Copyright © 1996 Elsevier Science Ltd
Paper No. 2044. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

COMPARATIVE ASSESSMENT OF SHAKING TABLES

P.G. CARYDIS, H.P. MOUZAKIS & E.A. VOUGIOUKAS
Laboratory for Earthquake Engineering, National Technical University of Athens, Greece

A.J. CREWE & C.A. TAYLOR
Earthquake Engineering Research Centre, University of Bristol, Bristol BS8 1TR, UK

G. FRANCHIONI
Structural Testing and Survey Department, ISMES, Bergamo, Italy

R. BAIRRAO
Centre for Special Studies in Earthquake Engineering, LNEC, Lisbon, Portugal

ABSTRACT

The results of an extensive comparative study of four large capacity shaking tables are described. One, three degree-of-freedom and three six degree-of-freedom shaking tables have been studied and their dynamic characteristics identified. The purpose and methodology of the tests are explained and the main conclusions are discussed. A very good match of the required acceleration, velocity and displacement time histories was achieved for both rigid and flexible payloads once sufficiently complex control algorithms were used. The importance of defining the critical criteria for any time history matching and the requirement for careful adjustment of the shaking table control hardware is also shown.

KEYWORDS:

Shaking Table, Calibration, Standardisation, Digital Control, Analogue Control.

INTRODUCTION

Earthquake shaking tables are devices for shaking large structural models and components with a wide range of simulated ground motions, including reproductions of recorded earthquakes. They are essential tools in earthquake engineering research since they allow the effects of true inertial forces on the test specimens to be studied. Several shaking tables throughout Europe are being used to research the dynamic effects of earthquake on structures. Each of these tables has its own performance characteristics and these are generally well known by the operators of the individual tables. However, as every experimentalist knows, different pieces of equipment designed to carry out the same experiment cannot be guaranteed to yield the same results. This is particularly true for complex equipment such as shaking tables. Therefore, if direct comparisons of results from different shaking tables are to be meaningful, it is essential that the potential effects of the performance characteristics of each table are well understood. Prior to the project, no detailed comparative study of two or more shaking tables had been done. A principle aim of the comparative assessment, therefore, was to explore methodologies for such a comparison with a view to establishing standardised benchmark tests that could be used to validate shaking table usage. The four shaking tables that formed the European Consortium of Shaking Tables (ECOEST) were well suited to such a study as they have a range payload capacities and very different hardware and software control systems and performance characteristics. The three shaking tables at the National Technical University of Athens, Bristol University and at ISMES, Bergamo, Italy are six degree of freedom tables whilst the shaking table at LNEC, Lisbon, Portugal is a large three degree of freedom table. The studies looked at the software used at each site, the management and test procedures followed, at the performance characteristics of the four shaking tables and at the ability of each control system to drive the platform so as to reproduce a predefined motion under different load conditions.

SHAKING TABLES STUDIED

Three of the four shaking tables studied have full, six degree of freedom control (i.e. two horizontal and the vertical translational degrees of freedom, and the associated pitch, roll and yaw rotational degrees of freedom). They have capacities ranging between 15t and 50t. The Bristol table has a 3m by 3m platform, while the Athens and ISMES tables are 4m by 4m. These three tables are each driven by 8 servo-hydraulic actuators, but the actuator capacities and geometrical arrangements differ. The fourth table studied at LNEC is mechanically restrained (Duarte *et al.* 1994) in the three rotational degrees of freedom and can move only in the three translational degrees of freedom. This table is driven by 4 servo-hydraulic actuators, the table platform is 5m by 5m and has a capacity of 60t.

The tables were designed and built by different companies and have significantly different analogue hardware and computer control systems. The Athens and ISMES tables were built by MTS and have sophisticated analogue hardware control systems which allow fine adjustment of acceleration, velocity and displacement feedback to smooth out the system frequency response. In Athens a PDP11/34 mini-computer controls the driving signals and acquires the data from the table and test specimen. In ISMES software written by Concurrent Software running on a UNIX workstation generates the driving signals and acquires the test data.

