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Development and performance of single-axis shake table for earthquake simulation

Piyush Sinha and Durgesh C. Rai*

Department of Civil Engineering, Indian Institute of Technology, Kanpur 208 016, India

The exact simulation of earthquake motion has been a serious challenge to researchers and engineers. Shake table testing is being increasingly used in earthquake engineering research centres worldwide, as it is the only available means of nearly truly reproducing the dynamic effects that earthquakes impose on structures. To upgrade the dynamic testing facility at IIT Kanpur, a uniaxial shake table has been installed which is servo-hydraulic-operated and supported on low-friction ball bushing bearings. A relatively simple system has been assembled with care to ensure an adequate replication of input motion by the shake-table system. Subjective comparisons of input signal vs shake-table response, in both time and frequency domain have been utilized to provide a measure of the capabilities of the simulator to reproduce earthquake motions scaled according to similitude laws. This communication discusses briefly various components of the shake table, its assembly and the investigations that were carried out to provide specific insights into its response characteristics.

Keywords: Assembly, earthquakes, performance verification, shake table.

THE shake table is an indispensable testing facility for development of earthquake-resistant techniques. A shaking table is a platform excited with servo-hydraulic actuators to simulate different types of periodic and random motions, such as artificial earthquakes and other dynamic testing signals of interest in the laboratory. This is the only experimental technique for direct simulation of inertia forces, which can be used to simulate different types of motion such as recorded earthquake ground motions, sine sweeps, etc. Shake table test results enhance further the understanding of the behaviour of structures and calibration of various numerical tools used for analysis. This facility can be utilized for verification of earthquake-resistant design of buildings, other structures, mechanical components, devices, etc.

The ground motion is multidirectional in reality and its simulation in the laboratory with multi-axial shake-table system is complex and costly[1]. A single-axis table is the simplest form of earthquake simulator which is not only useful for many investigations when it is only desirable to excite the specimen in one axis, but also simplifies subsequent interpretation of the results. Further, the current trends suggest that structural laboratories worldwide, are finding uniaxial shake tables easy to operate and maintain. For example, at the EUCENTRE, priority was given to platform size and driving power rather than number of directions of shaking in order to perform tests on full-scale or large-scale models of test structures and foundations. Consequently, a large, powerful, uniaxial shake-table platform was chosen instead of a small, six degree-of-freedom table with limited performance capabilities[2]. For similar reasons, a uni-directional shake table was chosen for the large outdoor facility developed under the NEES program at University of California, San Diego[3].

Smaller-sized shake tables are also better suited for small-scale model analysis. In addition, they avoid high operational and development costs, but are versatile enough in the case of dynamic experiments for instructional and research purposes. However, like every system, the small-sized uniaxial shake-table also has certain limitations. In spite of advanced hydraulic actuators and servo control system, and low-friction high-rigidity ball bushing bearings, the shake-table system may possess certain imperfections. The resulting distortions in table

*For correspondence. (e-mail: dcrai@iitk.ac.in)

Table 1. Specifications and characteristic properties of the shake-table system at IIT Kanpur

Global shake-table specifications	
Table size	1.2 m × 1.8 m
Weight of table	8 kN
Maximum payload	40 kN
Maximum displacement	± 75 mm
Maximum velocity	1.5 m/s
Maximum acceleration	~5 g
Frequency range	up to 50 Hz
Actuator specifications	
Make	MTS, USA (Model 244.21 str)
Thrust	50 kN
Peak-to-peak stroke	150 mm
Pump flow	235 lpm (litres per minute)
Accumulators	1 litre on actuator and 7.6 litre on line
Servo valve	190 lpm (three-stage)
Specifications of supports	
Ball bushing bearing pillow	Thomson, USA (model: XPBO-48-OPN)
Linear rail guide	Thomson, USA (model: XSR-48), extra rigid
Coefficient of friction	0.001
Linear rail guide shaft diameter	75 mm
Surface finish	10 R_a microinch
Travel life	50 km
Hardness	60 HRC

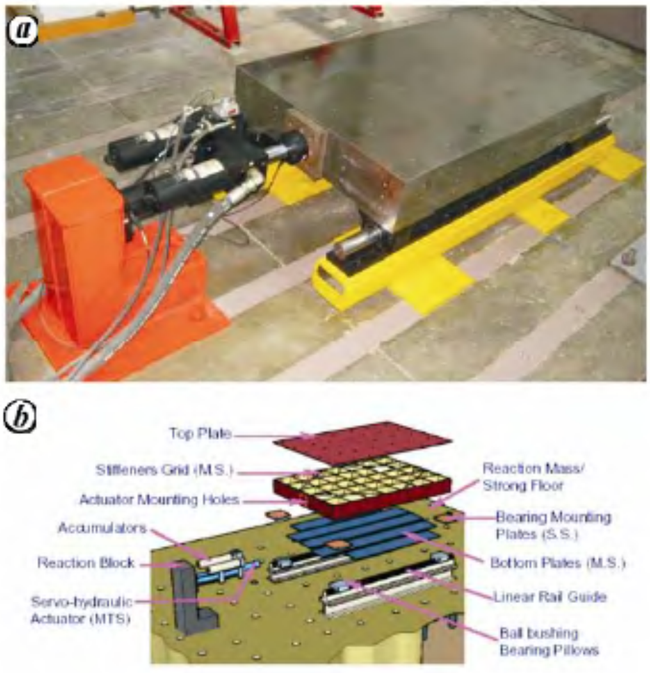

Figure 1. ***a***, A view of the shake-table system at IIT Kanpur. ***b***, Schematic diagram showing its various components.

motion from the desired motion are extremely complex in nature. The distortion of the shake-table motion is due to interference from vibrations of the oil column, foundation, and the test structure mounted on the shake-table platform, etc. These interferences need to be controlled in order to faithfully reproduce the required table motion. However, a single measure of the adequacy of motion reproduction is difficult to define. Comparison of input signal vs shake-table response in time and frequency domain can be utilized to provide some measures of accuracy of simulation. This communication discusses the components of the shake-table system in the Structural Engineering Laboratory, IIT Kanpur and the investigations that were carried out to give specific insights into its response characteristics by utilizing sinusoidal signals and scaled earthquake time histories for amplitude as well as frequency content.

