EQUIPMENT QUALIFICATION USING THE SERC EARTHQUAKE SIMULATOR

J. M. W. Brownjohn[1], C. A. Taylor[2], A. Blakeborough[2], and R. T. Severn[3]

ABSTRACT

Earthquake simulators are commonly used in a primary research role to study the dynamic and seismic behaviour of structures and for validating numerical structural analysis techniques. In commercial applications, earthquake simulators are used for assessing the operational performance of safety-critical structures during simulated earthquakes. The Science and Engineering Research Council Earthquake Simulator and research facilities at the University of Bristol have been adapted and upgraded for use in full-scale seismic qualification of equipment, and this paper describes some of the relevant standards and specifications and provides details of the experimental and management systems at Bristol.

INTRODUCTION

Where a safety-critical structure or item of equipment is located or installed in a situation where large loads may occur and where significant damage or injury would result from unsatisfactory dynamic performance of the structure or equipment, it is necessary to check by 'dynamic qualification' either that failure is unlikely to occur or that it will occur safely. In civil engineering structures, the large dynamic loads are most likely to result from accelerations at the base or supporting points of the structure primarily due to earthquakes and to a lesser extent due to transmission of vibrations from machinery. Dynamic qualification against earthquake loads is referred to as seismic qualification.

Analytical techniques are commonly used for seismic qualification of large new structures such as buildings. Other methods are dynamic testing of the prototype structure[9], testing of a physical model, observing performance under severe dynamic loading service[14] or comparison with existing structures which have been qualified by any of these means.

While analytical methods can be applied to building structures, for the vital equipment they contain, such as control systems for nuclear power plant, the only reliable means of dynamic qualification is physical testing during which the performance of the mechanisms or electrical systems is closely monitored. In such testing the equipment is subjected to a base excitation whose form is strongly influenced by the analysis of the containing building structure. The devices used for simulating the base motion during an earthquake are generically termed earthquake simulators

[1]Research fellow [2]Lecturer [3]Professor
Department of Civil Engineering, Queens Building, University Walk, Bristol BS8 1TR, UK

APPLICATIONS OF EARTHQUAKE SIMULATORS

Earthquake simulators or 'shaking tables' have a range of applications other than purely for seismic qualification. For example the SERC Earthquake Simulator at Bristol has been used for:

Basic Research

This is aimed at investigating certain aspects of the dynamic behaviour of structures, such as interaction of structures with foundations and fluid reservoirs, effects of structural non-linearities on performance and damping mechanisms[8].

Modal Survey

When the dynamic characteristics of the structure need to be represented as a set of frequency response functions (FRFs) these FRFs can be obtained from measurements at points on the structure while subjected to low levels of excitation[4]. The set of FRFs contain information about modal frequencies, shapes and damping ratios (but not modal mass or stiffness). A limited form of modal survey may be included in a programme of seismic qualification.

Parametric Study and Evaluation of Designs

Structures with particular features are tested to determine their effect on dynamic performance. These features could be particular distributions of mass and stiffness or novel energy absorbing mechanisms[4,11].

Validation Of Simulation Software

The accuracy of mathematical models depends, amongst other things, on the level of detail and the simplifications used, the physical parameters associated with the structural elements and the principles applied in the analysis software. The validity of the analytical principles and the accuracy of the numerical methods used can be checked if data from a test of a physical model corroborates results from analytical studies using the same forcing function[12].

Tests to Destruction

If structural failure cannot be avoided it can at least be made to happen in a manner that minimises damage or injury. It can be instructive to examine the failure modes of particular concepts and details of structural design[13].

Provision of Secondary Response Data

In the same way that analytical techniques can be used to specify the motion at points in a building where vital equipment is located, secondary equipment located on or in the equipment can be qualified by further testing or analysis using input motions derived from physical testing of the host equipment using an earthquake simulator.

SPECIFICATIONS OF EARTHQUAKE SIMULATOR MOTION USED FOR TESTING

Reproduction of Specific Earthquake (Time History)

Acceleration time histories of a large number of earthquakes are available in digital form and are commonly used by earthquake engineering researchers as a form of benchmark for comparing the performance of different structures. This type of signal, which may be scaled in duration or amplitude, is used for basic research, parametric studies, tests to destruction and software validation.

