SHAKING TABLE TESTING OF CIVIL ENGINEERING STRUCTURES - THE LNEC 3D SIMULATOR EXPERIENCE

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SUMMARY

Shaking tables are nowadays a valuable tool for the seismic behaviour assessment of civil engineering structures. The main purpose of this paper is to present some aspects of the recent experience obtained throughout the accomplishment of several series of tests (on different types of structures) which were achieved using the new LNEC 3D earthquake simulator. It should be mentioned that the tests results are not presented, as the emphasis is focussed on the main issues found in order to perform the tests as close as possible both to the nature occurrences and the structural behaviour. Some of the adopted solutions and procedures are described and eventual alternatives are discussed.

Among the problems involved, the following are briefly highlighted:

- Physical scales (dimensional analysis and similitude theories) to be adopted in the specimens design;

Instrumentation, respecting the type of transducers and the option between relative or absolute measurements;

- Signal acquisition, in regard to the kind of sampling and filtering to adopt;
- Test strategies, defining the successive stage increments.

Signal analysis, concerning the definition of the most “profitable” inputs, as well as control algorithms, related to the input signal reproduction and “real time” compliance with the dynamic characteristics modifications, are discussed in a separate paper (Duque and Bairrao, 2000).

Moreover, handling and solving the above referred problems produced a valuable enhanced knowledge in what concerns the design and construction of auxiliary structures required by typical set-ups involving the dynamic behaviour of models associated to large moving masses or inertia forces and also concerning all the connection systems, mainly about the maximum allowable gaps and the required range of stiffness levels.

INTRODUCTION

The use of shaking tables for the assessment of the dynamic and seismic behaviour of civil engineering structures is effective since the sixties. At the beginning, shaking tables had important limitations concerning the power available and they have been used to study the dynamic characteristics (natural frequencies and mode shapes) of small models behaving essentially in the linear range. Meanwhile, bigger and more powerful shaking tables have been put in operation allowing for the adoption of lower scaling factors and therefore involving very important dynamic forces.

Nowadays a significant amount of research using shaking tables can be found in the literature. This research has been oriented mainly for the ultimate behaviour of steel and rc building structures, structural elements (with a clear emphasis on rc and masonry walls, rc frames with infills and dissipating devices) and global models of structures at smaller scales. Among the most paradigmatic examples of the use of shaking tables are the two

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series of tests performed at the Tsukuba facility on 1:1 scaled models; the first one was performed in the framework of the US-Japan Cooperative Earthquake Research Program on a building model with 7 storeys; more recently (Minowa et al, 1996) two 3-storey building models have also been tested to failure. In what concerns shaking table tests on bridge structures and bridge piers, information is rather scarce and just a few results are found in literature. The tests performed at LNEC (Carvalho et al, 1978), at the University of California (Williams and Godden, 1976) and at ISMES facilities (Casirati et al, 1996) are among the few papers published on the subject. Those tests have been performed on models at 1:100 scale (LNEC), 1:30 (UC) and 1:8 (ISMES).

In order to advance its experimental activity in engineering, which started in the late fifties, LNEC decided to study and build a new type of earthquake simulator mainly conceived for the testing of civil engineering structures, such as buildings and bridges, being, however, also useful for the validation of the dynamic behaviour of some mechanical and electrical equipment.

This very particular simulator has three independent translational degrees of freedom which are driven by hydraulic actuators, whereas its rotational degrees of freedom are minimised by torque tube systems, one for each axis (roll, pitch and yaw). Under the horizontal cranks, either passive gas actuators, to cope with the dead weights of the shaking table and of the testing specimen, or rigid blocks, eliminating the vertical motion of the table, can be inserted (Figure 1).

At each end, the torque tubes are linked, by means of a crank, with a stiff connecting rod between them and the moving platform. The vertical connecting rods are pinned at both ends, and horizontal motion of the platform is allowed. When the platform moves vertically, it either pulls or pushes the connecting rods, rotating both cranks by the same angular displacement, and the respective torque tube likewise. In fact, if there is an overturning moment inducing a rotation on the platform, then vertical movement in opposed directions appears at the upper end of the connecting rods, which, in turn, causes small opposite rotating forces in the cranks. However, this is resisted through a large reaction force generated by torsional stiffness of the concerned very stiff torque tube, resulting only in an insignificant platform rotation.