The shake table installed at IIT Kanpur is a uniaxial, servo-hydraulic operated shake table constructed with in-house knowledge and fabrication capability. The shake-table system comprises of the table platform, servo-hydraulic actuator with controls, ball bushing bearing support systems and the reaction mass. The overall characteristics of the system as well as individual components are summarized in Table 1. A view of the installed facility is shown in Figure 1 *a* and various components of the shake-table system and the assembly sequence are shown in Figure 1 *b*.

The table platform has been assembled by welding plates of stainless steel and mild steel. The top plate and the side plates are made of stainless steel, while the inner plates are made of mild steel. Stainless steel has been used because it is hard and can resist corrosion as well as wear and tear quite well. The seating of the bearing pillows has been made out of extra thick plates to avoid punching failure due to large reaction forces. Threaded holes in the top surface of the table have been made for mounting the test structure. Provisions have also been made to extend the table to accommodate larger-sized specimens. Figure

1 *b* shows the arrangement of the longitudinal, transverse and diagonal stiffeners, as well as the support boundary condition assumed for finite element modelling. The diagonal stiffeners have been introduced to spread out stresses resulting from the significant actuator force applied over a smaller area.

One of the challenges in designing the table platform is that it should be stiff so that it does not vibrate into resonance with the drive signal. An eigenvalue analysis was performed using the SAP 2000 (ref. 4). The first and second modes of vibration are shown in Figure 2. The natural frequency of 373 Hz in the first mode of vibration was obtained for the table platform with restrained translations of the supports. Thus, the lower two frequencies of the table are sufficiently higher than the operating frequency range (0–50 Hz) for which the table has been designed.

The servo-hydraulic actuator is the most vital part of the system responsible for causing movement of the table. It was custom-ordered (make: MTS, USA) with specifications to meet the requirements for global performance characteristics of the table using other components of the system already available in the laboratory, such the hydraulic power supply, servo-controller, etc. A full view of the actuator and its dynamic performance in terms of acceleration is shown in Figure 3.

In order to make the system move fast and respond to the rapidly changing ground motion, the actuator was provided with a three-stage servo valve[5]. Motors of servo valves for positioning of the spool have limited power capability, which limits the hydraulic power capacity of single-stage servo valves and in some applications may also lead to stability problems. To overcome this problem of limited hydraulic capacity of single-stage servo valves, a three-stage servo valve is preferred which utilizes three stages of hydraulic amplification to achieve high-capacity flow control, the functioning of which is characterized by an 'inner feedback control loop'. The servo valve command signal is at first processed by the controller through the so-called 'inner control loop' to yield the inner loop conditioned servo valve command signal. This electrical command signal now controls the rotation of the pilot flapper which generates a differential pressure in the pilot stage. The differential pressure thus created controls the position of the pilot spool, which in turn controls the flow of the hydraulic fluid into the third stage and the location of the third-stage spool. Finally, the location of the third-stage spool controls the flow of high-pressure hydraulic fluid into the actuator pressure chamber[6].

The accumulators of large capacity as given in Table 1, are provided with the actuator so that extreme demands of oil flow above the base flow from the hydraulic pump can be accounted for. An accumulator of 1 litre capacity is mounted on the actuator body so that the hydraulic supply circuit can respond more quickly to meet any peak demand of short duration, which is essential for high-velocity pulse motions typically observed in near-field earthquake, such as Kobe, Northridge, etc.

The shake-table platform is supported on ball bush bearing and linear rail guide system, which facilitates the movement of the table in only a horizontal direction and prevents motion in the unwanted degrees of freedom. The low-friction ball bushing bearing used (make: Thomson, USA) utilizes a special 'return ball mechanism' which comprises of a sleeve and a cage which are mounted on a shaft member, as shown in Figure 4. The ball bushing has

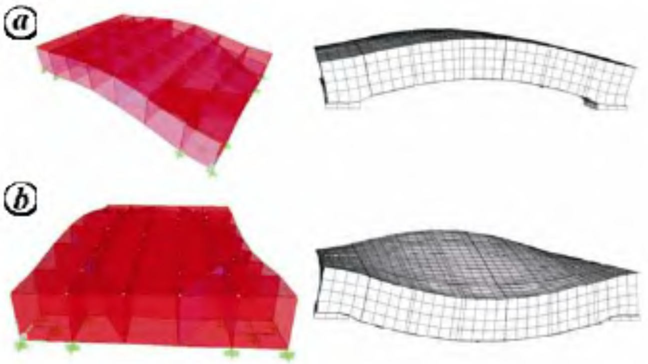

Figure 2. Deflection of the shake table in the first mode, frequency = 373 Hz (***a***) and second mode, frequency = 496 Hz (***b***) of vibration.

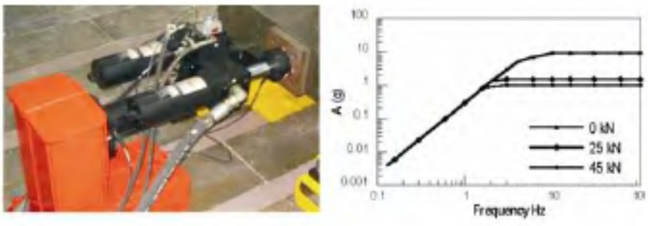

Figure 3. Servo-hydraulic actuator and its performance curve.