Reproduction of Generic Earthquake (Time History from Response Spectrum)

In the UK recorded data from relevant strong ground motion is sparse so that UK earthquakes are usually characterised as response spectra derived by considering earthquakes that have occurred in sites with similar geology and seismicity. Response spectra are a useful form of specifying excitation for seismic qualification, since they represent the peak amplitude response of oscillators subjected to ground base excitation. Random time histories can be generated from response spectra, and for realistic simulation, simultaneous motion in three axes (triaxial) is often required.

Sine Sweep

This is a sinusoidal signal varying in frequency, amplitude and duration. The rate of change of frequency varies and resonances can readily be identified since excitation near a resonance lasts long enough to supply sufficient energy to build up large amplitudes. Specifications for seismic qualification take this form for some specific types of control equipment, e.g. flow valves. Sine sweeps are also used for modal surveys.

Random or Multi-sine Excitation

A combination of sine waves of all frequencies to generate simultaneous response in many modes. The frequency spectrum of this signal is usually flat and the power available at each frequency is low, although the total power may be quoted as an RMS value. This type of excitation is mainly used for modal surveys.

REQUIREMENTS AND STANDARDS FOR EQUIPMENT QUALIFICATION

A variety of standards exist which give guidance and general and specific requirements for seismic qualification of equipment. One widely quoted and applied specification is IEEE 344[2] which deals with aspects of seismic qualification by testing, analysis and experience. IEEE 344 does not give any absolute values, but IEEE 382[9] gives details of the acceleration levels and frequency values for qualification of valve actuators.

In the UK, the specification relating to Sizewell B also describes testing requirements without giving any particular levels, and the Lloyd's type approval scheme[10] specifies a rather different type of severe resonance search and vibration aging test such as would be applied for equipment used in offshore installations.

Where specific excitation levels are not given, these may be provided by the client as 'site specific' response data for a particular installation. Sometimes 'all-sites' spectra are designed to envelope spectra from different sites and reduce the number of qualification tests required, but this simplification can lead to significant overtesting.

While the above standards give some level of detail about arrangements and levels for testing, they relate to only one part of the whole seismic qualification operation which has to be project managed within a properly organised laboratory environment, and this organisation is effected as part of a quality system.

The organisations for whom qualification is conducted generally make the provision of adequate quality assurance (QA) a contractual requirement. The arrangements for QA are embodied in a quality system which must conform to certain standards, almost all more rigourous than BS5750/ISO9000.

The earthquake engineering activities at Bristol are brought together within the Earthquake Engineering Research Centre (EERC) which has developed its own quality system, originally to cater for commercial testing. The requirements for quality assurance (as applied in EERC) for activities related to nuclear installations in the UK are covered by BS5882[6], and for particular requirements of testing laboratories by BS6460[7] and BS5781[5]. Among other things these standards require that

1) testing activities are carefully planned and documented,
2) drawings, documents and other information are controlled and logged,
3) equipment being qualified is properly identified and handled,
4) instrumentation is properly calibrated and its use controlled and monitored,
5) data processing software is validated and verified,
6) test records are witnessed by the contractors representative and
7) all data is backed up.

Clients are entitled and expected to check the quality system and its operation against the relevant standard by means of audits.

The SERC Earthquake Simulator was commissioned as a research facility with financial support provided for a limited period, but in order to provide for its continuing operation beyond this

funding, EERC has had to attract commercial contracts, the bulk of which are equipment qualification. In order to secure these contracts EERC has had to implement an effective quality system which includes as a central part the management of the earthquake simulator and commercial testing project.

EXPERIMENTAL SYSTEMS FOR EQUIPMENT QUALIFICATION

Figure 1 shows the SERC Earthquake Simulator[3]. It is in the small to medium class of servo-hydraulic simulators but is one of the handful of simulators worldwide that can rotate and translate under control.