The Bristol table was built by Servo Consultants Ltd (formerly Silveridge Technology Ltd). It has a much simpler analogue control system, with fewer options to control the feedback loops. The main control is done through a non-real time, digital adaptive control algorithm implemented on a standard 486 class personal computer. A second 486 PC collects data from the test specimen.

The table control at LNEC was built by Instron and has sophisticated digital control hardware which eliminates the electrical noise that can be a problem in analogue control systems. The drive signals are generated by the Instron control software which also controls the acquisition of any test data.

SCOPE OF THE STANDARDISATION PROGRAMME

The specific aims of the standardisation programme can be summarised as :

I. To produce a detailed characterisation, to a common specification, of the dynamics performance of the four shaking tables.

II. To identify strengths and weaknesses and possible enhancements for all the tables.

III. To compare, validate and verify existing signal generation, control and data processing software at each site, based on a common specification.

IV. To produce a standard set of calibration tests and procedures for
   A. Routine pre-test calibration.
   B. Regular system performance review.

V. To develop an adaptable database system and appropriate access software, common to all sites, to facilitate data exchange.

VI. To establish arrangements for sharing skills and experiences with the aim of developing efficient, common operating procedures.

To achieve these aims the standardisation programme was split into three sections. The software review compared and validated the control, acquisition and data processing software at all the sites. The software review also compared and contrasted the control techniques embodied in the software. The operations review compared the management, maintenance and experiment design procedures. The primary objective here was to bring together the best practices from each site with the aim of enhancing the quality of research at all four sites. Finally, the performance review explored and compared the performances of the four shaking tables. The main aim of the performance test was to characterise the performance of each table in a common way and in doing so set the basis of a standardised procedure for shaking table calibration.

SOFTWARE REVIEW

Central to the validation of the performance of the shaking tables was the validation of the data acquisition and data processing software. Unless such software is demonstrated to be correct, comparisons of table performance would be meaningless. A major part of the software review, therefore, concentrated on this problem and as part of the software review the data processing and acquisition software at each site was validated against a previously validated software package known to be correct. In this way it was verified that the software at the four sites was consistent and produced the correct results.

Comparison of the software used to control each of the shaking tables was complicated by the number of different and incompatible techniques employed in each system. The four shaking tables studied each incorporate two distinct control systems that are used to control table movement. The hardware control system controls the individual actuators in the shaking table and incorporates the feedback loops that allow the system to be 'tuned' to minimise specimen - table interaction. The hardware control system provides the basic table control and generates the actual actuator signals from the drive signals. When tests require movement in fewer axes than there are degrees of freedom in the table system, this restriction on table movement is generally provided for within the control hardware. However, tests have shown that current hardware control systems cannot always restrict motion in the unused axes to acceptable limits. In this case the control software must be used to compensate for any inadequacies in the hardware.

The control software is used to compensate for any inaccuracy in the 'tuning' of the hardware control and provides much more accurate control over the table motion. The software in use at the four sites does this by recording the table motion achieved during a seismic test and then correcting the drive signal so that the table motion for the next test will be closer to the required motion. In Bristol, the time histories are segmented into overlapping blocks and converted to the frequency domain using the Fast Fourier Transform (FFT). The inverse transfer function for each block is computed and an updated drive signal for each block created using the inverse FFT. This approach leads to a time dependent transfer function that can deal with non-linearities in the shaking table system itself, but at the expense of the frequency resolution of the transfer function.

The time history matching methods used in Athens, ISMES and LNEC work on the same principle but are each different in detail. They measure the system transfer function at low to moderate amplitudes for the particular test configuration and pre-compensate the driving signals using the inverse transfer function. Broad band random noise is applied to the shaking table for several minutes, preferably with the specimen mounted, and an averaged inverse transfer function is computed. This averaged transfer function is used to generate an initial estimate of the required drive signal. Once the actual table motion has been recorded an inverse transfer function for the error between the acquired and required time history is computed and an updated drive signal created.

