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ORIGINAL RESEARCH PAPER

Original technologies for proven performances for the new LCPC earthquake simulator

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Abstract The European Quaker project has been a powerful opportunity to accelerate the development of the ability to carry out earthquake simulations at reduced scale in the centrifuge in LCPC—France. This paper summarizes the main original technologies of this simulator. The quality of the checked performances is demonstrated in terms of ability to perform since earthquakes as well as to simulate scaled records of real earthquakes. The consistancy of the results is presented in the time and in the frequency domains.

Keywords Reduced scale modelling · Centrifuge · Earthquake simulation · Sine input · Real record simulation · Quality of input

1 Introduction

Centrifuge modelling has no longer to demonstrate its relevance in the domain of earthquake engineering: the increasing place taken by this experimental approach in research publications shows a large worldwide acceptation. In the framework of the importance given to earthquake hazards in the French State disaster prevention programs, the Ministry of Civil Works and the Ministry of Research funded the Laboratoire Central des Ponts et Chaussées (LCPC) in 2003 for the development of a facility for reduced scale simulation of earthquakes. The Région des Pays de la Loire also brought a significant funding. The involvement of LCPC in the European Quaker Program gave a powerful acceleration to this investment.

The specifications of the earthquake simulator correspond to the orientations of LCPC in this domain: mono and multi-frequency inputs for a wide range of use with a high level of control on the movements, especially spurious movements. These efforts for such a control of the performances and purity of the frequency content is a posteriori justified by a recent publication by Madabhushi et al. (2006): they showed, in a slope spreading problem, that

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Table 1 Specified performances of LCPC earthquake simulator

Payload	400 kg	Velocity peak	1 m/s
Payload dimensions	$1.00 \times 0.5 \times 0.6$ m	Displacement peak	5 mm
Centrifuge g-level	20–80g	Maximum test duration	1 s
Seismic g-level (Y direction)	40g or 0.5 centrifuge g-level	Frequency response (in sine)	20–200 Hz

Spurious movements: X and Z mean accelerations <0.1. Y acceleration

sinusoidal earthquakes can generate less down slope movements than more realistic input. The authors explain that the time history of the input has a strong link with the cyclic evolution of the pore pressure and then with the mobility of the soil. Testing with a well controlled input appears then of main scientific importance. For the preservation of the centrifuge facility, LCPC chose to remain limited to 1D shaking and to pay much care to the isolation from vibrations transferred to the centrifuge machine. Of course, there is a contradiction between 1D shaking and "realistic" shaking but, considering the technological difficulties of 2D or 3D devices, LCPC thought this prudent compromise adapted event for exploring the effect showed by Madabushi et al. The device is shortly presented here (see Chazelas et al. (2006) and Derkx et al. (2006) for details). The focus is put here on the checked performances: quality of the mono and multi-frequency seismic input (spurious movements and frequency content) and the simulator–centrifuge decoupling.

2 The ACTIDYN SYSTEME QS80 earthquake simulator (EQS)

The specified performances were chosen from a bibliographic state of the art and adapted to the capacity of the 200 ton-g LCPC centrifuge. The definition of a compromise has been simplified by the earlier study by R. Phillips at C-Core (N. F., Canada) who operates the same centrifuge. At LCPC, the maximum displacement is increased to 5 mm (Table 1).

Main design features can be summarized as follows:

- the device is powered by two double-storey TEAM Corp. servo-valves acting on two jacks, one on each side of the shaking table,
- the mobile set embarked in the basket of the centrifuge is composed of the payload itself and a counterweight moving permanently in opposite phase and providing a global dynamic equilibrium to the mobile set. The jacks are established laterally between two superimposed shaking tables: one table bearing the counterweight on the shaker basis and one bearing the payload on the counterweight table. All these elements reduce the vibrations transmitted to the basket and the arms,
- the tables are not laterally guided; the signal driving the jacks are computed to keep the perfect 1D displacement of the payload table,
- the control system is composed of a Data Physics Abaqus Controller at the pivot of the centrifuge and a multi-axis Data Physics Matrix Signal Star software operated from the command room of the centrifuge.

3 Checked performance during acceptance test

The acceptance tests where performed with a rigid concrete 400 kg block as a payload. Accelerometer placed at an end of the payload table indicates the input acceleration $\ddot{Y}$, the

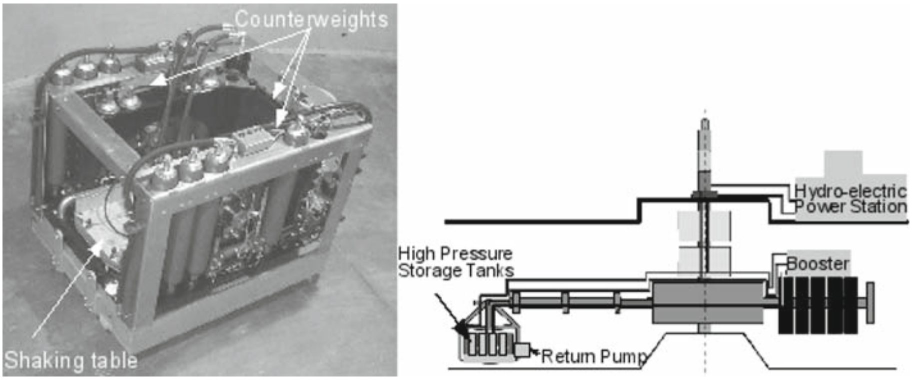

Fig. 1 Left: View of the EQS part embarked in the centrifuge basket (fron counterweight withdrawn to see the shaking table); Right: Diagram showing the hydraulic power supply and storage organization

Table 2 Relative amplitudes of the secondary frequency peaks in the *Y* acceleration records for sine inputs

