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Comparative shaking table studies at the National Technical University of Athens and at Bristol University

P.G.Carydis, H.P.Mouzakis & E.A.Vougioukas
Laboratory for Earthquake Engineering, National Technical University of Athens, Greece

C.A.Taylor & A.J.Crewe
Earthquake Engineering Research Centre, University of Bristol, UK

ABSTRACT. The preliminary results of an extensive comparative study of the performances of two, six degree of freedom shaking tables are described. The purpose and methodology of the study are explained and some of the initial conclusions discussed. Good matching of required and achieved time history and response spectra can be achieved for both rigid and flexible payloads provided great care is taken in tuning the analogue and software control systems. Small variations in control settings can lead to large errors in the matching.

1 INTRODUCTION

Shaking tables play a vital role in earthquake engineering research by enabling structures to be subjected to true inertia loads representative of earthquake ground motions. As with any experimental apparatus, it is essential that the user has a clear understanding of the capabilities of the apparatus and how the apparatus interacts with the test specimen. No experimental apparatus is perfect and will always have undesirable aspects. The more complex the apparatus, the more difficult it is to identify and cater for these aspects. This is particularly so for shaking tables. Although an individual table might be similar to others, it will always have features peculiar to itself, which will affect its performance. For shaking table experiments to be meaningful, it should be possible to perform identical tests on different tables and achieve identical results. It is therefore highly desirable to establish a standardised methodology for determining the performance characteristics of shaking tables so that they can be adjusted to perform to a common standard. This paper presents an overview of a major comparative study of two, large, six degree of freedom shaking tables that had the objective of establishing such a standardised methodology.

1.1 Shaking tables used in the study

The shaking tables in question were those at the University of Bristol, UK, and at the National Technical University of Athens, Greece. Both tables have full, six degree of freedom control (i.e. two horizontal and the vertical translational degrees of freedom, and the associated roll, pitch and yaw rotational degrees of freedom). They have similar payload capacities of about 15t. The Bristol table has a 3m by 3m platform, while the Athens platform measures 4m by 4m. Both tables are driven by servo-hydraulic actuators, but the capacities and geometrical arrangements differ.

The tables were designed and built by different companies and have significantly different analogue and computer control systems. The Athens table was built by MTS and has a sophisticated analogue electronic control which allows fine adjustment of acceleration, velocity and displacement feedback to smooth out the system frequency response. A PDP11/34 minicomputer controls the driving signals and acquired data from the table and test specimen.

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 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.

2 SCOPE OF THE STANDARDISATION PROGRAMME

The programme was split into three parts. The software review compared and validated the control, data acquisition and data processing software at both

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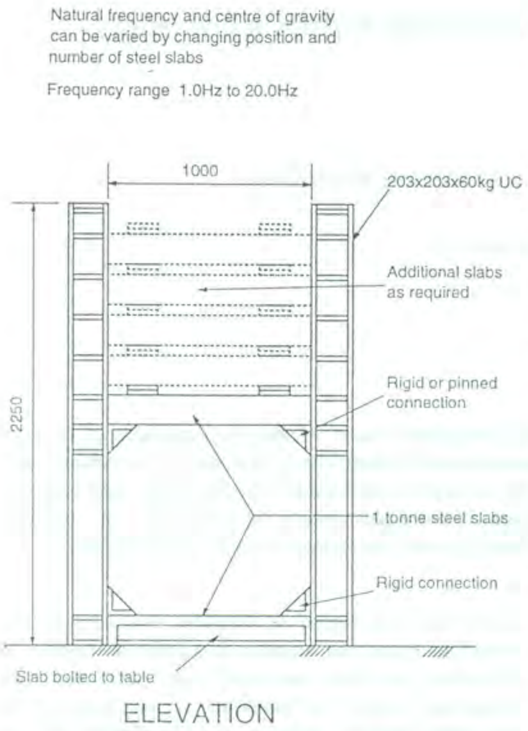

Fig.1 General arrangement of test specimen

sites. The operations review compared the system management, maintenance and experiment design procedures. The performance review explored and compared the performances of the two shaking tables and in doing set the basis of a potential standardised procedure for shaking table calibration. Only the performance review will be discussed in this paper

3 PERFORMANCE REVIEW

The performance review had two main aims. The first was to characterise the performance of each shaking table in a consistent manner. The second was to compare the performances of the two systems by carrying out identical tests on identical specimens. The results of these two activities would enable the strengths and weaknesses of each facility to be identified and the improvement of performance by sharing of best practices.

Of greatest interest to the experimenter is the fidelity of the frequency and time history response of the shaking table. Both will be strongly affected by the frequency response of the shaking table system itself, which in turn is dependent on the frequency responses of the mechanical and electronic hardware and the control system. An essential part of the performance review was therefore the measurement of the frequency response of the shaking table under a wide range of test conditions.

