximum and average response spectral misfits in the period range of 0.1-2 seconds were reduced from about 50% to about 15%, and from 5% to less than 2.5%, respectively.

Keywords: structural dynamics, shake table testing, structural testing, structural control

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INTRODUCTION

Background and motivation

Servo-hydraulic, servomotor, and mechanically actuated shake tables are a common fixture in many earthquake engineering and structural dynamics laboratories. Servo-hydraulic shake tables are the most common type in current use for medium- to large-scale seismic shake tables, and are the focus of this paper. "Large-scale" shake tables may be defined as those with a platen of at least $3\text{m} \times 3\text{m}$ and a payload of at least 10 metric tons (Filiatrault et al. 2013). There are at least seven of these tables in current operation in the United States, seven in Europe, and approximately 30 in Japan (Abrams et al. 1995, NEA 2004). In addition to these flagship facilities, perhaps hundreds of small-and medium-sized tables are in current operation at commercial and academic laboratories worldwide.

Shake tables provide the optimal tool for engineers and researchers to reproduce realistic seismic environments. As such, they are often in near-constant demand, often leaving little downtime for maintenance and repair. Many, if not most, of the large-and medium-sized tables in the United States are now over 20 years old. The shake table at the University of California, San Diego (UCSD) that is the subject of the current paper was initially constructed in 1988 (Magenes 1989), and there are several tables nearing 50 years old (e.g. Penzien et al. 1967). This combination of aging test infrastructure and steady demand for seismic research and testing means that repair frequency must be low, and when repair actions are necessary they must be carried out quickly and efficiently. A consistent methodology for evaluating the performance of such tables, particularly one that can be implemented before and after major repair actions is needed to support these goals. Such a methodology consists of careful selection of target motions, establishing reasonable performance metrics, and assessment.

Previous investigations of shake table performance

There have been a number of efforts to quantify the performance of shake table systems through various metrics. Typically, predictions of table performance constitute part of their initial design, and performance is usually evaluated during commissioning (e.g. Penzien et al. 1967, Magenes 1989, Ozcelik 2008, Luco et al. 2010). Only a few studies have investigated performance characteristics before and after a retrofit action, such as changing the control system from analog to digital (e.g. Filiatrault et al, 2000). These investigations have used a variety of different motion types and performance evaluation criteria. Studies related to initial table design and commissioning have often expressed table performance in terms of spectral acceleration, velocity, and/or displacement, often as a function of table payload. An example of a bare-table performance curve for the table investigated in this paper is shown in Figure 1. Such curves may be derived from actuator and hydraulic system performance characteristics, or determined from tests under sinusoidal motions. While this approach provides a general description of table performance as a function of frequency, it does not describe the performance of the table under its typical intended function, i.e. reproducing earthquake motions with high fidelity.

An alternative approach, used by Filiatrault et al. (2000), is to evaluate table performance solely on the basis of the target versus achieved acceleration response spectra from a suite of recorded earthquake motions. This approach is attractive for several reasons. Direct evaluation on the basis of a characteristic of an earthquake motion makes fundamental sense, as reproducing such motions is the *raison d'être* for the majority of shake tables. Additionally, force quantities are often of paramount importance in structural testing, and acceleration response spectra are directly linked to inertial forces. Finally, evaluation on a spectral metric allows quantification of

the impacts of modes related to table features, such as those related to the oil column and those related to the coupled table-foundation system. However, the results of such an approach may be highly dependent on the characteristics of the particular motions selected, making testing of a large suite of motions necessary to provide an overall impression of table performance.

Some, but not all, shake table tests additionally require high accuracy in the time domain. Luco et al. (2010) describes the performance of a large-scale shake table under sinusoidal, earthquake, and white noise motions using metrics of command versus achieved peak acceleration, 3%-damped response spectra, and root-mean-square error of the command versus achieved acceleration time series. Such a balanced approach, considering several different motion types and performance metrics is attractive from a practical standpoint because it allows broad assessment of table characteristics of likely interest in future test campaigns. The exact characteristics of evaluation motions will obviously be dependent on the specifications of the table under consideration, as well as its intended use. However, these three basic motion types formed the basis for the current investigation.