Although the details of the algorithms used at each site vary quite considerably (Crewe *et al*, 1996) each package was able to control the table motion very effectively under most conditions. Where it was possible to compare directly different algorithms at one site, those that employed more complex methods for modifying the drive signal to reproduce the required table motion generally performed better. However, the more complex algorithms had a tendency to become unstable if the 'matching' process was continued for too many iterations. The use of the same, validated, data processing and plotting package throughout the series of tests at the four sites greatly helped with the comparison of the results from all the tables and ensured that any conclusions drawn were based on data with a common starting point.

OPERATIONS REVIEW

Effective operational procedures covering maintenance and control of the shaking tables and test planning are vital for successful experiments. The principle aim of this review was to compare the practices at all sites and draw together the best aspects, thus enhancing the quality of experimental work at all four sites.

Because the four table groups have very different structures direct comparison of their specific requirements was difficult. However, over the years each site has developed many detailed procedures to ensure the quality of their research and the exchange of personnel between the four sites during the tests enabled the transfer of a great deal of experience between all the research groups.

PERFORMANCE REVIEW

The aim of the performance review was to compare the actual performances of the four shaking tables. These tests ultimately aimed to prove that identical tests could be performed on each of the shaking tables and to create a standardised procedure for shaking table calibration.

The test sequence performed on each table was designed firstly to characterise and understand the performance of each table in its own right. Then, the ability of each table to reproduce accurately several earthquake motions was tested. In the first phase, frequency response tests were used to characterise the dynamic characteristics of each table under a variety of load conditions. The frequency response tests also examined the extent to which the hardware controllers could compensate for specimen - table interaction. The second phase of testing looked at how well each software control system could drive the platform so as to reproduce a predefined motion. Of central importance to this is the interaction of the shaking table with the test specimen. This led to the development of an adaptable test specimen that could be configured to have a variety of natural frequencies, payloads and centres of gravity.

Design of the Test Specimen

To study the shaking tables under realistic conditions, each table was tested under various payloads. These were the bare table, 4t and 8t rigid payloads, and 4t and 8t flexible payloads with an natural frequency of 10 Hz and 6 Hz respectively. The design of a sufficiently adaptable specimen proved to be quite difficult and is described in detail by Carydis *et al.* (1994). Two flexible test specimens which had an adjustable mass and a variable natural frequency were designed and built in Bristol. The comprised of four 250x250mm universal columns supporting 1m square, 1 tonne steel blocks. Up to eight 1 tonne blocks could be mounted on a single frame at centres of gravity ranging from 0.5m to 3.5m above the base. The foundation consisted of another 1 tonne steel block that was rigidly bolted to the shaking table platform. The specimens were shipped between the four laboratories as required of the table testing.

Selection of the Input Motions

Two real earthquake records were selected as the basis for the prescribed table motions. One was the single component El Centro earthquake, while the other was a three-component record measured during the Kalamata earthquake. Both records were filtered to remove frequency components below 1 Hz and further

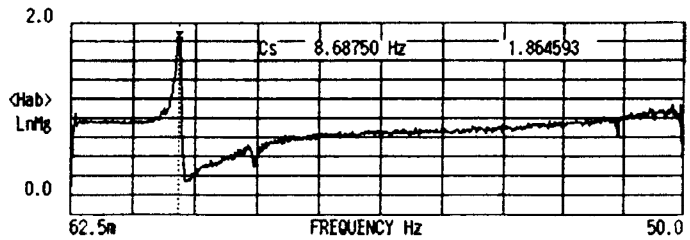

Fig 1a. Typical Frequency Response Function recorded with flexible specimen on table.

processed to give consistent sets of acceleration, velocity and displacement time histories. The El Centro record has a duration of about 40s and significant frequency content in the range 1 Hz to 12 Hz. The Kalamata records have a strong motion duration of about 6s and a frequency content between 1 Hz and 8 Hz.

Test Methodology

Initially a comprehensive set of tests was performed on the tables in Athens and Bristol. During these tests the most critical items were defined and a reduced test programme was developed which was subsequently used on the ISMES and LNEC tables. This reduced programme is now being used as a procedure for shaking table calibration and for testing table performance if any major change is made to the table hardware or software.