APPENDIX 1 SERC EARTHQUAKE SIMULATOR SPECIFICATION

size, type	3m x 3m, hydraulic	
DOF	6	
platform mass, construction	3.8t, 4 piece cast aluminium	
payload mass, height	15t, 4m	
operating bandwidth	0.1-100Hz	
performance	**vertical**	**horizontal**
actuator(s)	4, total 180kN	4, total 200kN
max. acceleration	4.5g (0 payload)	3.1g (0 payload)
max. velocity	500mm/s	500mm/s
max. displacement	+/-150mm	+/-150mm
foundation	120t concrete block on air springs	
resonances	< 2Hz	
powerpack	300 litres/min, 210 bar	
control	IBM AT	
acquisition	IBM AT, 48 channels	
manufacturer	Silveridge Technology	

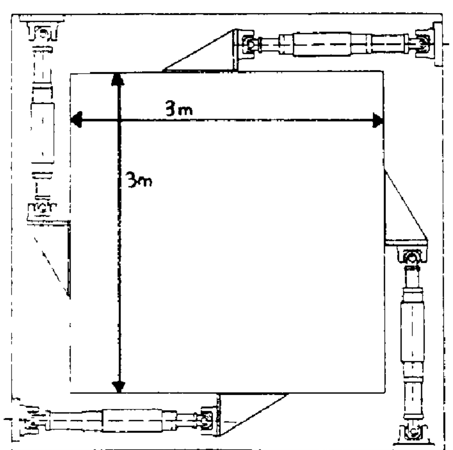


Figure 1a
SERC earthquake simulator: plan view

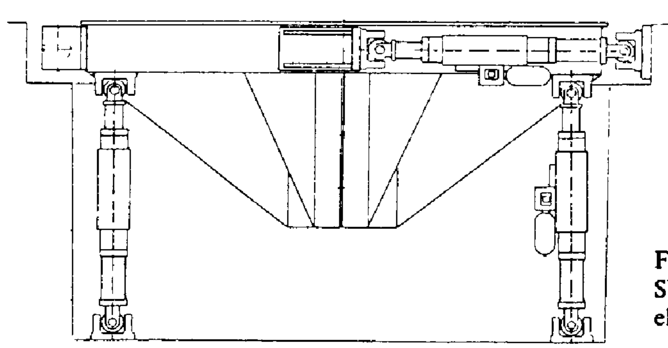


Figure 1b
SERC earthquake simulator: elevation

Construction

The specification for the SERC Earthquake Simulator is given in Appendix 1. Specimens are mounted on a rigid platform which is constructed from four hollow cast aluminium sections which bolt together as an inverted pyramid, stiffened by a honeycomb of webs and diaphragms and topped by a five piece segmental arrangement of aluminium plates to provide a mounting surface for specimens. An arrangement of four servo-hydraulic actuators in each of the horizontal and vertical planes connects the platform to a massive concrete 'block' which sits in a pit in the laboratory. The pit foundations are on bedrock and the block sits on inflatable air springs to reduce transmission of reaction loads to the building.

The actuators take high pressure oil from a ring main supplied by a hydraulic pump (powerpack) and an array of hydraulic accumulators. Command signals for the actuators derive from an analog computer which converts analog input for each of the six translational and rotational axes to command signals for servo-valves in the eight actuators. The vertical actuators can support dead weight of specimens by means of static preload sections in the cylinders.

Idealised Performance Limitations

For research applications, the ultimate performance limitations are usually academic since the excitation levels are quite modest, but specifications for commercial testing can test the capabilities of the simulator itself. Figure 2 shows (solid lines) the original performance specification for the simulator which serves to illustrate, in a simplified analysis, the principle limitations on capability. Figure 2 is on a logarithmic scale and the maximum acceleration values $\ddot{x}_{max}$ are for sinusoidal excitation.

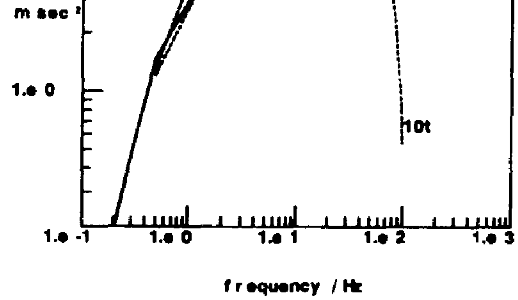


Figure 2 SERC Earthquake Simulator maximum sinusoidal acceleration in vertical (Z) axis for 10 tonne and 0 tonne payload

In the lowest range, up to 0.5Hz, the performance is displacement limited due to the stroke L of the actuators i.e.

$$\ddot{x}_{max} \approx (2\pi f)^2 L/2 \tag{1}$$

where f=frequency.