The main characteristics of this shaking table are an area of 5.6 m x 4.6 m, a table mass of about 40 t, a maximum allowable specimen weight of 400 kN, a frequency range from 0 to 15 Hz, maximum accelerations of 1.1, 0.5 and 1.8 g for the transverse, vertical and longitudinal axis respectively, and maximum displacements of ± 175 mm for all the three axes. Detailed information on the characteristics of the shaking table can be found in (Emilio et al, 1989).

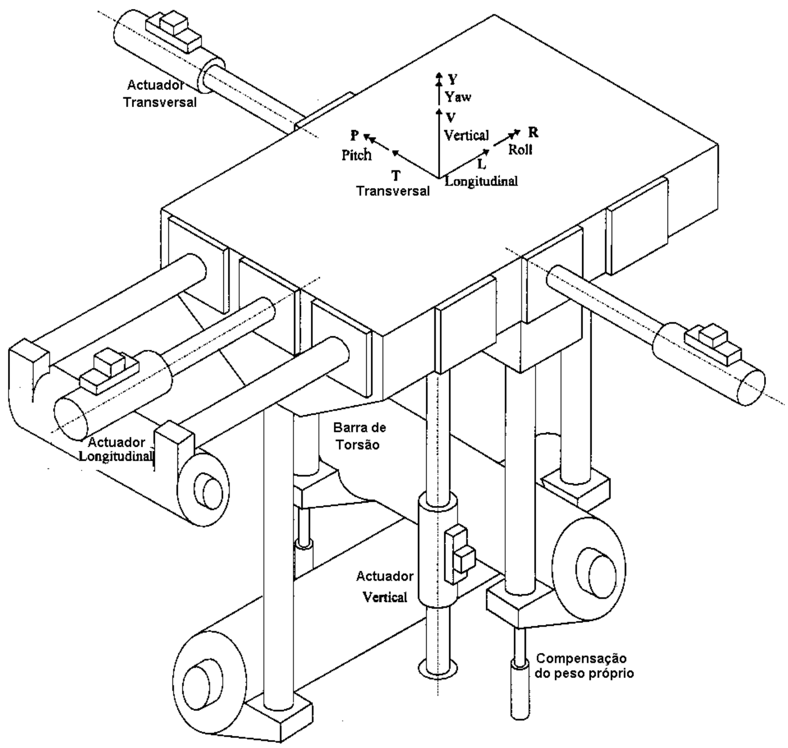

Figure 1

PHYSICAL SCALES AND SIMILITUDE LAWS

In structural problems involving scaled models 2 types of similitude are most commonly considered. One of them is the Cauchy similitude, based on the Cauchy number and expressed as $C_N = \rho\ v^2 / E$, which shall be the same in the prototype and in the model. This type of similitude is adequate for phenomena in which restitution forces are essentially elastic. The other type of similitude is the Froude similitude, adequate for situations in which gravity action plays a primary role. In this case the Froude number, expressed as $C_F = v^2 / (L\ g)$ shall be similar in the prototype and in the model. In the previous expressions for the Cauchy and Froude numbers ρ represents the specific mass, v the velocity, E the elasticity modulus, L the length and g the gravity acceleration. In Table I the Cauchy and Froude similitude relationships for the some quantities more usually considered in structural engineering are presented (symbol M refers to the model and symbol P to the prototype).

Table I – Similitude relationships.