The second essential part of the review was to assess the ability of the shaking table to reproduce prescribed platform motions. 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.

3.1 Design of the test specimen

The design of the test specimen proved to be a difficult task, even though the final result was a simple structure (Fig.1). A basic requirement was for a test specimen that could be configured to have natural frequencies between 1Hz to 20Hz in order to evaluate the capability of the shaking table control systems to compensate for specimen resonances in this range. In addition, the specimen had to have a variable payload in the range 1t to 10t, with a variable centre of gravity up to 3m above the shaking table platform. Cost was a limiting factor, so the number of components had to be a minimum. The specimen would be subjected to repeated testing and therefore had to remain in the elastic range. Some redundancy was important in case the specimen was accidentally overloaded. At low frequencies, the specimen had to be capable of sustaining large enough deflections to allow reasonably large specimen accelerations, and hence overturning moments, to be achieved. This had to be balanced against the required stiffness to achieve the high frequency response.

Many design concepts were evaluated, ranging from a single large steel cantilever column with masses attached to it, to a stack of masses supported on sets of small diameter, high yield steel bars. All of these were rejected in favour of the final design shown in Fig.1. The test specimen comprised of four 203x203x48kg universal columns supporting, initially, up to eight, 1m square, 1t steel masses. The columns were attached to a 1m square, 1t steel base slab through rigid bolted connections. The base slab was in turn bolted to the shaking table platform. A similar steel slab was bolted to the tops of the columns through rigid connections. Bolts could be left out of the joints to change the degree of fixity and hence stiffness and natural frequency

Additional steel masses could be bolted to the top slab through flats welded to the top and bottom faces of each slab. The stiffened columns were drilled with holes to allow the upper stack of masses to be

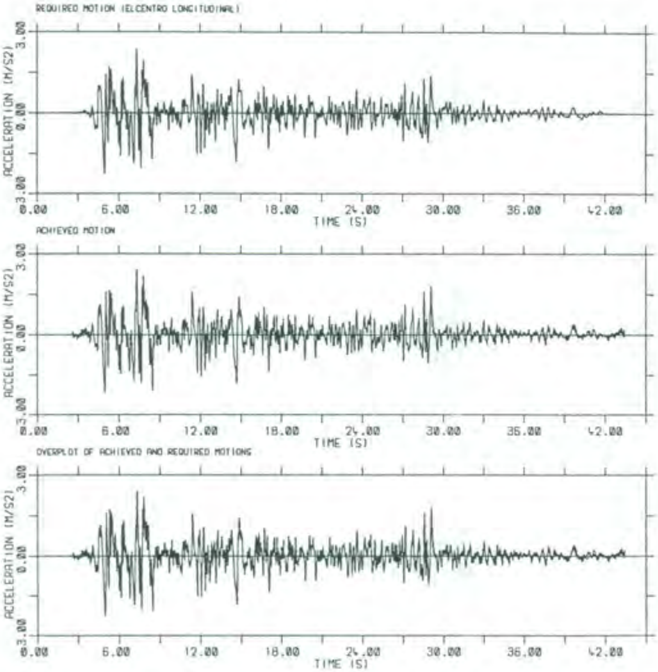

Fig.2 Typical acceleration match - El Centro motion

positioned at a variety heights. The design also allowed the 1t masses to be bolted directly to the shaking table to give a variable, rigid payload with a centre of gravity of up to 0.75m. The final model had frequency ranges between about 3Hz to 40Hz and proved to be an effective solution. Two identical specimens were built in Bristol at a cost of about £15K each. One specimen was shipped to Athens.

3.2 Selection of test motions

Two real earthquake accelerograms were selected as the basis for the prescribed table motions. One was a single component of the El Centro earthquake, while the other was a 3-component recorded measured during the Kalamata earthquake. Both sets of records were filtered to remove frequency components below 1.0Hz and further processed to give consistent sets of acceleration, velocity and displacement time histories. The El Centro record has a significant response spectrum frequency range from 1Hz to 12Hz and a duration of over 40s. The Kalamata records have a strong motion duration of about 6s and a narrower response spectrum from 1Hz to 8Hz. Both sets of records were applied at various peak accelerations to check the linearity of the overall shaking table gains.

3.3 Frequency response function tests

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

The frequency response tests showed the importance of carefully tuning the shaking tables. Slight variations in the centre positions of the actuators and in the individual actuator servo-controller gains led to significant, sometimes severe, resonances and instability. When properly tuned, both tables gave acceptably flat frequency responses for rigid payloads. In fact, both performed better with a rigid 4t payload than without, presumably because, in this range, the actuators were operating around the middle of their performance range.