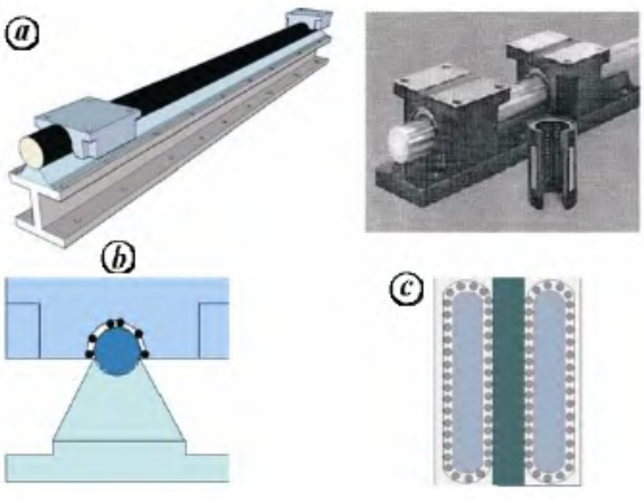

Figure 4. Linear ball bearing support system. (***a***) Guide rails and supports. (***b***) Arrangement of ball bearings. (***c***) Return ball bearing mechanism.

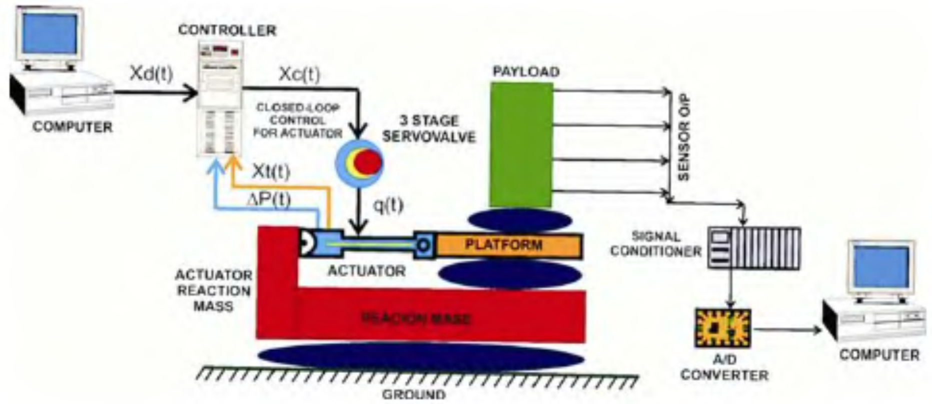

Figure 5. Working of the shake-table system.

a number of closed ball paths and the balls are loaded between the sleeve and the shaft. The sleeve has a number of countersunk longitudinal profiles which define internal raceways for the loaded balls. Though this ball bearing arrangement is effective in reducing kinetic friction significantly, when there is a change in the direction of motion it may cause some distortion to the motion of the shake table. At the point of change in direction, ball bearings go from dynamic condition to static condition and then again to the dynamic condition in small time-span. The high static friction may cause spikes, especially in acceleration response.

Moreover, the extra rigid linear rail used to support the bearing is able to provide significant stability against overturning and torsional moments. Dynamic load capacity of the bearing is 4 kN, while the uplift capacity is 20 kN. The overturning moment causes compression in one ball bush bearing, while the other may experience tension. It is necessary to ensure that uplift on the bearing is below the limiting value, which can be used to develop a limiting relationship between weight of the structure, height of the structure and operational frequency of the shake table. Specifications of the bush ball bearing used in the shake-table system at IIT Kanpur are provided in Table 1.

The key elements in the operation of the shake-table system are depicted schematically in Figure 5, which shows how the command and data signal gets transferred from one component to other. The desired displacement time-history or an equivalent for acceleration time-history is fed into the controller. The input displacement command is then converted by the controller to voltage time-history, which is used to control the spool openings in the servo valve. The spool opening and the pressure difference across it determine the flow of oil, which further determines the force which the actuator applies on the shake table to produce the desired displacement. After implementing the command given by the controller, the error is calculated between the actual and desired motion. The controller has an in-built feedback mechanism which utilizes in correcting the voltage time-history in real time. The correction made is applied to the next input command signal, such that finally the same motion is depicted at the table end. This process is fast, and happens nearly every 0.02 s. Data acquisition forms another major part of the shake-table system. Sensors like peizo-accelerometer, LVDT and SS-1 are generally used to measure the response of the shake table.

The motion of the shake table is obtained through the servo-hydraulic actuator, whose stable control is a complex affair. The performance curve of the uniaxial shake table is essentially the same as that of the actuator for different moving masses as shown in Figure 6, which covers a broad spectrum of frequencies dominated by displacement, velocity and acceleration of vibration. The objective of the control system is to ensure high-fidelity reproduction of earthquake motion without jeopardizing the stability of the system. At low frequencies, the table motion has to be governed by displacement for high fidelity which shows considerable roll-off at high frequencies, if only displacement control is used. Similarly, at high frequencies the acceleration-controlled system will accurately reproduce the motion, whereas velocity-controlled system is suitable for intermediate range of frequencies. Therefore, an accurate control will require the simultaneous feedback of all these three variables appropriately weighted for the frequency content.