Quantity	Symbol	Cauchy similitude	Froude similitude
Length	L	$L_P = \lambda\ L_M$	$L_P = \lambda\ L_M$
Modulus of elasticity	e	$E_P = e\ E_M$	$E_P = e\ E_M$
Specific mass	ρ	$\rho_P = \rho\ \rho_M$	$\rho_P = \rho\ \rho_M$
Area	A	$A_P = \lambda^2\ A_M$	$A_P = \lambda^2\ A_M$
Volume	V	$V_P = \lambda^3\ V_M$	$V_P = \lambda^3\ V_M$
Mass	m	$m_P = \rho\ \lambda^3\ m_M$	$m_P = \rho\ \lambda^3\ m_M$
Velocity	v	$v_P = e^{1/2}\ \rho^{-1/2}\ v_M$	$v_P = \lambda^{1/2}\ v_M$
Acceleration	a	$a_P = e\ \rho^{-1}\ \lambda^{-1}\ a_M$	$a_P = a_M$
Force	F	$F_P = e\ \lambda^2\ F_M$	$F_P = \rho\ \lambda^3\ F_M$
Moment	M	$M_P = e\ \lambda^3\ M_M$	$M_P = \rho\ \lambda^4\ M_M$
Stress	σ	$\sigma_P = e\ \sigma_M$	$\sigma_P = \lambda\ \rho\ \sigma_M$
Strain	ε	$\varepsilon_P = \varepsilon_M$	$\varepsilon_P = \lambda\ e^{-1}\ \rho\ \varepsilon_M$
Time	t	$t_P = \lambda\ e^{-1/2}\ \rho^{1/2}\ t_M$	$t_P = \lambda^{1/2}\ t_M$
Frequency	f	$f_P = \lambda^{-1}\ e^{1/2}\ \rho^{-1/2}\ f_M$	$f_P = \lambda^{-1/2}\ f_M$

Considering the materials commonly used in the construction of structures, significant advantages appear if and when it is possible to have e=1 (E_M=E_P). In this case, and provided that the relationship $\lambda = e/\rho$ is verified the Cauchy and Froude similitude laws result in the same numerical values for all quantities listed in Table I. With e=1 results $\rho = 1/\lambda$, meaning that additional mass should be artificially added to the model.

Usually, the mass to be added has some detrimental effects concerning the operation of the simulator since the apparent weight of the ensemble simulator+model results significantly increased. On the other hand complicated mechanical devices to support the added mass are necessary, thus making the simulator control much more difficult and, in some cases, even introducing unacceptable noise in the signals to be acquired. For those reasons test setups need careful thinking.

SETUP, INSTRUMENTATION AND SIGNAL ACQUISITION

Setup

Due to the above mentioned reasons it seems more advantageous to design a test setup in which the additional mass is located outside the simulator. A typical device, used at LNEC to perform tests on bridge pier models, and accomplishing this condition consists of a set of masses assembled and rigidly connected to constitute an inertial mass device. This set is connected to an L-shaped steel structure laying on teflon pads which are attached on a fixed supporting structure located outside the shaking table. The L-shaped structure together with the attached mass is presumed to be able to slide over the supporting structure with very low friction forces and is linked to a ring at the top of the pier by means of a connecting rod. The connection of this rod to the ring and to the L-shaped structure is made with spherical swivels, thus allowing free rotations along all directions. A schematic aspect of this setup is shown in Figure 2A. Alternatively, the masses could be considered directly at the top of the pier, as shown in Figure 2B; obviously this alternative would present some important problems, namely:

a) The need of another type of auxiliary structure to support the masses. Such a structure seems to be considerably more complicated that the one corresponding to Figure 2A and would introduce important disturbance under severe shaking condition;
b) The location of the masses would introduce significant overturning moments which make the simulator control not as easy as it is in the case of Figure 2A.