Scope of paper

The primary objectives of this paper are:

1. To develop a practical methodology for the evaluation of seismic shake table performance following major control or mechanical repairs or upgrades. This methodology includes suggested motion types, brief guidelines for selecting their characteristics, and evaluation criteria.
2. To illustrate the utility of the proposed methodology via presentation of an example, namely the rebuilding of a large-scale, uniaxial shake table. This discussion includes a description of physical wear, quantification of the frictional response of the table, and an assessment of the pre- and post-repair performance using the proposed evaluation criteria

This paper is intended to be of general interest to experimentalists utilizing both commercial and academic shake tables; therefore, it does not discuss performance under any specific motions used to qualify structural or nonstructural components, such as AC-156 (ICC 2010) or IEEE-344 (IEEE 2013). Additionally, this paper does not include a detailed discussion of control algorithms, except as they relate to the behavior observed during testing.

EVALUATION METHODOLOGY

Motion selection

The proposed motion suite consists of sinusoidal, broad-band white-noise, recorded earthquake, and triangular wave motions. Displacement-controlled triangular motions are useful in determining the frictional characteristics of a table because they contain regions of constant velocity over which the dynamic friction force is expected to be constant. Examples of each motion type are shown in Figure 2.

The capabilities of large-scale shake tables vary widely in terms of numbers of degrees of freedom, maximum table displacements and accelerations, capabilities of hydraulic systems, and control systems (NEA 2004). For this reason, the specific selection of motions must be made on a case-by-case basis. However, some broad guidelines may be formulated considering typical performance goals:

- Sinusoidal motions should include frequencies in the range of significant energy content of typical seismic recordings, typically in the range 0.2–30Hz. Ideally, sinusoidal motions should exceed the theoretical acceleration and displacement limits

of the table to ensure that the actual limits of the table are established. Additionally, if the table is expected to reproduce long-duration, high-intensity motions or has limited hydraulic accumulator capacity, cycling at relatively high amplitude may be considered in order to test the sustained volume and pressure limits of the hydraulic system. The latter may be assessed by evaluating the swept (cumulative) displacement of the table.

- Broad-band, low-amplitude, white noise motions are used for a variety of purposes, including specimen system identification (e.g. Astroza et al. 2015), calibration of control algorithms (e.g. Luco et al. 2010), and identification of table-foundation or other coupled modes (Filiatrault et al. 2000, Ozcelik 2008). White noise motions for table performance evaluation should include amplitudes in the range of those expected of the table while in service, as well as long-duration, low-amplitude motions to evaluate the ability of the table to provide "gentle" excitation to fragile structures. Amplitude of white noise motions is generally measured in terms of the root mean square (RMS) of the signal. RMS values of about 0.5–4%g are often used for modal identification purposes, values of 6% or higher may be used for evaluation and calibration of control algorithms.
- Triangular motions are useful to evaluate table frictional characteristics, due to periods of constant velocity in which the force input of the table is proportional only to the frictional feedback (described in detail later in this paper). Such motions should be considered if there is reason to believe that friction is causing degraded table performance. Triangular motions with several different amplitudes and constant-velocity values should be considered in order to evaluate the position- or velocity-dependence of friction. The selection of velocity and displacement values will depend on the performance characteristics of the table.
- Shake tables are primarily used for re-creation of earthquake motions, therefore, they should be an important part of any evaluation program. In terms of motion characteristics, experimentalists may be interested in a variety of target spectral accelerations, peak ground accelerations (PGAs), peak ground displacements (PGDs), Arias Intensities, or other metrics. The selection process may benefit from using motions from a variety of different seismic source mechanisms and recording distances, such that a range of the various metrics is virtually assured.

A motion program based on the aforementioned criteria and implemented for the current investigation of a uniaxial table is summarized in Table 1. It is important to note that many modern tables are multi-axial. Recommendations for the evaluation of multi-axial tables are outside the scope of the current paper, however the motion selection and evaluation metrics presented herein are likely applicable to the evaluation of multi-axial tables in single directions

Table 1: Motion selection criteria and recommended values for shake table performance evaluation

Motion type	Recommended selection criteria and values
Sinusoidal	<ul style="list-style-type: none"> - Frequency range: 0.1–30Hz (max) - Maximum command peak (as ratio of theoretical table performance at given frequency): 10 - 200%*
White noise	<ul style="list-style-type: none"> - RMS values: 0.5%g - 6%g or higher (depending on typical use of WN motions) - Frequency content: 0–50Hz maximum**
Earthquake	<ul style="list-style-type: none"> - PGA and PGD: as required for typical table use - Response spectral peak and spectral values: as required for typical table use - Arias intensity: as required - Duration of strong shaking - Earthquake source mechanism: normal, reverse (particularly deep subduction), strike-slip, oblique
Triangular	<ul style="list-style-type: none"> - Peak displacement: several cycles up to maximum table limits - Peak velocity: up to theoretical maximum of table
<p>*The maximum actuator displacement may not be exceeded. Values >100% only apply if the table is limited by oil supply or accumulator performance for a given frequency.</p> <p>** Tables for earthquake engineering are generally limited to values < 25Hz. Tables for vibration qualification may have significantly higher limits.</p>	