The shake-table system at IIT Kanpur is controlled by shake-table displacement, which is the most common control parameter. A closed-loop servo system has been utilized to monitor table displacement response relative to input command generating continuous correction signals for control of table response. A displacement transducer has been used as a feedback measuring device. Displacement signals are necessary for input command to the table and integration of the acceleration time-history input is achieved through 'Wavegen' program for FlexTest GT controller (make: MTS, USA) available in the laboratory for controlling several of its servo-hydraulic actuators. Software like Station Manager, Station Builder provided

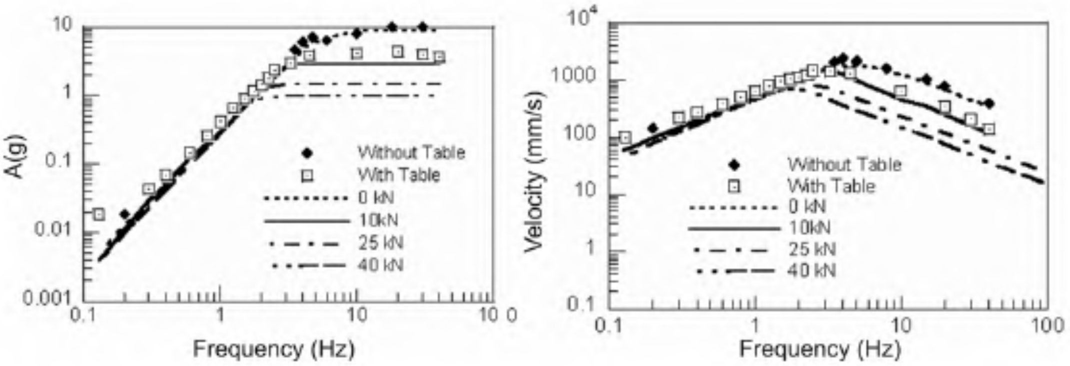

Figure 6. Performance curve of the shake table at IIT Kanpur.

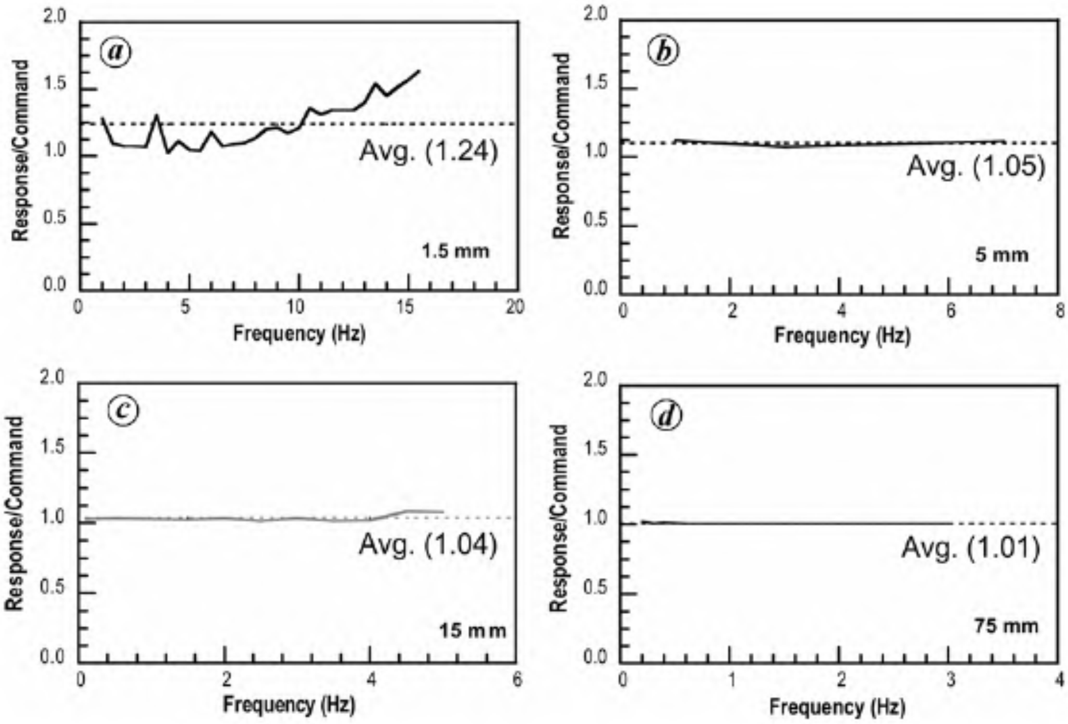

Figure 7. Shake-table amplitude envelopes for sine wave motion.

by Multi Purpose Test Ware (MTS) were used for managing the control system.

The primary focus of such algorithms is on controlling the displacement, while the prime focus of earthquake simulation is on mimicking acceleration time-history as closely as possible. Though acceleration is theoretically related to displacement, it is difficult to get the same quality of reproducibility for acceleration time-history, as one can have for displacement time-history of table motion[1]. It is primarily due to high-frequency noise from support bearings as well as error introduced in taking the second derivative of the displacement.

The shake-table motion and corresponding distortions of that motion are of an extremely complex nature and, therefore, a single measure of the adequacy of ground motion reproduction is difficult to define. Subjective comparisons of input signal vs shake-table response, both in time and frequency domain can be utilized. An investigation into table performance generally utilizes periodic and random motion. Each form of the motion would provide specific insights into the shake-table response characteristics. To identify the performance limitations and table response characteristics, runs of the shake table for sine wave and real earthquake ground motions scaled in amplitude and frequency were performed.