For the flexible specimen payloads, peak and notch effects were evident. Here, the complex

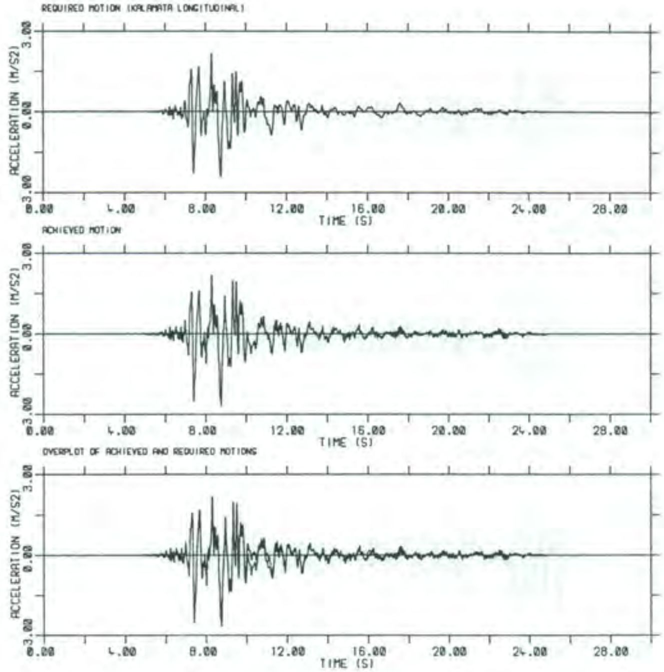

Fig.3 Typical acceleration match - Kalamata motion

analogue control system of the Athens table proved its worth, as it was easier to reduce significantly the frequency response distortion by tuning the electronics than it was for the simpler Bristol analogue control. Given careful adjustment, both tables gave good frequency responses.

In general, cross coupling between degrees of freedom was not significant, although there was some slight coupling between the roll and pitch axes and the associated translational axes. Once again, careful tuning minimised this effect. Although notionally identical, the horizontal axes of each shaking table had different response characteristics.

3.4 Time history matching

The time history matching methods for the Athens and Bristol shaking tables work on the same principle, but are different in detail. Both 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.

For the Athens shaking table, broad band random noise is applied to the shaking table for several minutes, preferably with the specimen mounted, and an averaged inverse transfer function computed.

The Bristol software control works directly on the acquired, target and drive signals. The time histories are segmented into overlapping blocks, the inverse transfer function for each block computed and an updated drive signal for the block created. This approach leads to a time dependent transfer function that can deal with non-linearities in the shaking table system itself.

The El Centro record was applied to each translational axis in turn to check on axis similarities. As noted previously, the axes on both tables were slightly different, which led to different degrees of compensating control for each axis. It was possible, however, to achieve almost identical responses in each axis.

The Kalamata earthquake was used to examine the performance with a triaxial input. Both control systems were able to match the required time histories well, especially for bare table and rigid payloads. It was found that, for both the El Centro and the Kalamata inputs, either a good acceleration match or a good displacement match could be achieved, but usually not both at the same time. To achieve a good response spectrum match it was essential to achieve a good acceleration time history match. Matching displacements did not accommodate the higher frequencies present in the acceleration signal, which in turn controlled the detail of the response spectra.

In the cases of flexible specimens with masses of 8t and natural frequencies of around 4-6Hz, the tuning and drive signal compensation had to be more rigorous if the effects of table-specimen interaction were to be minimised to acceptable levels.

Figs.2 and 3 show some typical acceleration time history matches for the El Centro and Kalamata inputs respectively, demonstrating the levels of accuracy that can be achieved with care.

The El Centro and Kalamata records were unscaled in terms of frequency. For most scale model tests, the input motions must be time compressed to satisfy the overall scaling relationships, thereby increasing the frequency range in which the shaking table must operate. The effects of such frequency scaling have yet to be explored.

4 FUTURE TESTS

The tests reported in this paper are the first phase of a longer test programme in which it is intended to explore the effects of frequency scaling and non-linear specimen reactions. The future studies will also review the suitability of the chosen time histories, which it is believed do not fully exercise the shaking table systems.

5 CONCLUSIONS

The shaking table comparison has been carried out under the European Union's Human Capital and Mobility Programme, the primary aim of which was the exchange of personnel and experience. It has proved a highly successful and valuable exercise in this respect, resulting in improved performance of both the Bristol and Athens facilities and the dissemination of the enhanced understanding to other collaborating laboratories. A rigorous, preliminary standardisation test programme has been identified, together with sub-sets of tests for more rapid system evaluation.