Performance metrics and acceptance criteria

Evaluation of table performance under sinusoidal motions may be based on two criteria: 1) the ability of the system to attain the maximum command peak and 2) the ability of the system to maintain the maximum command peak through multiple cycles. Criterion 1 may be evaluated as a simple ratio of the maximum achieved to command peaks:

$$C1 = \frac{u_{a,max}}{u_c} \quad (1)$$

where $u_{a,max}$ is the maximum achieved peak and u_c is the time-synchronized command peak in the direction under consideration. Criterion 2, $C2$, may be evaluated similarly, except the value of u_a is taken from the final full-amplitude cycle of the motion. Criterion 2 is important because it is indicative of the ability of the system to maintain the required hydraulic flow for an extended period of time, as may be required for the reproduction of deep subduction earthquakes with long duration and significant low-frequency content. The ability of the table system to maintain high-volume, sustained high pressure is affected by the condition of the accumulators, which were rebuilt and recharged as part of the investigation of the table described later.

Performance under white noise motions may be evaluated using at least three different criteria:

- Target versus achieved RMS (RMS_a/RMS_t). This measures the ability of the table to reproduce the desired power of the input motion in a time-average sense
- Time-synchronized target versus achieved maximum acceleration ($\ddot{u}_{t,max}/\ddot{u}_{a,max}$). This measures the ability of the table to apply the desired motion without under- or over-shooting the desired maximum acceleration, which may be damaging to some acceleration-sensitive test specimens.
- Power spectral evaluation may be undertaken to examine the relative prominence of peaks associated with physical table modes that may cause control issues, particularly coupled foundation-table modes and oil column modes. This evaluation method is

particularly important for rebuilds that change the support and/or hydraulic characteristics of the table.

Performance under earthquake motions is perhaps the most important evaluation metric, as most tables are primarily used for earthquake engineering research under real or synthetic seismic motions. Evaluation of the fidelity of earthquake records may be conducted using several different criteria:

- Testing on general-purpose shake tables often consists of acceleration-sensitive components such as equipment, building components, and model structures and displacement-sensitive components such as bearings or multiply-connected systems. Therefore, the ratio of the maximum time-synchronous achieved to target acceleration and displacement should be evaluated ($\ddot{u}_{max,a}/\ddot{u}_t$ and $u_{max,a}/u_t$, respectively)
- Acceleration response spectra are commonly used to select motions and evaluate structures. A review of recent projects on the table described herein indicates that the periods of interest are generally within 0.1–2s (10–0.5Hz). Spectral accelerations S_A within this period range of interest may be evaluated by comparing an average and maximum misfit. The average misfit quantifies the expected error with respect to a structure with a random period within the range, while the maximum misfit places an upper bound on the error for any period within the range. For the current work, evaluation within this period range was based on approximately 50 points, evenly spaced in base-10 logarithmic space. The evaluations were made on the basis of 5% damping, although 3% has been used in previous investigations (Luco et al. 2010). The maximum spectral acceleration ratio (or error) is defined as:

$$\mathcal{E}_{\max} = \max \left(\frac{S_{Aa}}{S_{At}} \right) \quad (2)$$

where S_{At} and S_{Aa} are the target and achieved spectral accelerations within the period range of interest, respectively. The average spectral acceleration error was defined as:

$$\mathcal{E}_{\text{avg}} = \frac{\sum_{i=1}^n \frac{S_{Aa,i}}{S_{At,i}}}{n} \quad (3)$$

where n is the number of points at which the response spectrum is evaluated within the period range of interest. The errors may alternatively be expressed normalized to the target acceleration.

- Shake-table specimens are often expected to behave inelastically, therefore, some measure of damage potential should be considered. For the current work, Arias intensity (I_A) was compared as a ratio of achieved versus target, I_{Aa}/I_{At} . Constant-ductility response spectra may also be considered for this purpose (Luco et al. 2010), in which case evaluation criteria similar to Eq. 2 and 3 may be used.

No performance metrics are established for triangular motions herein. However, the measured friction feedback is used later in this paper to quantify changes in the friction characteristics of the table based on rebuild actions.