In the mid-range (0.5Hz to just over 3Hz) the performance is velocity limited since the sizing of the pipework and actuator valves restricts the maximum oil flow rate (Q) into each actuator, hence the velocity of the pistons i.e.

$$\ddot{x}_{max} \approx 2\pi f Q/A \tag{2}$$

where A is cylinder cross sectional area. The capacity of the hydraulic pump is a final limit on performance if high velocities are to be sustained for several cycles of motion; hydraulic accumulators in the system can help since they act like capacitors, smoothing out transient demands and temporarily making up for restricted pump output.

In the range from 3Hz to 50Hz or more the performance is acceleration limited due to the system pressure (P) and the actuator area (A) i.e.

$$\ddot{x}_{max} \approx \frac{PnA}{(M + m)} \tag{3}$$

where n is the number of actuators, m is the mass of the moving parts of the simulator and M is the payload mass.

Other Factors Affecting Performance

The actual performance curves for the SERC Earthquake Simulator (swept sine input) are also given Fig. 2 (broken lines). There is some resemblance to the specification but several other factors are at work, particularly above 10Hz.

A servo-hydraulic simulator such as this is a complex mixture of electrical, hydraulic and mechanical systems. The electrical system is the easiest to control but resonances and non-linearities in the mechanical and hydraulic systems are harder to cope with. The most obvious is the 'oil column resonance' involving the mass of the platform and the compressibility of the oil in the actuators and occurring at a frequency of approximately

$$f_h = \frac{A}{\pi}\sqrt{Nn/[(M+m)\,V]} \tag{4}$$

where V is enclosed volume of cylinder and N is bulk modulus of the oil. For the SERC Earthquake Simulator when unloaded f_h occurs between 15 and 20Hz, depending on the axis. Resonance of the platform itself usually occurs above the seismic range. Even with careful design the mechanical connections are bound to have some flexibility and backlash and this may result in further resonance or performance dropout as well as harmonics.

Harmonics of the fundamental driving frequency can also result when driving the simulator for maximum performance. This is because the servo valves will be full open or fully closed to meet the demand of the driving signal resulting in a square force waveform.

While some simulators facilities have 'three-variable control' systems which use feedback of acceleration, velocity and displacement signals derived from accelerometers and displacement transducers to improve the level of control it cannot be assumed that the simulator response will be a faithful reproduction of the input signal. The SERC Earthquake Simulator has a relatively simple analog electronic control system and (for time history signals at least) uses iterative procedures to obtain the drive signal giving the closest match to the required earthquake. This is called 'time history matching'. A similar process is used to obtain drive signals for a given response spectrum and is called 'signal shaping'.

INSTRUMENTATION

Instrumentation and Signal Conditioning

An equipment qualification test can take weeks of organisation but the actual shaking may last only a few seconds. Processing the data obtained can take several hours and the results are only as good as the original signals. It is therefore crucial that the right instrumentation is used correctly. While it might be argued that as much instrumentation as possible should be used to make the most of the occasion, increasing the number of transducers multiplies the chances of failure, signal interference and delays as well as the processing time and should therefore be considered very carefully. For triaxial seismic qualification a set of three accelerometers is used to measure input acceleration and response at only one point on each piece of equipment tested.

Accelerometers

Accelerometers are most commonly used for dynamic qualification; strain gauges, force and displacement transducers are mainly found in research applications. Piezoelectric accelerometers are commonly used; they can be small and have good high frequency response, but low frequency response is poor (e.g. below 1Hz) and they require special amplifiers and careful management of signal cables. Servo-type accelerometers are heavier and more expensive but are used in the most demanding applications and are probably the best choice for dynamic qualification. EERC Bristol uses a mix of capacitive accelerometers and low impedance Voltage mode accelerometers, which are inexpensive and perform well.

Filters and Amplifiers

If the analog signals are to be recorded on a computer they must be converted to digital form.

When digitising an analog signal the maximum frequency component that can be recognised in the digital representation is half the frequency at which the signal is sampled, so that electronic low pass filters must be used to prevent aliassing of frequencies above this value. Even with high order filters with a sharp cutoff characteristic it may be necessary to sample at a frequency of about three times the highest frequency required in the digitised signal.

Amplifiers are used to match the output ranges of the accelerometers to the analog to digital converter input, to provide a convenient gain factor, and to remove DC signal offsets.