Frequency Response Function Tests. The frequency response functions of the four tables were measured in all six degrees of freedom for bare table, 4t and 8t rigid payloads, and 4t and 8t flexible payloads with natural frequencies of about 10 Hz and 6 Hz respectively. The frequency response between the input driving signal and the table acceleration was computed using an Advantest modal analyser. Broad band 0.1g random noise (up to 100 Hz) was played through each degree of freedom in turn. The frequency response was measured in the direction of excitation and in all other degrees of freedom to check for cross-coupling effects.

The frequency response tests showed the importance of following a methodical and efficient hardware tuning routine. Slight variations in the individual actuator servo-controller gains could lead to significant and sometimes severe resonances and instability. The 'tuning' of the shaking tables was also very dependant on actual payload on the shaking table. If the tables were 'tuned' for a rigid payload of 4t and then the payload was increased to 8t the frequency response function often changed dramatically. This emphasised the need, in a real test, to 'tune' the hardware with the test specimen on the table. However, this 'tuning' must then take place at low vibration levels to avoid damaging the specimen before the real tests commenced.

For each table careful adjustment of the feedback parameters in the hardware controller produced acceptably flat frequency response for rigid payloads. However, the frequency response curves for the flexible payloads showed peak and notch effects (Fig. 1). The more sophisticated Athens and ISMES hardware was better able to compensate for these effects but none of the tables could be adjusted to achieve a flat frequency response curve for all of the load cases tested.

Once the table hardware had been adjusted at each load level to give the best possible system transfer function the time history reproduction tests were performed.

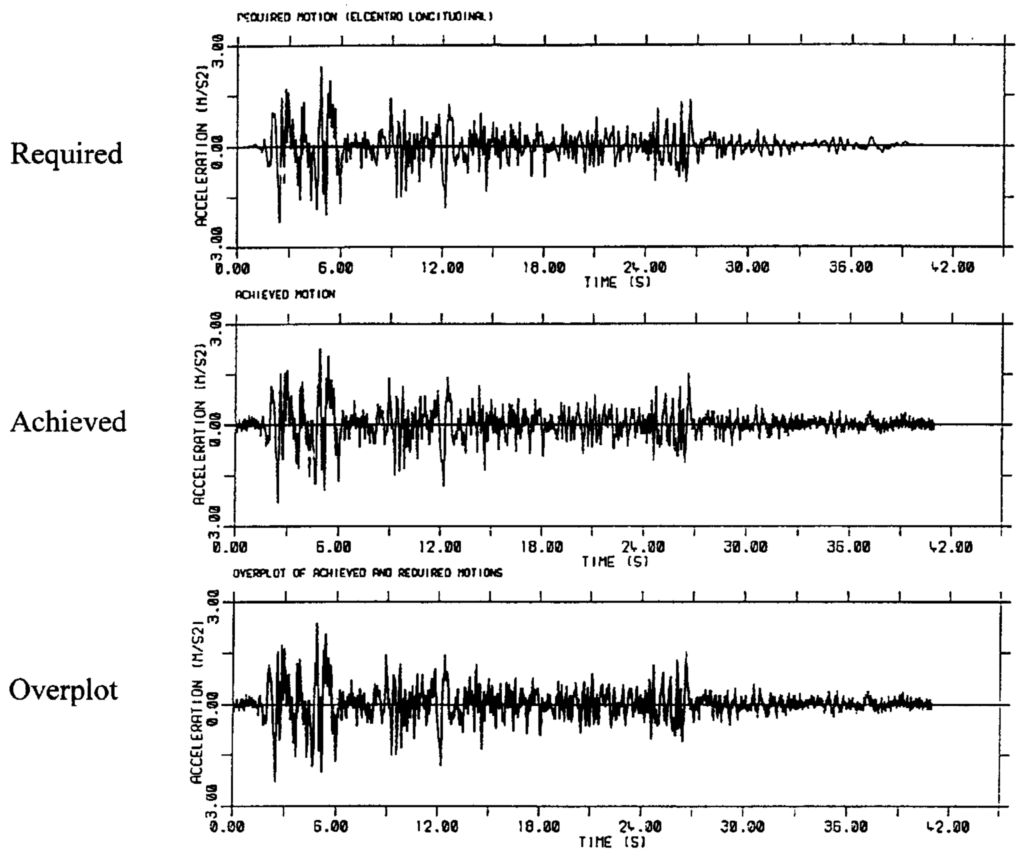

Fig. 2a. Comparison of acquired and achieved acceleration histories for an acceleration match