METHODOLOGY APPLICATION EXAMPLE

Shake table description

The UCSD Powell Laboratories uniaxial shake table has platen dimensions of 4.9m (shaking direction) $\times$ 3.1m, with a 16 mm-thick deck plate. The primary purpose of this table is to

reproduce earthquake motions. As a result, it has been used for a variety of different earthquake-engineering related research purposes, involving a myriad of different input motions encompassing a wide variety of intensities and durations (e.g. Fischer et al. 2001, He et al. 2009, Widditch et al. 2015).

The table is recessed such that test specimens are readily accessible at floor level (Figure 3a). The table is designed for a payload of up to 350 kN and moment capacity of 420 kN-m (Magenes 1989), although the table is typically used for payloads that require a fraction of this capacity. The table slides horizontally on two stationary shafts driven by a fatigue-rated double-acting hydraulic actuator with a total dynamic stroke of 305 mm, a static capacity of 490 kN, and a dynamic capacity of 405 kN. In the current paper, the x-direction is the drive direction of the table, with displacement u taken positive away from the reaction wall (actuator push direction). Directions y- and z and their displacement components are shown in Figure 3. The bearing system consists of eight 125 mm Garlock self-lubricating cylindrical bearings, four on each side (Figure 3b). The flow rate of the hydraulic system, consisting of up to three high-pressure, high volume pumps, allows a peak sinusoidal velocity of over 1,000 mm/s (Figure 1). The system includes both service and return line accumulators. The actuator can induce peak horizontal accelerations of over 9g on the bare table (Figure 1), and up to 1g on a fully-loaded table. The weight of the table platen, framing, and moving bearings is approximately 42.7 kN.

Initially equipped with a single analog displacement feedback controller, the table was later retrofit with a digital controller (Filiatrault et al. 2000). This digital controller introduced several improvements, including three-variable control (TVC), in which command and feedback of displacement, velocity, and acceleration are accentuated in low, middle, and high frequency domains in order to improve system performance. Other improvements included addition of two signal conditioning techniques: 1) adaptive inverse control (AIC), a procedure that applies a succession of linear compensation filters in order to derive an improved drive signal, and 2) on-line iteration (OLI), a procedure that involves derivation of a drive correction signal by playing the initial drive signal through the system and comparing it to the desired output. The system can therefore be used in one of three configurations: 1) using TVC alone with a single, unmodified drive signal, 2) with AIC to derive a modified drive signal prior to the "real" test, and 3) with OLI and AIC to derive a modified drive signal. However, practical issues have prevented the use of these table control algorithms in recent test programs. Primary among these is friction introduced by the cylindrical bearings. Most modern systems, including a larger shake table at UCSD, use hydrostatic bearings with very low coefficients of friction, on the order of 0.5% (Van Den Eende 2004, Ozcelik 2008). However, Coulomb-type friction developed in self-lubricating bearings such as those on this table is inherently nonlinear. This presents particular problems for the linear AIC algorithm. The usefulness of the OLI procedure is also diminished. Generally, OLI is implemented on the bare table prior to specimen installation. However, since the frictional force is proportional to the payload, the drive modification signal developed for the bare table may not be sufficient to improve overall motion fidelity when the table is subsequently loaded with the test specimen, because frictional feedback also changes. Additional complications may be encountered if the friction is rate- or position-dependent. For these reasons, in the past ten years, the UCSD has been run using an unmodified command signal. The tests presented in this paper involve this type of "unmodified" control.

Motivation for current rebuild

The table rebuild was primarily motivated by declining high-frequency earthquake and white noise motion fidelity. Examples are shown in Figure 4. Time-domain fidelity of low-intensity motions, such as the 0.75% root-mean square (RMS) white noise shown in the figure are particularly poor, with maximum accelerations and RMS values often 200% larger than targets. This presents a particular problem for system identification of "fragile" structures, in which determination of system properties by white noise excitation is necessary, but where large repeated accelerations may result in specimen damage. For earthquake motions, the spectral accelerations exceed the target by more than 30% at frequencies as low as 5 Hz (Figure 4b). This problem has increased significantly in severity over the lifetime of the table, based on previous records of table performance (Filiatrault et al. 2000, Chang 2011). Adjustment of table control parameters, including the feedback and feed-forward parameters of the TVC system, has not improved table performance.

Disassembly and visual inspection of the table was performed in early 2016. This inspection revealed severely worn bearing surfaces and malfunctioning accumulators in the hydraulic service manifold. As a result, a physical rebuild of the table was conducted, consisting of replacement of bearing surfaces, rotation of the stationary shafts 180 degrees about their long axis (presenting the bottom surface as the new bearing surface), and replacement of the malfunctioning accumulators. To quantify the performance improvements from this rebuild, a suite of motions was selected using the criteria in Table 1 and evaluated using the criteria presented previously.