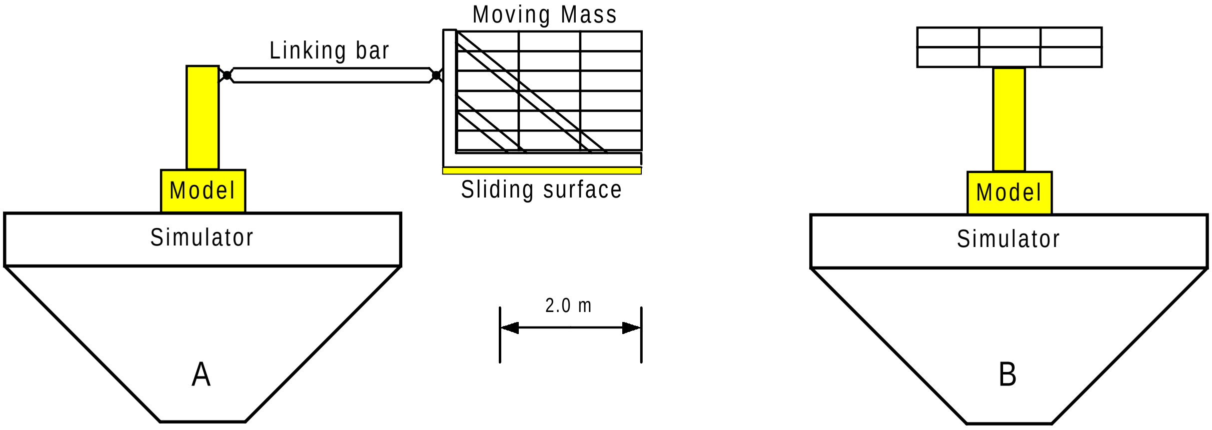

Figure 2

Instrumentation

Concerning the transducers more commonly used in LNEC, for signal acquisition during seismic testing, five different types should be referred: strain gages, linear displacement transducers (LVDT – Linear Variable Differential Transformers), in-plane displacement transducers, load cells and accelerometers. As, among this equipment, the in-plane displacement transducers are the only ones not widely spread, special attention is now paid to this type of equipment.

The simplest in-plane displacement transducers, referred above, are optic-electrical and allow the acquisition of a bi-dimensional position of a target point defined on a specimen. Each optical device must be fixed on an external auxiliary structure, according to a previously defined orientation, in order to have an optical beam as perpendicularly as possible to the selected in-plane movement (typically a surface on a specimen).

These auxiliary structures must be fixed externally (out of the shaking table platform) because this type of equipment should not be subjected to a typical seismic level of vibration. Consequently, the absolute displacements measured must be deduced of the ones reproduced and controlled on the shaking table.

The measurement range of this type of transducers depends on the distance between the optical device and the target. Typically, for a 3 m beam, the range is about 30 cm and the precision is about 0.3 mm, which is clearly enough for the grate majority of the civil engineering seismic tests.

Still concerning the in-plane displacement transducers usually used in the LNEC Earthquake Testing Division, it should be referred another very useful specific type of optical device. In a similar way of the previously defined, this specific equipment allows the simultaneous acquisition of the bi-dimensional position of a set of seven in-plane target points within an area of about one square meter.

These two different types of optical displacement transducers present two very big advantages. First: They do not need any kind of mechanical connections between the optical device and the target, thus avoiding all the usual problems concerning cabling. Second: The only devices on the specimens are the targets, thus avoiding any important equipment deterioration, or even destruction, during tests conducted up to the rupture.

Signal Acquisition

Concerning the signal acquisition, the sampling rate usually adopted for earthquake testing in LNEC is 5 ms, allowing, according to the Nyquist theorem, the analysis of signals up to about 100 Hz without aliasing problems. Concurrently, the chose of an adequate filtering procedure pays a very prominent role in a correct interpretation of the obtained results and must be decided for each specific testing case.

Just as a typical example, the four following diagrams show exactly the same testing phase, but having been obtained under different filtering conditions. They were obtained during a tests series of reinforced concrete 2.15 m height piers, with a circular hollow section (external and internal diameters of 26 cm and 14 cm, respectively), whose materials were an 80 MPa concrete and a 500 MPa steel. An axial 187.5 kN pre-stressed cable was applied to each specimen, as well as an exterior 12 Ton top mass in order to produce the inertial effects (Bairrao et al., 1999).

The following pictures represent an aspect of one of these piers behaviour (Horizontal Force / Top Displacement) when its footing was submitted to a sinusoidal horizontal vibration of 36 mm amplitude, 20 s duration and 0.9 Hz frequency. Figure 3 shows a diagram with signals acquired below 40 Hz, Figure 4 below 20 Hz, Figure 5 below 10 Hz and Figure 6 below 2 Hz. Just looking to the different aspects of these diagrams is obvious the importance of the adopted filtering.

Although the overall relatively good representation of the initial elastic phase, and its correspondent stiffness, it is clear that it is not the case during the non-linear phase. In the first figure is already possible to understand the main behaviour of the structure, being however necessary the use of a high frequency filtering. In the following figures the maximum frequency is successively reduced until an extremely low value, just to prove that very important phenomena, as the pinching effect, can even disappear if the filtering procedure is not adequate.