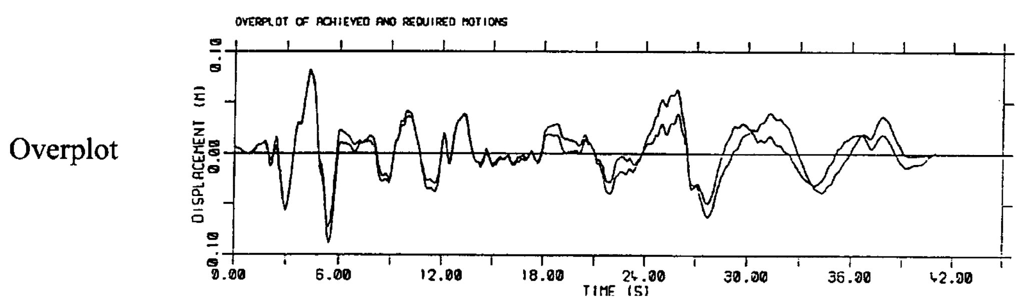

Fig. 2a. Comparison of acquired and achieved displacement histories for an acceleration match

Time History Reproduction Tests. Two earthquake records were used to test the software control systems. The El Centro record was used to check the similarity of each of the translational axes. The Kalamata earthquake record was then used to check the performance of the tables with a tri-axial input. Both sets of records were also applied at various peak accelerations to check the linearity of the overall shaking table gains.

It was found that each of the four tables could reproduce the required motions with the table bare or with rigid payloads. For each input record, either a good acceleration match or a good displacement match could be achieved, but usually not both at the same time. A good response spectrum match was also achieved when the acceleration time history was accurately reproduced. In the case of the flexible specimen, the tuning and the drive signal compensation had to be more rigorous if the effects of table-specimen interaction were to be minimised to acceptable levels. Some typical acceleration and displacement time histories recorded during the El Centro time history reproduction tests are shown in Fig. 2. These plots show how effectively the matching methodology reproduced the El Centro earthquake motion with a rigid payload of 8t on the table. In this case the software was trying to achieve the best possible match between the required and achieved acceleration records. These results show the accuracy that can be achieved after two iterations of drive correction. The displacements shown alongside were those recorded at the same time as the accelerations and show a low frequency error. If a specific test requires that the control of the table displacements is more accurate than this then the software should be set-up to get the best match between the required and achieved displacement records. However, in this case it is likely that some of the high frequency detail in the acceleration signals will be lost as shown in Fig. 3.

Overplot

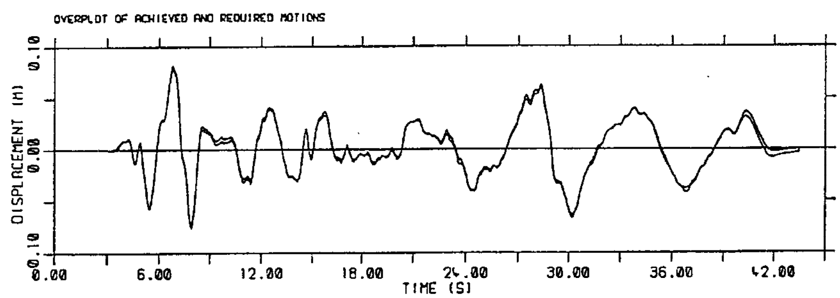

Fig. 3a. Comparison of acquired and achieved displacement histories for a displacement match