TABLE REBUILD AND PERFORMANCE ASSESSMENT

Motion series

The planned motion series consisted of 14 sinusoidal motions, three white-noise motions, seven earthquake motions (plus three repeated motions run in displacement control), and three triangular motions for a total of 30 tests. The specific characteristics of the motions are summarized in Tables 2-4. Because the UCSD table is a general-purpose table used primarily for earthquake engineering research, earthquake records from a variety of different magnitudes, source mechanisms, and source-recording distances were selected based on the criteria given in Table 1. The white noise, triangular, earthquake, and the lower-frequency sinusoidal motions were run with a payload of approximately 37kN, consisting of the concrete blocks shown in Figure 4. The blocks were rigidly attached to the table with shear and uplift restraints. The blocks were removed from the table for the high-frequency sinusoidal tests, as the tiedown system could not provide the required strength. Analysis of the motions, including a discussion of the performance metrics listed in these tables, is presented in the following sections.

Friction characterization and bearing condition

Upon disassembly of the table, the eight bearing bushings were recovered, cut along the axis of the shaft, and examined. In all cases, the low-friction coating was severely worn over the top half of the cylinder and the backing was pitted and galled (Figure 5a). This wear pattern was expected, given that the bearing is loaded on the top for the majority of its service life, and only loaded on the bottom half when significant overturning is resisted. Measurements of the thickness of the bearing, confirmed severe wear resulting in erosion of the bushing itself (Figure 5b). Based on nominal specifications for this bearing, these measurements suggest that approximately 0.170mm of thickness was removed, including all of the low-friction coating and approximately 0.145mm of the backing (BF Goodrich 2016). Visible wear, but no galling was observed on the shafts. On the top side of the shafts, there was pronounced polishing in the areas

nearest the point of zero table displacement. The underside of the shafts, which were rotated into the upper (bearing) position were visibly damage free.

Triangular motions (Figure 2d) were used to probe the frictional response of the table. The motions had constant-velocity regions between 20 and 200 mm/s and peak displacements between 25 and 150mm. The total applied force from the actuator F_a normalized by the weight of the table plus payload W_{tot} , is shown as a function of displacement for each velocity in Figure 6. The force histories were low-pass filtered at 10Hz. A comparison of Figure 6a and 6b reveal significant differences between the pre- and post-rebuild runs, highlighted with arrows: 1) The peak frictional force associated with direction change is approximately 25% lower in the post-rebuild case, and 2) the applied force has significant nonlinearities within the constant-velocity portions of the test prior to the rebuild. The post-rebuild curve is essentially constant throughout the constant-velocity regime. The role of the frictional force in this behavior may be analyzed by decomposing the total applied force F_a into frictional and inertial components, F_f and F_i :

$$F_a = F_i + F_f \quad \text{Eq. 3}$$

$$F_f = F_a - F_i \quad \text{Eq. 4}$$

$$F_f = F_a - m_{tot}\ddot{u}_t \quad \text{Eq. 5}$$

where $\ddot{u}_t$ is the measured table acceleration in the x-direction (zero during periods of constant velocity) and m_{tot} is the sum of the table and payload mass.

Assuming Coulomb friction, the friction coefficient, μ , is then:

$$\mu = \frac{F_a - m_{tot}\ddot{u}_t}{m_{tot}g} \quad \text{Eq. 6}$$

where g is the acceleration of gravity. The friction coefficient is plotted for several constant-velocity loops as a function of position in Figure 7, showing that rate and position dependence was nearly eliminated. Both before and after the rebuild, the coefficients of static friction varied about 10%, depending on position. The maximum variability of μ_k , however, was reduced from about 50% (-20% to +30% in the normalized space) before the rebuild to about 15% (-5% to +10%) after. The pronounced "dip" in measured friction values at the zero-displacement position prior to the rebuild is related to the observed polishing of the shaft. Most earthquake records run on this table have near-zero mean displacement and many low-amplitude cycles. Repeated use under a collection of such motions should lead to a normal distribution of wear centered at zero-displacement. Prior to the rebuild, μ_k also appeared to be highly velocity dependent. A logical explanation is the advanced and uneven wear of the bearing surfaces, which would allow different parts of the bearings with different frictional characteristics to engage depending on the velocity of the table. The velocity dependence was greatly reduced following the rebuild, dropping to about -1% to +10% for all positions considered. Reduction of peak frictional force and more linear frictional response allows easier table control and improved results with drive signal modification techniques such as AIC and OLI.