Data Acquisition

The most useful form for data is as digitally represented time histories, and these are obtained by analogue to digital conversion (ADC) of the filtered and amplified signals. At Bristol this conversion is done by ADC hardware in a personal computer for up to 48 channels of data, although restriction to 16 channels is recommended.

Data processing and Presentation

The digital time histories are commonly processed and output

1) as scaled and calibrated time histories,
2) as response spectra,
3) as power spectral density (PSD) functions or
4) as transfer functions between two data channels.

Transfer and PSD functions can also be computed directly from analog data using dedicated spectrum analysers, but signal processing software used at Bristol has been developed and validated to provide reliable time histories and response spectra.

PROJECT MANAGEMENT OF SEISMIC QUALIFICATION OF EQUIPMENT USING THE SERC EARTHQUAKE SIMULATOR

Figure 3 shows some of the steps involved in a typical project for seismic qualification of an item of equipment for a nuclear installation.

Pre-test Activities

When evaluating a client's testing specification the important information is the expected scheduling of the test, the size and weight of the specimen, the type of qualification and the 'required response spectrum' (RRS) of base excitation. If the test can be accommodated, an EERC project manager prepares a quality plan showing how QA is applied to the testing project and a test method statement (TMS) detailing the EERC schedule and arrangements for the testing; this is the working document and is made available to the client.