Single-frequency sine wave motion provides considerable amount of information about the behaviour of the shake-table system. Adequacy of performance is measured by comparing amplitudes of input and response at various frequencies of sine wave motion, which yields an amplitude spectra envelope of the shake-table response[7]. This comparison helps in defining the accuracy of the shake table control settings and shake-table frequency performance limitations. Figure 7 shows the amplitude

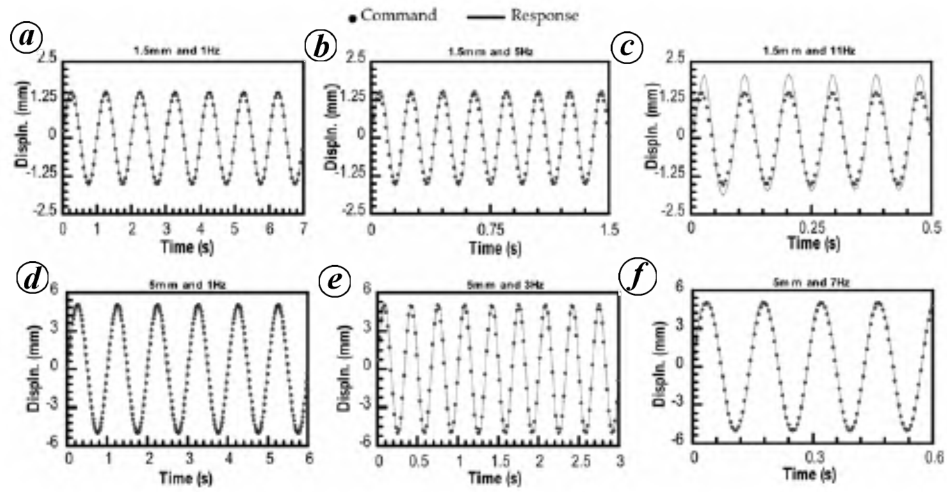

Figure 8. Comparison of displacement time-histories for sine wave motion.

spectrum for four different displacement amplitudes of sine wave motions, namely 1.5, 5, 15 and 75 mm. It can be seen that the difference between the desired and the table displacement motions is significant for small-amplitude motion nearly at all frequencies of operation, from 1 to 16 Hz. For high-amplitude sinusoidal signals, this difference is negligible at all frequencies. Further, the table displacements were observed to be always greater than the required displacement at all frequencies and at all displacement levels.

Quality of simulation of displacement and acceleration differs with the change in frequency and amplitude. As shown in Figure 8 for low amplitude of displacement, namely 1.5 mm sinusoidal motion, the amplitude distortion is observed at higher frequencies, whereas such distortion is minimal at lower frequencies. Similar trend was observed for higher amplitude of displacement, namely 5 mm sinusoidal motion in the frequency range 1–7 Hz. Other than amplitude, the general characteristics of the required and the table response compare reasonably well.

In the corresponding acceleration simulation, for 5 mm amplitude sinusoidal motion, the distortion has been observed in the amplitude as well as in waveform due to the presence of additional frequencies, as shown in Figure 9. This distortion due to high-frequency noise in the acceleration response can come from the actuator, table, supports, reaction block assembly, servo response coupling, or a combination of these. Tests conducted with and without the shake table showed that larger spikes were observed with the shake table, indicating support bearings as a significant source of these high-frequency spikes (Figure 10). Furthermore, Figure 11 shows acceleration and displacement response of the actuator under constant-velocity slow motion (triangular waveform), where acceleration is almost zero, except at the turning point. However, acceleration levels associated with these spikes are small compared to the overall response acceleration.

Errors are significant near the peaks when the table changes its direction of motion and comes to rest momentarily. Numerous runs with varying amplitude and frequencies show that there is a good match in the displacement time-histories at low frequencies. However, as the frequency increases, a poorer match between the command displacement time-history and shake-table displacement response was observed.

The shake table is to be primarily used for simulation of earthquake ground motions which are specific to a particular earthquake event and location and are characterized with random variation in the amplitude, frequency, duration, sequence, etc. To assess the performance of the facility, three ground motions were employed from three different earthquakes, namely Chamoli (1999), Kobe (1995) and Taft (1952). Chamoli and Kobe earthquakes are near-field ground motions, while Taft is a far-field motion. Unlike Chamoli and Kobe, the frequency content of the Taft motion is rich in high frequencies as well, as can be seen from the normalized FFT plots in Figure 12. The displacement and acceleration response of the shake table were measured using LVDT and FBA respectively. The acceleration time-histories were filtered with a band-pass filter of 0–25 Hz, as frequencies above 25 Hz are not significant enough to affect the structural response.

For ground-motion simulation, the displacement time-history was observed to have an excellent match without any phase lag or peak-to-peak mismatch for larger displacement amplitudes associated with the typical real ground acceleration used for simulation. Further, acceleration time-histories also match well and both peaks and phases have been reasonably reproduced considering the simplicity of displacement as the only control variable. A closer inspection reveals that the acceleration time-histories of the Kobe and Chamoli earthquakes have a better match than that of the Taft earthquake. This may be due to presence of higher frequencies in the Taft