COMPARATIVE RESULTS

Sinusoidal motion test series

The parameters and test results from the sinusoidal test series are shown in Table 2. As suggested (Table 1), the theoretical performance of the table as calculated by valving and flow rate limit, was intentionally exceeded in several of the tests. At frequencies at and below 2Hz, the ability of the table to achieve the command peak was generally good, both before and after the rebuild. At frequencies at and above 5 Hz, the ability of the table to achieve the command peak became limited, as expected. Overall, the performance of the table under sinusoidal command was not

modified significantly. This was somewhat expected, as the smooth sinusoidal motions do not require abrupt direction changes that may be sensitive to the frictional characteristics of the table. There were two important exceptions. Namely, in Test 2, the ability of the table to reach the command peak at the last cycle was improved by almost 40%, most likely due to the improved performance of the repaired hydraulic accumulators. Second, Test 6 could not be run to completion prior to the rebuild, due to repeated exceedance of a 9g acceleration interlock. This problem was believed to be related to loss of control due to the nonlinear friction characteristics discussed previously. This test was successfully run to completion after the rebuild.

Table 2: Summary of sinusoidal test results

Test	Table payload (kN)	Frequency (Hz)	Table theoretical performance, u_p^1 (+/- mm)	Duration (s)	Target peak, u_t (+/- mm)	u_t/u_p (%)	C1 Pre and [post] rebuild	C2 Pre and [post] rebuild
1	36.1	0.5	152.4	60	101.6	67	100.1 [100.0]	99.6 [100.1]
2					139.7	92	100.2 [100.0]	63.8 [100.0]
3	36.1	1.0	137.7	60	101.6	74	100.1 [99.5]	99.7 [99.6]
4					139.7	102	99.2 [99.1]	85.1 [84.0]
5	36.1	2.0	70.0	25	50.8	73	99.4 [97.6]	100.1 [95.3]
6					88.9	127	40.5² [92.6]	40.5 [70.3]
7	36.1	5.0	28.0	20	12.7	45	96.8 [91.4]	96.4 [90.8]
8					31.8	114	73.3 [78.8]	⁻² [74.2]
9	0	10.0	14.0	15	7.6	54	87.3 [72.7]	87.0 [72.4]
10					20.3	145	66.9 [65.0]	⁻²
11	0	15.0	9.3	15	7.6	82	81.0 [84.7]	78.3 [78.9]
12					15.2	163	⁻²	Test not run
13	0	20.0	5.7	15	5.1	90	79.0 [75.5]	78.1 [74.9]
14					7.6	133	⁻²	Test not run

Notes:

¹As estimated per Nelson et al (1999).

²Acceleration interlock tripped. Test not run to completion.

White noise test series

The rebuild resulted in very significant improvements to the ability of the table to reproduce white noise drive signals. Achieved RMS (RMS_a) and achieved maximum accelerations, ($\ddot{u}_{max,a}$) as well as the "flatness" of the resulting power spectral density (PSD) P_{xx} were greatly improved. Typical time- and frequency-domain comparisons are presented in Figure 8. PSD was estimated using Welch's method with eight segments over the duration of the signal with a 50% overlap between segments. The peak in the PSD identified as P_{xx1} around 25Hz is the coupled table-foundation mode. The characteristics of this peak were evaluated as foundation resonance presents challenges to high-frequency control of the table (Filiatrault et al. 2000).

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Table 3: Summary of results from white noise tests

Test Number	RMS_t (%g)	$\ddot{u}_{t,max}^1$ (g)	RMS_a (%g) ²	$\ddot{u}_{a,max}$ (g)	RMS_a/RMS_t (%)	$\ddot{u}_{t,max}/\ddot{u}_{a,max}$ (%)	Reduction in P_{xx1} , dB ³
15	0.5	0.020	1.72 [0.689]	0.122 [0.054]	346 [139]	611 [270]	5.7 (26%)
16	2.5	0.100	5.40 [2.42]	0.241 [0.139]	216 [98]	241 [139]	8.6 (36%)
17	5.0	0.200	5.40 [5.25]	0.286 [0.310]	114 [105]	143 [155]	3.3 (20%)

NOTES:

¹ Motions were clipped to have precisely the maximum target accelerations listed.² Pre-rebuild results are in plain text and post-rebuild results are in square brackets³ See definition of P_{xx1} in text