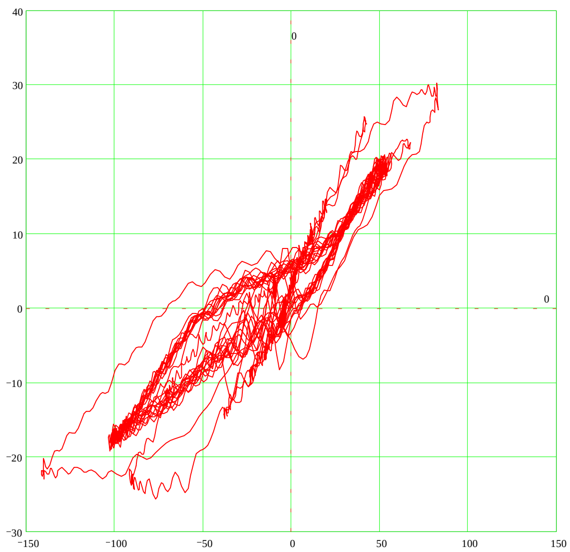

Figure 3

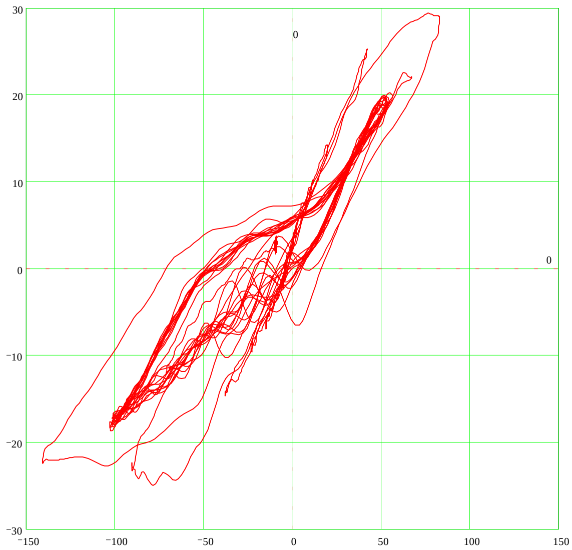

Figure 4

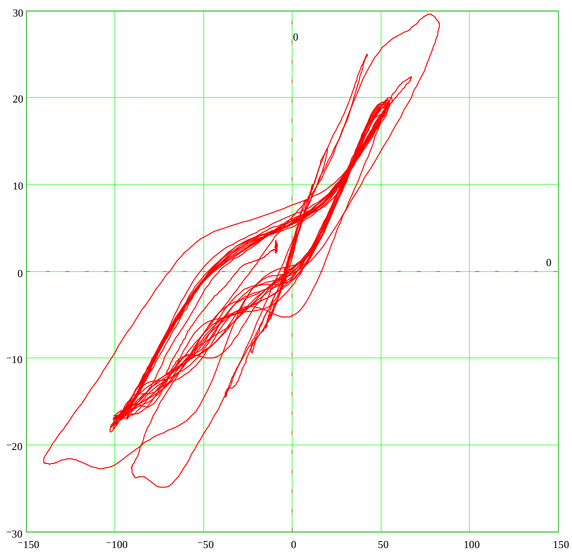

Figure 5

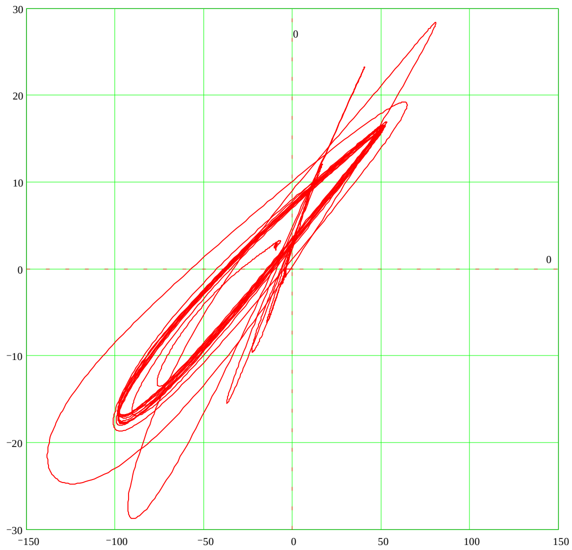

Figure 6

ESTABLISHMENT OF TEST STRATEGIES

In general, the number of models available is limited due to their high cost. In the extreme situation of having just one model available, the important issue is to define the testing strategy so that the maximum information can be retained, i.e., what should be the optimal increase of shaking intensity. In fact, the option for very small increments of the intensity probably will cause a premature damage of the model when the relevant intensities are reached; on the other hand, very large increments can lead to misrepresentative information, in the sense that the relevant intensities are overpassed. The methodology to establish the optimum test strategy is based on knowledge of the vulnerability function. This function is a non-linear function which relates the parameters describing the severity of earthquake actions (h) with the variables that describe their effects in the structures (c). An efficient procedure to estimate the vulnerability function, based on the application of the theorem of Bayes, has been developed.