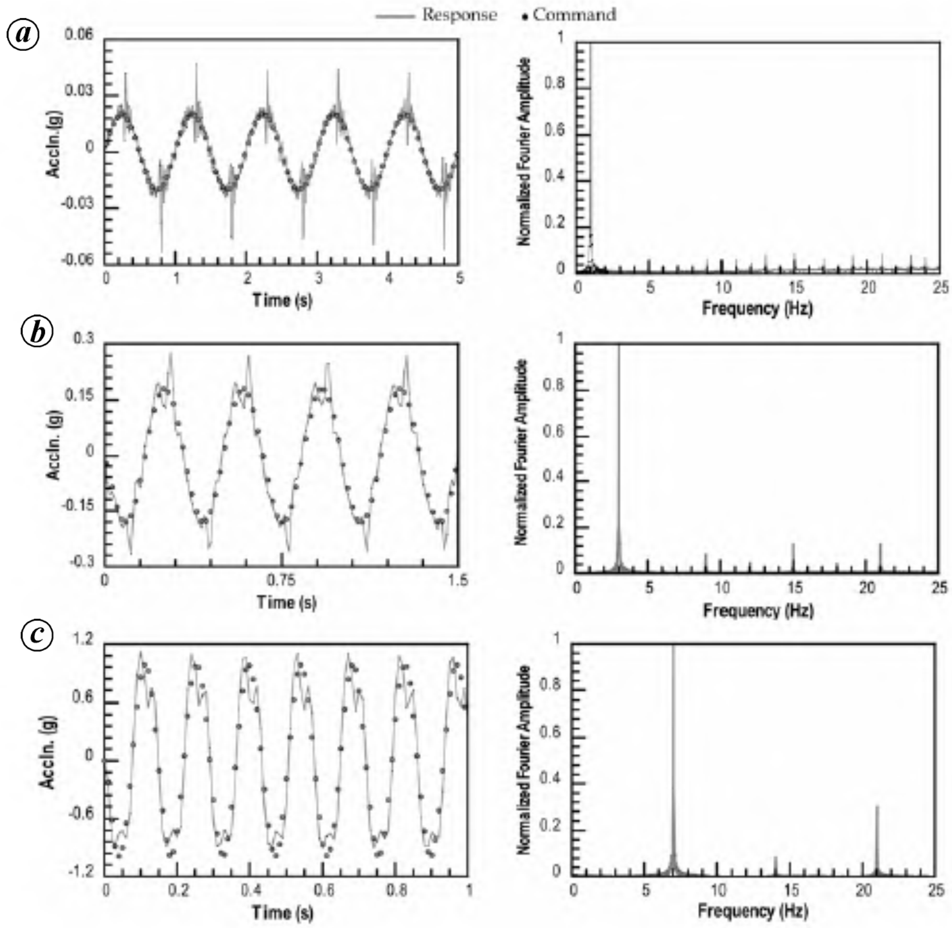

Figure 9. Comparison of acceleration time-histories. (***a***) 5 mm and 1 Hz sinusoidal signal; (***b***) 5 mm and 3 Hz sinusoidal signal; (***c***) 5 mm and 7 Hz sinusoidal signal.

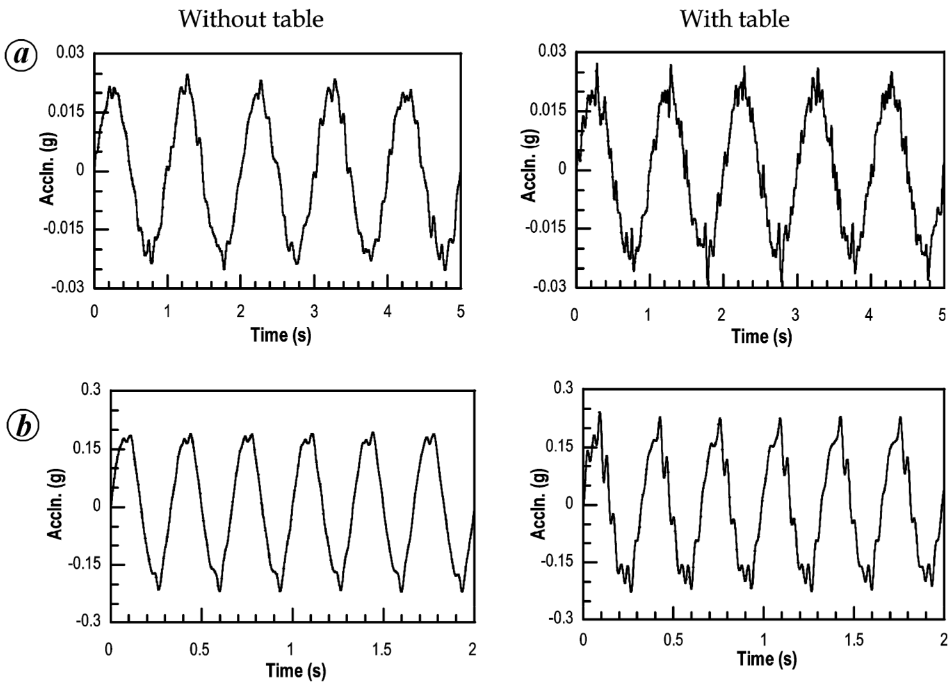

Figure 10. Comparison of acceleration time-histories without and with table. (***a***) 5 mm and 1 Hz sinusoidal signal; (***b***) 5 mm and 3 Hz sinusoidal signal.

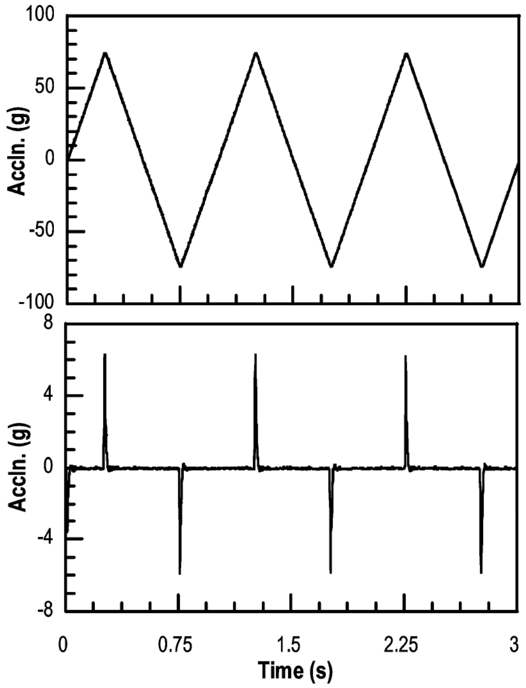

Figure 11. Response of triangular waveform.