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Quantitative results from all WN tests are summarized in Table 3. These results indicate that the maximum ratio of RMS_a/RMS_t fell from almost 350% to 140%. For the 2.5% and 5% tests, the RMS values following the rebuild were within 5% of the target. There were also significant drops in the ratio of the maximum achieved versus target accelerations, up to a nearly three-fold improvement at the lowest applied RMS. Overall, the results represent a very significant improvement in the ability of the table system to apply the desired power to the specimen without potential damage due to over-driving. The prominence of the foundation mode peak was also reduced by more than 20% in all cases (dB scale). Although this peak value does not have specific physical significance to the current work, the relative prominence of this peak may be taken to indicate the relative severity of table control challenges around this frequency. The smaller prominence of this peak is believed to be associated with the better control and lower peak actuator forces associated with improved friction characteristics, resulting in lower excitation of the foundation mode. For reasons unknown, the frequency associated with this peak also fell approximately 10% in all tests.

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407 Earthquake motion test series

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Significant improvements in the fidelity of earthquake motions were realized from the rebuild. Typical changes in the acceleration history and acceleration response spectra are shown in Figure 9, and summary results are presented in Table 4. Note that the "A" and "B" versions of tests 18, 21, and 24 refer to acceleration- and displacement-controlled versions of the same motion, respectively; all other tests were conducted in acceleration control only. Errors in the achieved maximum acceleration, maximum response spectral misfit ϵ_{max} , and error in the Arias intensity were reduced an average of 16, 31, and 48%, respectively. These three criteria are most related to inertial forces and damage, and are arguably the most important measures for the type of research this table is used for.

The shake table was used for dynamic testing of a heavy, half-scale mechanically stabilized earth bridge immediately after the rebuild. The weight of this specimen was 320kN (91% of the rated capacity of the table). For the scaled 1940 Imperial Valley earthquake motion (El Centro station), which was run in displacement-control mode, the time-synchronous target versus achieved maximum acceleration and displacement ratios were 127% and 100%, respectively. The target and achieved response spectra, as shown in Figure 9c, indicate a good agreement, and the maximum and average response spectral acceleration ratios were 174% and 104%, respectively. Specifically, for this MSE bridge abutment with a fundamental frequency of 11.9 Hz, the target versus achieved response spectral acceleration ratio was 93%. These results

426 are a substantial improvement over shake table performance with heavy specimens prior to the
427 rebuild.

Table 4: Summary of results from earthquake tests

Test Number ¹	Event Name, Station, (Direction)	Target PGA (g)	Target PGD (cm)	Moment magnitude, Distance (km), Fault type ²	Dominant freq. (Hz) ³	$\ddot{u}_{max,a}/\ddot{u}_c$ ⁴ (%)	$u_{max,a}/u_c$ (%)	ε_{max} (%)	ε_{ave} (%)	I_{Aa}/I_{At} (%)
18A	El Centro (1940), Pekkold Version (000°)	0.223	148	6.9	4.5	196	34	172	116	342
				11.5		[168]	[34]	[116]	[98]	[182]
18B				SS		151	100	252	114	225
						[142]	[100]	[106]	[100]	[352]
19	San Fernando (1971), Pacoima Dam (254°)	1.159	118	6.6 1.5 RV	2-10 (broadband)	95 [90]	74 [73]	121 [105]	100 [96]	157 [124]
20	Loma Prieta (1989), Golden Gate Bridge (270°)	0.233	114	6.9 80 RV-OBL	2.0	177 [168]	62 [60]	145 [134]	102 [99]	382 [167]
21A	Loma Prieta (1989), Corralitos (000°)	0.650	107	6.9	3.1	130	62	139	105	170
				3.9		[126]	[62]	[134]	[101]	[120]
21B				RV-OBL		123	98	143	107	196
						[112]	[100]	[135]	[102]	[350]
22	Maule (2010), Universidad de Chile (000°)	0.281	146	8.8 250 RV	0.5, 3.0 (bi-modal)	164 [155]	81 [81]	140 [110]	100 [95]	211 [142]
23	Chi-Chi (1999), TCU071 (090°)	0.567	140	7.6 5.3 RV-OBL	4.0	142 [127]	57 [57]	122 [109]	101 [97]	159 [119]
24A	Edgecombe (1987), Matahina Dam (353°)	0.344	26.7	6.6	2.5,6.0 (bi-modal)	178	84	139	102	344
				16.1		[138]	[82]	[130]	[98]	[185]
24B				N		165	100	118	103	393
						[136]	[100]	[104]	[99]	[363]
Average:						152.1 [136.2]	75.2 [74.9]	149.1 [118.3]	105.0 [98.5]	257.9 [210.4]
Difference of average pre and post rebuild ⁵ :						+15.9%	+0.3%	+30.8%	+6.5%	+47.5%