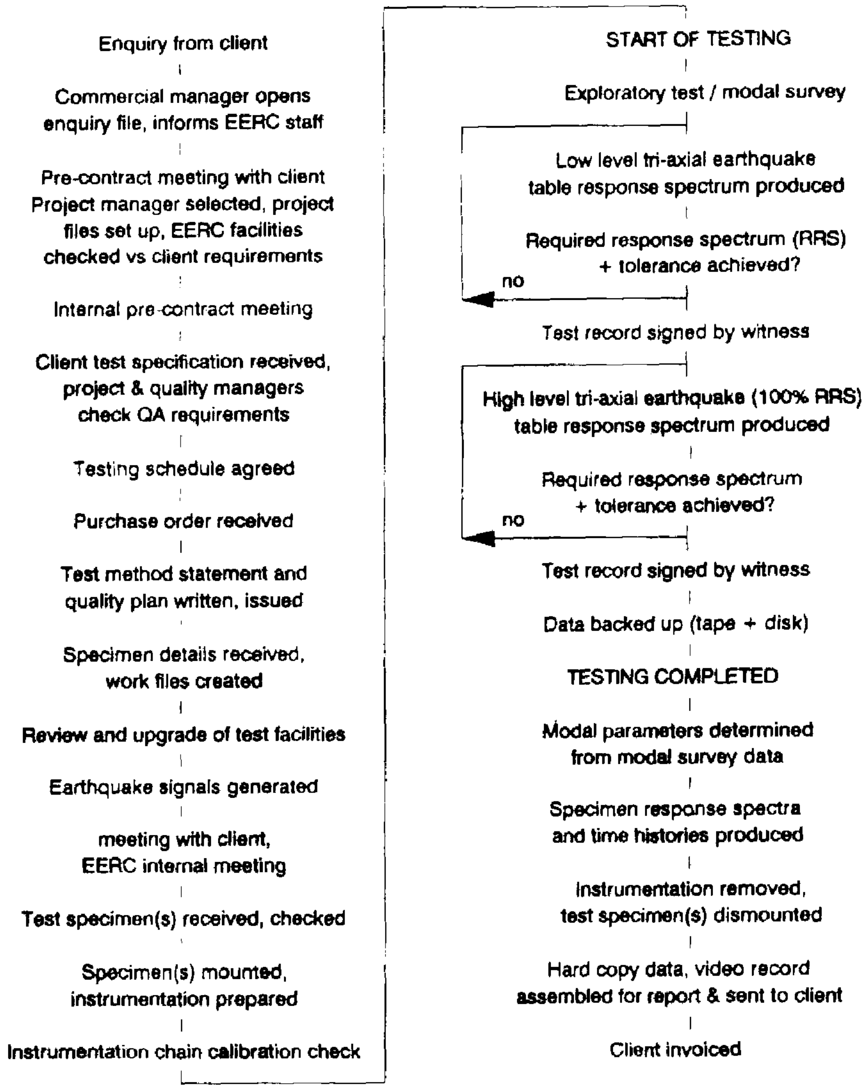


Figure 3 Procedure for seismic qualification

Signal Shaping

If the testing specification requires a multi-axial shake with various percentage levels of the RRS (e.g. 25%RRS, 100%RRS etc.), first-pass time histories are generated for 25%RRS with the 'bare table'. The acceleration time history obtained for each shake must envelope the %RRS with a wide enough margin to allow for the calibration uncertainty, generally about 10%. Depending on the mass and height of the test specimen the response will change when mounted on the simulator, but the 'bare table' testing is used to obtain the best fit to the %RRS without damaging the test specimen, and for the first low level test a large margin is allowed to accommodate the effect of the specimen on platform response. Time histories for higher levels are adjusted according to the effect the specimen has on the response for the first low level test.

Mounting and Instrumentation

On arrival the test specimen is identified against the client drawings and descriptions, labelled and placed on the earthquake simulator for marking out bolting positions. These must be the same as or representative of the bolting positions on site and to allow for this, bolt holes are drilled and tapped in a 'sacrificial plate' or false platform top. The specimen is bolted down with the specified bolt sizes and torque values.

Positions for measurement of acceleration will have been specified by the client; qualification may require measurement at only one point but in three axes. Accelerometers are bolted to the simulator platform, but to avoid damage, accelerometers are cemented in place on the specimen.

The capacitive accelerometers used have a flat response characteristic over the seismic range from DC so that calibration tolerances and overtest margins are reduced. The accelerometers require a stabilised power supply and amplifiers to provide output such as 1 Volt/g. Anti-alias filtering attenuating steeply between 50 and 80Hz allows for sampling rates of at least 200Hz for digital acquisition during triaxial shakes. All the instrumentation is calibrated by a suitably accredited laboratory as matched sets or 'chains' of accelerometers, amplifiers and filters in order to minimise calibration tolerances. Simple function checks of the instrumentation are also done before each stage of the testing.

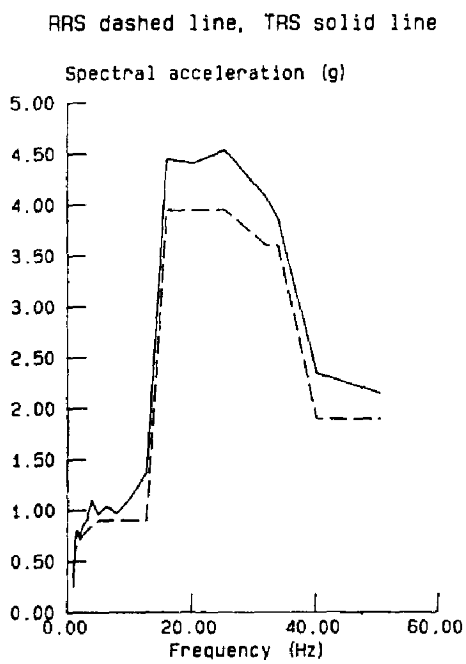
Exploratory Test

The first stage of testing is the 'exploratory' test in which the equipment is shaken in one axis at a time at low level (e.g. 0.1g RMS or 0.2g peak platform acceleration) with a multi-sine or pseudo-random signal. The shaking may continue for several minutes or until enough data is obtained to permit simple estimation of modal frequency and damping with good statistical reliability. The estimates can be provided from frequency spectra obtained directly from a spectrum analyser or at a later date by processing of digitised data. The estimates will provide a check on values of natural frequency used or obtained with analytical procedures and on damping ratios used in determining response spectra.

Tri-axial Shakes

Depending on the test specification these will progress as successive earthquake inputs with increasing magnitude. The shakes last for a period of between 10 and 20 seconds during which time all accelerations are recorded, functioning of equipment is monitored and the action is recorded on a video camera. The acceleration records from the accelerometers attached to the simulator platform itself are processed immediately to obtain the test response spectra (TRS). From the EERC point of view the test is successful if the TRS envelopes the %RRS + calibration margin without overtesting. The client representative confirms the enveloping before the %RRS is increased for the next shake. If the %RRS is not enveloped the frequency content of the signal is adjusted and the test re-run.