The theorem of Bayes relates a priori probabilities with a posteriori probabilities, taking into account the occurrence of some event. Let S = $\{s_1, s_2, s_3, ...\}$ be a probability space in which states s_1, s_2, s_3, ... are mutually exclusive, $P(s_i)$ the a priori probability of state s_i and $P(r \mid s_i)$ the conditional probability of an event r, if state s_i stands. Then the a posteriori probability $P(s_i \mid r)$ of state s_i, if event r happens, is given by

$$P(s_i \mid r) = \frac{P(s_i)\, P(r \mid s_i)}{\sum_i P(s_i)\, P(r \mid s_i)}$$

Therefore changing from a priori to a posteriori probabilities corresponds to the changing of the knowledge due to the occurrence of event r.

Assuming total absence of information, the vulnerability function may be any function subjected to the restriction of being a non-decreasing function, since it seems reasonable that an increasing in the loads will correspond to an increasing in the load effects. Since, from a practical viewpoint, it doesn't make sense to find the "true" vulnerability function, the first step consists in generating a number of functions which, is finite (Duarte, 1991). One of the functions in this set will match the "true" vulnerability function under an appropriate norm. The set of functions is probabilised by associating to each function V_i a probability value p_i. Those probabilities must obey to the condition $\Sigma\, p_i = 1$. Each set of values $p = \{p_1, p_2, p_3, ...\}^T$ represents a state of knowledge. There is a good state of knowledge when all the functions in the set are associated to very small probabilities with exception of those ones which are close to the "true" vulnerability function.

As above referred, at the beginning the state of knowledge is non-informative, represented by a constant probability density in a logarithmic scale, i.e., the probability of the probability of failure lying in the interval $(10^{-3}, 10^{-4})$ is equal to the probability of it lying in the interval $(10^{-4}, 10^{-5})$, and similarly for the other similar intervals. Values of p_i may be easily computed to ensure approximately a non-informative distribution. The uncertainty associated to each state of knowledge may be quantified by the ratio between the 5% and the 95% fractiles of the probability distribution of the probability of failure.

Bayesian analysis

When a non-linear computation is performed, the value of the control variable is just an estimate of the "true" value of the vulnerability function, since earthquake actions are idealised by a stochastic model. However, several realisations (time histories of acceleration) of the stochastic process may be used and, consequently, a sample of values of the control variables is obtained and the sample mean value obviously is a better estimate of the "true" value of the vulnerability function.

The influence of the sample size constitutes an important issue but, (Duarte, 1991), the sample mean value approximately follows a gaussian distribution with a mean value equal to the mean value of the response to one realisation and a variance equal to the variance of the response to one realisation divided by the number of elements in the sample. Several past studies have shown that variance may be assumed to correspond to a coefficient of variation c.o.v.= 0.3.

Therefore it is possible to compute the conditional probability $P(c \mid V_i(h))$ of obtaining a mean value c of the control variable, if function $V_i(h)$ is the "true" vulnerability function, by

$$P(c \mid V_i(h)) = G\left(V_i(h)\,,\ \frac{\text{c.o.v.}^2\, V_i^2(h)}{n} \right)$$

where $G(\mu , \sigma^2)$ represents a gaussian distribution with mean value μ and variance σ^2 and n is the number of realisations. This result allows the computation of the a posteriori probabilities $P(V_i(h) \mid c)$ such that

$$P(V_i(h) \mid c) = \frac{P(V_i(h))P(c \mid V_i(h))}{\sum_i P(V_i(h))P(c \mid V_i(h))}$$

which represent a new state of knowledge with a new value of the probabilities associated to each function in the set $p_i = P(V_i(h) \mid c)$.