Required

Achieved

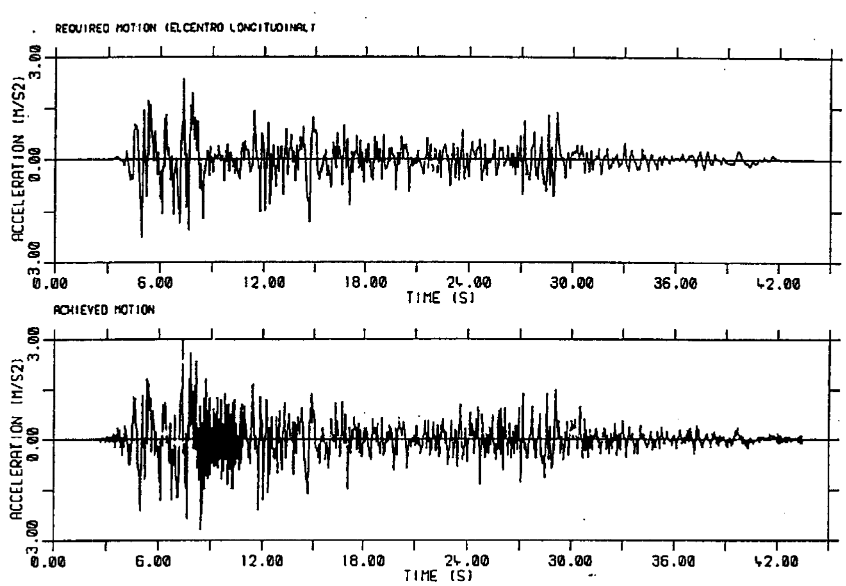

Fig. 3b. Comparison of acquired and achieved acceleration histories for a displacement match

When the specimen with a well defined natural period of 6 Hz was placed on one of the shaking tables the current control systems could not reproduce the required table motion as accurately as this. Although it was not possible to test the ability of the control systems to cope with a specimen that became non-linear during a shake, it can be assumed that the results would be worse than those recorded with the linear specimen on the table. The current control systems are completely passive and no adjustment of the table 'tuning' or the drive signal takes place during a seismic test. If the specimen characteristics change during a shake the specimen's interaction with the table will significantly effect the table motion. Unfortunately this type of non-linear specimen response occurs in many shaking table tests and unless it is possible to prepare and test many specimens as part of the matching process the error between the required and achieved table motion may cause difficulties.

FUTURE TESTS

The current series of tests at the four laboratories has been limited to the matching of full-scale time histories. However, because of the limited payload capacity of the shaking tables, most of the testing that takes place is the four laboratories uses scaled models. To fully understand the implications of using scaled time histories the test programme is currently being extended to look at various frequency-scaled earthquakes. In addition a non-linear specimen is currently being developed that will allow the table control systems to be tested repetitively under more severe load conditions and allow more complicated control systems to be developed. It is hoped that eventually it will be possible to develop some 'real-time' control algorithms that can continuously adjust the drive signal to keep to the required table motion even if the specimen exhibits significantly non-linear behaviour.

CONCLUSIONS

Shaking tables provide a test facility that will continue to be important in dynamic and seismic testing fields. This standardisation programme has proved that as long as a shaking table test is carefully planned, and is within the capacity of the table, it is possible accurately to reproduce any motion on any of the four shaking tables. The tests discussed in this paper have compared the performance of four of the shaking tables who form the European Consortium of Earthquake Shaking Tables (ECOEST). These comparison tests have been carried out as part of the European Union's Human Capital and Mobility Programme, the primary aim of which is the exchange of personnel and experience. This has proved to be a highly successful and valuable exercise and has resulted in improved performance at all four facilities. This programme of tests has also given each of the research groups a greater understanding of their own shaking table.

REFERENCES:

Duarte, R.T., Campos-Costa, A., and Vaz, C.T.. (1994). The New LNEC triaxial earthquake simulator. *10th European Conference on Earthquake Engineering, Vienna.*

Crewe, A.J., Taylor, C.A., Mouzakis, H.P., Vougioukas, E.A., Franchioni, G. (1996). The performance of the shaking table control systems at the National Technical University of Athens, Bristol University and at ISMES, Italy. *10th International Seminar On Earthquake Prognostics, Cairo.*

Carydis, P.G., Mouzakis, H.P., Vougioukas, E.A., Taylor,C.A. and Crewe, A.J. (1994). Comparative shaking table studies at the National Technical University of Athens and at Bristol University. *10th European Conference on Earthquake Engineering, Vienna.*