Notes: ¹ "B" test numbers were run in displacement control, all others were run in acceleration control ² SS - strike-slip, RV - reverse, OBL - oblique, N - normal ³ As determined by peak spectral acceleration ⁴ [] indicates post-rebuild value ⁵ + indicates improvement from rebuild

The individual results for these three criteria show significant and consistent improvements (Figure 10). An important exception is that the ratio of achieved to target Arias intensity, which became poorer in the three-displacement controlled tests (18B, 21B, 24B). This is due to significant high-frequency acceleration noise generated in these tests. However, displacement control is most often used when the specimen being tested require strict control of displacement and are relatively insensitive to acceleration. Therefore, this result is not particularly concerning, and will likely improve upon further adjustment of table control algorithms.

SUMMARY AND CONCLUSIONS

This paper describes the rebuilding and repair of a large, uni-axial servo hydraulic shake table used for earthquake engineering and structural dynamics research. The rebuild involved replacement of bearing surfaces and repair of damaged hydraulic accumulators. A suite of motions, including sinusoidal, triangular, white-noise, and earthquake drive signals, were run before and after the rebuild to assess the change in table performance. Major results and conclusions from the current work include:

- The ability of the table to reproduce sinusoidal motions was essentially unchanged. This is attributed to the fact that performance under these types of smooth motions is dependent primarily on the hydraulic flow capacity of the system and the response time of the hydraulic valves, neither of which was changed as part of the current work.
- The rebuild was successful in reducing the velocity and position dependence of table friction. The variability in the coefficient of kinetic friction was reduced from about -20/+30% to -5/+10%.
- Motion fidelity of white noise drive signals was improved significantly. Measured RMS accelerations improved from almost 250% over the drive signal to less than 40% over the drive signal for 0.5%g RMS nominal white noise, and from over 100% over the drive signal to within 2% of the drive signal for 2.5%g RMS nominal white noise. This improvement is most likely due to improved controllability of the table resulting from more constant frictional resistance.
- The fidelity of earthquake motions was also improved significantly. Errors in the achieved maximum acceleration, maximum response spectral misfit, and error in the Arias intensity were reduced an average of 16, 31, and 48%, respectively.

Ongoing work involves tuning of the table by adjustment of feed-forward and feedback gains, as well as implementation of motions using pre-filtering techniques such as AIC and OLI, which were impractical prior to the rebuild due to the observed nonlinear friction characteristics. It is hoped that the presented methodology may assist others in guiding shake table facility improvements.

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Figure 1: Estimated and actual performance of UCSD uniaxial shake table (after Nelson et. al 1999)

Figure 2: Typical examples of target motions: (a) 100-mm constant-amplitude sinusoidal (displacement control), (b) 2.5%g RMS white noise (acceleration control), (c) earthquake (acceleration control), and (d) ramped triangular (displacement control)

Figure 3: Photographs of (a) top side of shake table with mounted specimen, and (b) bottom side showing drive and bearing system (pictures taken along axis of shaking)

Figure 4: Examples of target versus achieved table performance prior to rebuild: (a) 0.75%g RMS nominal white noise, (b) 5% damped acceleration response spectrum from earthquake motion showing large exceedance of target response spectral quantities

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553 **Figure 5: Bearing condition: coating wear and visible damage correlated with measured**
 554 **bearing thickness**
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556 **Figure 6: Total applied force F_a normalized to total table and payload weight W_{tot} (Test 25)**
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Figure 7: Comparison of coefficient of friction versus displacement for multiple table velocities

Figure 8: Target, pre-rebuild and post-rebuild table performance under 2.5%g RMS white noise: (a) time domain comparison (b) frequency-domain comparison

Figure 9: Typical results from earthquake motions: (a) acceleration time history for Test 18A, (b) 5%-damped acceleration response spectrum for Test 18A, (c) 5%-damped acceleration response spectrum for the Imperial Valley motion of post-rebuild testing of MSE bridge abutment.

Figure 10: Comparison of acceleration-related quantities pre and post-rebuild: ratio of maximum accelerations $\ddot{u}_{max,a}/\ddot{u}_c$, maximum response spectrum error ϵ_{max} , and ratio of achieved and target Arias intensity I_{Aa}/I_{At} (top to bottom)