Preposteriori analysis

The value h of the intensity of earthquake vibration to be used in the non-linear computations may be selected to provide an optimal increase in knowledge through a preposteriori analysis. This basically consists in a probabilistic evaluation for a large number of h values whose change in the state of knowledge is expectable if the computations are performed for that value. This evaluation is carried out by computing for each value the 5% and 95% fractiles of the probability distribution of obtaining a value of the response, as may be computed from the probabilities p_i of the functions in the set, for each intensity. The optimal increase in the state of knowledge will correspond to the minimum value of the ratio between the 5% and 95% fractiles, the corresponding value of h being selected to perform the next series of non-linear analysis.

Example

Let α be the ratio between the intensities of 2 consecutive experiments on the same model. Values α=1.2, α=1.44 (1.2^2) and α=1.728 (1.2^3) have been considered, regarding 3 different models to be tested with different strategies. Assuming that for each model the starting intensity corresponds to a peak ground acceleration a_g=1 m/s^2, each one of these models will be tested considering the following intensities: 1.0, 1.2, 1.44, ... m/s^2 for the model with α=1.2,   1.0, 1.44, 1.44^2, ... m/s^2 for the model with α=1.44 and 1.0, 1.728, 1.728^2, ... m/s^2 for the model with α=1.728.

The relevant quantities to be controlled are the mean value of the probability distribution of the probability of failure and the corresponding values of the 5% and 95% fractiles. The variation of the estimates of those quantities for the different values of α are shown in Figure 7. From that figure fast convergence is evident. It should be noted that in those figures consecutive iterations do not correspond to consecutive (and increasing) values of the intensity but to the intensities "foreseen" as more informative according to the preposteriori analysis above referred. The values of the mean value and for the 5% and 95% fractiles of the probability distribution of the probability of failure for the analyses performed are shown in Figure 8 for the several values of α.

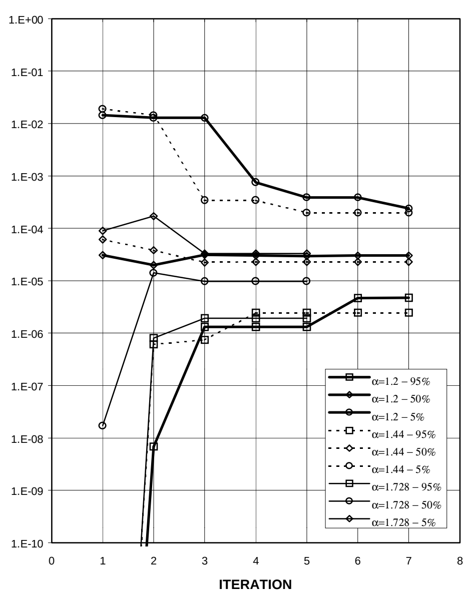

Figure 7

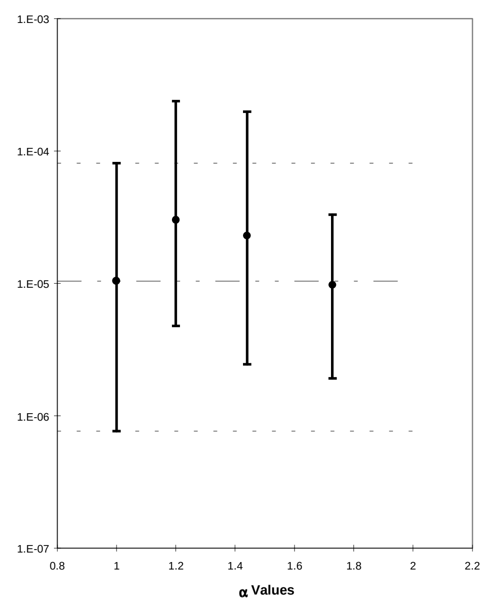

Figure 8

CONCLUSIONS

In this paper some of the experience gained with the operation of the LNEC 3D Earthquake Simulator was reported. Some specific aspects were referred to, namely:

a) Test setups;
b) Signal acquisition and processing;
c) Establishment of test stategies.

In what concerns test setups, some problems arising when high inertia forces are involved were discussed. The advantage of having the mass associated to that inertia forces located out of the simulator seems to be unquestionable from several points of view.

Signal acquisition and processing is also an important issue and some examples of the care to be put in the signal processing and interpretation were highlighted.

Finally, an analytical procedure, useful to define test strategies, was presented. That procedure allows the optimization of the testing sequence in tests performed by stages with increasing shaking intensities, thus producing the most profitable information to be obtained at the end of each stage.

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