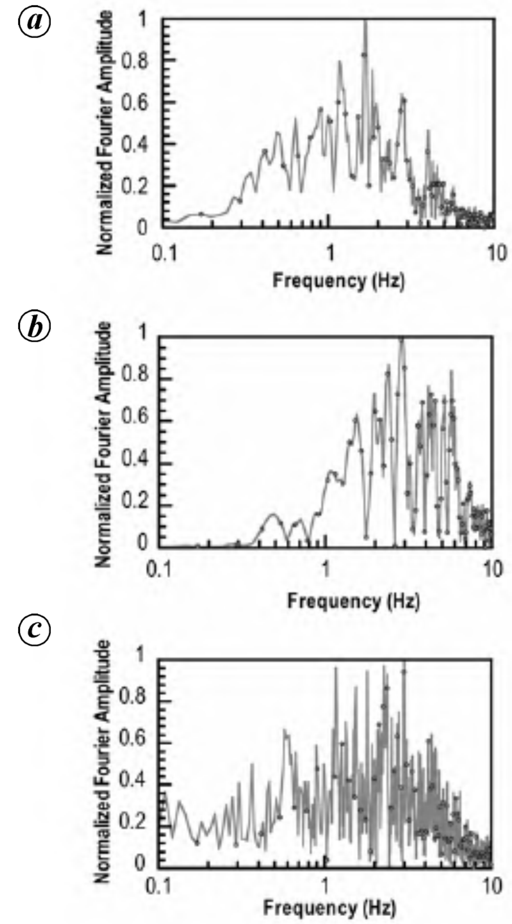

Figure 12. FFT plot of the earthquake ground motions. ***a***, Chamoli earthquake; ***b***, Kobe earthquake and ***c***, Taft earthquake.

motion, for which greater mismatch in acceleration time-history was observed.

As mentioned earlier, the shake-table tests are usually performed on reduced-scaled models. The dynamic similitude laws require that the frequency is scaled by square root of the scale factor. In other words, the time-histories have to be compressed in time by this factor[7]. As shown in Figure 13 *d*, the Taft motion is scaled in frequency by compressing it on time axis by a factor equal to 4.9, which corresponds to length scale factor of 12 and acceleration scale ratio of 2. The scaled model of a two-storey braced frame is shown in Figure 14, which was subjected to several runs of scaled Taft motions with peak ground acceleration ranging from 0.1 to 1.7 *g*. Even for the compressed time-history, the shake table was able to reproduce the motion satisfactorily.

In addition to time-history matching, a good match for the response spectra is also desirable. This is especially important as loads due to earthquake motion are often specified in the form of the response spectrum. The response spectrum is as variation of peak dynamic response of a single degree-of-freedom system for different values of its natural period (or frequency) for a given motion and damping. The response spectra of Chamoli, Kobe and Taft motions are compared in Figure 15, wherein the observed Table Response Spectrum (TRS) shows good match with the Required Response Spectrum (RRS) in the velocity and displacement-controlled region, while some departure is observed in the acceleration-controlled region. Average per cent departure of TRS from RRS was found to be about 10. Considering the simplicity of the one-variable control and simple support system of the shake table, this closeness of spectra is satisfying. Most importantly, even where there is departure, at no point is TRS below RRS. The results also lead us to conclude that though acceleration time-histories are not as close fit because of undesired high-frequency noise and some phase distortion, they appear not to disturb the overall energy input implied by the motion. However, the controls can be further tuned either using iterative or adaptable control algorithms, so that errors can be minimized further.

A uniaxial shake-table system has been developed and installed at IIT Kanpur, which uses servo-hydraulic system and controls usually available in a good structural engineering laboratory. This communication discusses the assembly and fabrication of the rigid shake-table platform for mounting the specimen and to support it on low-friction ball bushing bearing to restrain its motion in all but one direction. This low cost solution for table platform, with support and use of simple control which uses only displacement as control parameter, is shown to reproduce earthquake-type motion rather accurately and is suitable for not only instruction, but also for research problems. The other specific conclusions are as follows:

1. The construction and geometry of the shake-table platform make it significantly rigid, as its fundamental

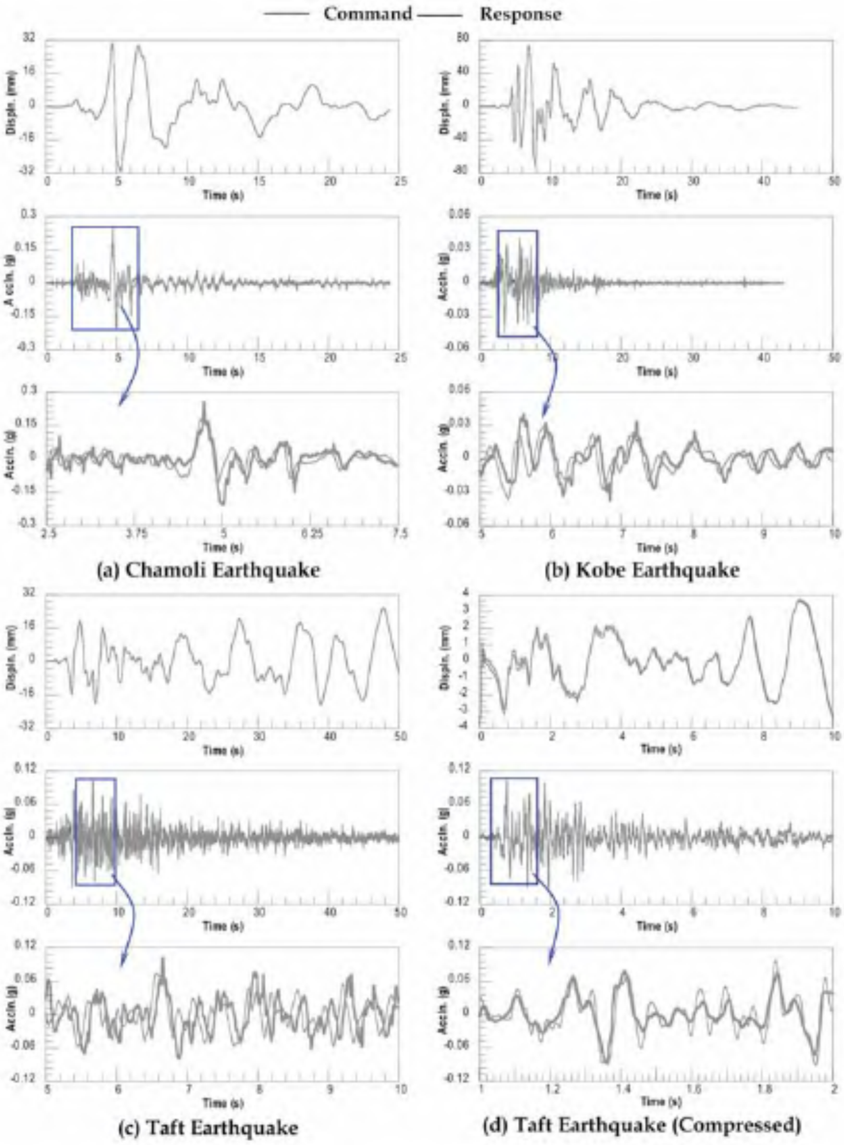

Figure 13. Comparison of command and response displacement and acceleration time-histories.

Figure 14. 1 : 12 scaled model of a braced frame for which dynamic similitude rules require real ground motions to be compressed in time.

frequency of vibration is well above the frequency range in which the table has been designed to operate.

2. The tests using harmonic signals show that the displacement time-histories of the command and table response matched nearly perfectly for low frequencies. However, some error was noticed for high frequencies.

3. Significant distortion was noticed in the acceleration time-histories, especially at the peaks, which is primarily due to relatively low-cost support bearings. Near the peaks, as there is change over from dynamic to static conditions in a short span for higher frequencies, a jerky motion causes spikes in the acceleration response of the shake table. Further, the controls are also poor for high-frequency vibrations and it cannot weight the displacement, velocity and acceleration control parameters in different operating frequency regions for better control.

4. A good match was observed for acceleration time-histories of earthquakes like Taft, Chamoli and Kobe and

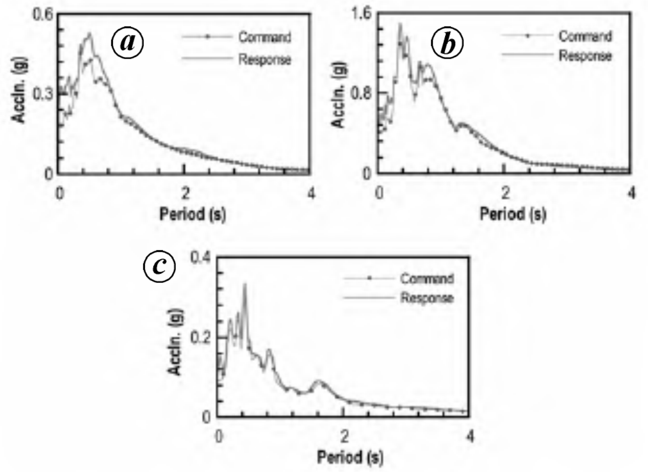

Figure 15. Response spectra comparison for (*a*) Chamoli, (*b*) Kobe, and (*c*) Taft earthquake ground motions.

for time-compressed motions according to similitude laws for reduced-scale test models. The comparison of response spectra was satisfactory and the departure was merely 10% on an average. Larger departure was noticed for high frequencies, which is consistent with the results obtained for high-frequency harmonic signals.

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Evaluation of transplanted and ratoon crop for double cropping of rice (*Oryza sativa* L.) under organic input management in mid altitude sub-tropical Meghalaya

G. C. Munda*, Anup Das and D. P. Patel

Division of Agronomy, ICAR Research Complex for NEH Region, Umiam 793 103, India

In mid-altitude of the North Eastern Hill (NEH) region of India, a second crop of rice following the harvest of main kharif (July to mid-November) rice is not possible due to early onset of low temperature (<15°C) from November onwards, which causes spikelet sterility in rice. A field experiment on double cropping of rice was conducted under mid-altitude subtropical wetland valley ecosystem of Meghalaya from 2004–05 to 2005–06 at Umiam (950 m amsl), Meghalaya. Out of the six varieties tested, IR-64 (43.2 q/ha), Aerobic rice IR 72176 (42.1 q/ha) and Krishna Hamsha (40.5 q/ha) performed well during pre-kharif season. Double cropping (main + ratoon) of IR-64 produced 75.4 q/ha of grain yield compared to 40.5 q/ha under improved monocropping of rice variety Sahsarang-1. Ratooning could save time (nursery and field preparation, transplanting, etc.), resources (labour, seeds, etc.) and gave higher productivity. The ratooning ability of Sahsarang-1 (33.0 q/ha) and IR-64 (32.2 q/ha) was found to be highly promising. The sequence IR-64 in pre-kharif followed by its ratoon also gave 86 and 202% higher productivity over improved (40.5 q/ha) and local practice (25.0 q/ha) of monocropping respectively. It was found equally good with the best combination of IR-64 in pre-kharif followed by late kharif transplanted crop of Vivek Dhan-82 (system productivity of 80.4 q grain/ha). Duration of main crop varied from 135 to 158 days, whereas in case of ratoon it varied from 70 to 95 days. Therefore, it was concluded that ratooning has ample opportunity, especially in the NER region of India, where climatic conditions and non-availability of resources restrict the double cropping of rice by the farmers. The practice of double cropping would not only add to the national food basket, but would also increase the farmers' income and generate more employment in the region.

Keywords: Mid-altitude, mono and double cropping, organic production, ratooning, rice, subtropical wetlands.

CROPPING systems in the North Eastern Region (NER) are predominantly rice-based with exception in Sikkim, where maize is the main food crop. Rice is the major staple food crop of the region occupying 3.5 m ha, which

*For correspondence. (e-mail: mundagc@yahoo.com)