Figure 4 shows an example of enveloping of RRS by TRS.



Freq (Hz)	RRS (g)	TRS (g)	TRS/RRS
1.00	0.25	0.36	1.42
1.26	0.60	0.68	1.13
1.58	0.65	0.81	1.24
2.00	0.70	0.73	1.04
2.52	0.75	0.85	1.13
3.17	0.80	0.90	1.13
4.00	0.85	1.10	1.29
5.04	0.90	0.96	1.06
6.35	0.90	1.04	1.16
8.00	0.90	0.97	1.07
10.08	0.90	1.12	1.24
12.70	0.90	1.37	1.52
16.00	3.95	4.45	1.13
20.10	3.95	4.41	1.12
25.40	3.95	4.54	1.15
32.00	3.60	4.07	1.13
34.00	3.60	3.85	1.07
40.22	1.90	2.35	1.24
50.56	1.90	2.14	1.13

RSPA v1.05

Figure 4 Successful enveloping of required response spectrum (RRS) by test response spectrum (TRS) in seismic qualification test

Post-test Activities

After successful testing the test data is backed up, instrumentation dismantled and the specimens removed from the simulator. Processing of the data may involve presentation of acceleration time histories for each instrument in each shake, computation of test specimen response spectra (additional to TRSs already computed) and extraction of modal parameters from transfer functions between specimen and platform accelerations. The test report will include all this data with details of the testing equipment, calibration and data processing.

DEVELOPMENT OF EERC FACILITIES

Facilities

The earthquake simulator facilities have recently been upgraded by addition of accumulators to improve low frequency velocity limited response of the simulator and acquisition of new signal generation and processing equipment and data presentation facilities. Future enhancements being considered include installation of new servo valves to further improve performance, an improved analog control system and new digital signal generation and control software.

Management Systems

The quality system for commercial testing is now fully operational but is being continually fine tuned as part of a management system review, part of which provides for an extension of quality management to cover research activities.

Although the laboratory facilities have been upgraded and a quality system introduced so that commercial qualification tests could be taken on, other commercial and research activities in EERC have benefited by use of the facilities and adoption of the quality management principles applied to qualification work.

Management of Research Projects

Research projects differ from commercial tests in many ways.

1) They can be long term, depending on the duration of the research contract, and unless goals and objectives are set the research can become ill-defined and inefficient.
2) The research will usually be a conditional or iterative process so that short-term objectives are frequently redefined.
3) Research staff are transient and a high proportion of their time is taken up in tracing back previous work and learning how to use facilities.
4) The emphasis on management is different; the research project manager will not be involved with day to day activities but will supervise or advise the research. The effectiveness of this supervision and advice depends on the feedback of information from the researcher.

Because of the emphasis on project management and documentation, quality management has a great deal to offer research projects. It requires specification of objectives at all stages and enforces planning in as much detail as is practical. The level of documentation and reporting required is high, forcing researchers to log the sort of test and analysis details that are often lost, and to submit regular progress reports.

The planning leads to more efficient use of time spent in all research activities and the sum total of documentation means that the research can be taken over or back-tracked with few problems.

Use of Hardware

Full records of mechanical and electrical equipment are kept. These records include details of purchase, service and calibration history and faults or repairs and usage. Equipment details and history are maintained in a computer database which is used to schedule appropriate calibration and maintenance.

Computers and Software

The EERC operates a collection of personal computers and uses other University facilities. It applies its own rules in addition to the University common sense regulations, so that valuable information and software is protected. As well as individual data backups as part of projects, a system of tape backups is implemented.

When accuracy of results depends on analysis software, evidence of validation and verification of the software is required, in the same way as calibration certificates are required for transducers. This results in tighter control on in-house software development and a tendency towards standardisation.

Documentation of Facilities

With a high turnover of research staff and acquisition of new facilities, much time can be saved if comprehensive documentation of equipment is available. Proprietary documentation (when available) varies in standard and complexity so that simple explanations of how to use equipment or software and deal with problems can be particularly useful. All documentation relevant to a piece of hardware or software or to a particular activity is collated in an 'equipment file'.

CONCLUSION

Significant effort and expense has been devoted to providing the right facilities and a professional standard of management. This effort has enabled EERC compete with other commercial facilities and has benefited a whole range of research activities at EERC.

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