40 gc 32 Hz 20 gh		40 gc 62 Hz 20 gh		40 gc 90 Hz 20 gh		40 gc 120 Hz 15 gh	
Freq	%	Freq	%	Freq	%	Freq	%
21.50	0.5	62.00	100	90.00	100	109.50	1.7
32.00	100.0	186.50	2.2	180.00	9.3	120.00	100
42.50	0.8	214.00	1.4	270.00	1.4	130.50	1.7
95.50	1.7	248.00	1.7	294.00	1.3	239.50	2.3
128.00	7.4	310.00	5.6	319.00	1.1	300.00	2.9
140.50	2.6	338.00	1.8	335.00	2.0	332.50	0.7
159.50	2.5	372.00	2.0	360.00	8.0	348.50	0.7
192.00	1.3	399.50	1.1	384.50	1.7	360.00	9.2

yawing acceleration $\ddot{X}$ and the rocking acceleration $\ddot{Z}$ (according to the local repair attached to the payload). Figure 1 is a synthesis of the results of the acceptance tests with a sine inputs at 40 gc full payload (gc for centrifuge acceleration in g's and gh for horizontal seismic acceleration). Each test is marked in Fig. 1 according the agreement with the acceptance criterion detailed under the figure: at 40 gc, the EQS covers almost perfectly the expected specifications. At 80 gc, the maximum possible centrifuge acceleration, the test were less satisfying over 120 Hz and below 50 Hz (spurious accelerations around 20–30%) but recent improvement of the control validated at 40 gc call for new tests.

Though not contractually specified, the quality of the sine input was also appreciated through the frequency content. Table 2 is an extract of this analysis; frequency peaks were pointed on the Fourier transform of the payload table accelerations for different levels of inputs at 40 gc. It shows that harmonics and non-coherent frequencies are always lower than 10% even up to 120 Hz. The results at 80 gc are very similar and the recent improvement of the cross calibration of the accelerometers in the control loop largely improved this behaviour.

For the control of the ability of performing multi-frequency inputs, the records of four reference earthquakes were selected for their specific signature: Kobe, 1995, Landers, 1992, Northridge, 1994, Mexico, 1985. These records were filtered to match the 20–350 Hz frequency bandwidth (wider than for sines) and scaled to the physical limits indicated in Table 1

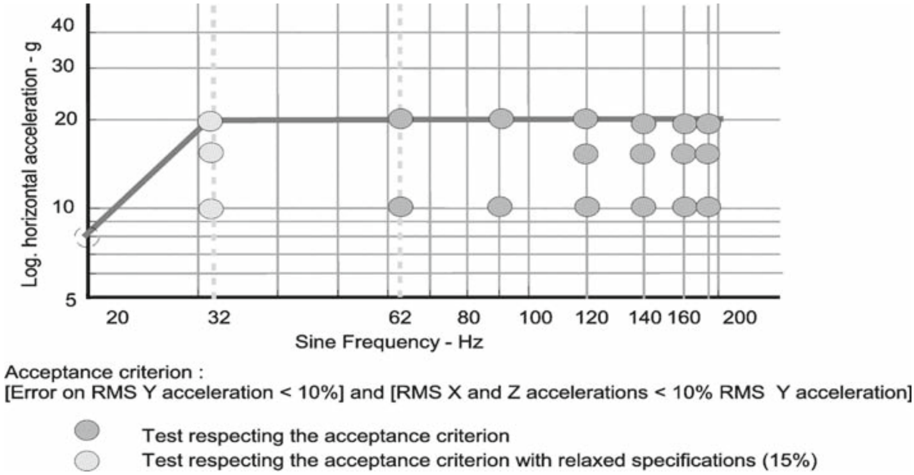

Fig. 2 Check chart of the specification at 40*g* centrifuge

according to the scaling laws. Figure 2 shows almost perfect match of the responses to the references. This is true for the four types of earthquakes. For Kobe at 70 gc, "reference—3.2 dB" indicates the reduction factor to match the velocity the limit: 1 m/s. In the same way, as the lowest controlled frequency is 20 Hz, Kobe cannot be correctly modeled below the scale of 1/50th, due to its strong frequency content between 0.4 and 0.5 Hz at real scale. The ratio of the yawing and rocking to the earthquake inputs were of the same order than for the sine inputs untill 200 Hz (Fig 3).

Looking globally on the quality of the fit of the frequency content, Fig. 4 shows, for example, the frequency analysis of the simulation of a record of the 1992 Landers earthquake. It proves that—in the 20–300 Hz bandwidth- the FFT of the reference acceleration—in thin dashed line—is perfectly fitted by the *Y* acceleration—in dark solid line—recorded on the table. On the other hand it also shows that the spurious movements, the X (yawing) and Z (rocking) accelerations, recorded at the end of the table are of very reduced amplitude as regard to the Y component. It must be noted that there also is a permanent 830 Hz component due to the dither movement applied to the jacks of the shaking table. Considering the amplitude of this acceleration, it can be considered as negligible, especially in terms of displacement.

The vibration insulation level could be appreciated through the comparison of the recorded acceleration on the arms of the centrifuge and the acceleration calculated in case of the classical inertial insulation, simply due to the ratio between the masses of the payload and the basket. The insulation observed is 5–9 times better than the inertial one, from 40 to 100 Hz under 40 gc. Below 40 Hz it reduces to 3 and over 100 Hz, the insulation reduces progressively to the inertial level. However, at these frequencies, the generated displacement are so weak that the risk of damage is negligible.

4 Conclusions

LCPC proposes now to the scientific and operational community the most advanced reduced scale earthquake simulator in Europe. The device developed by Actidyn Systemes has been submitted to an important series of acceptance tests and behaviour analyses. The proven

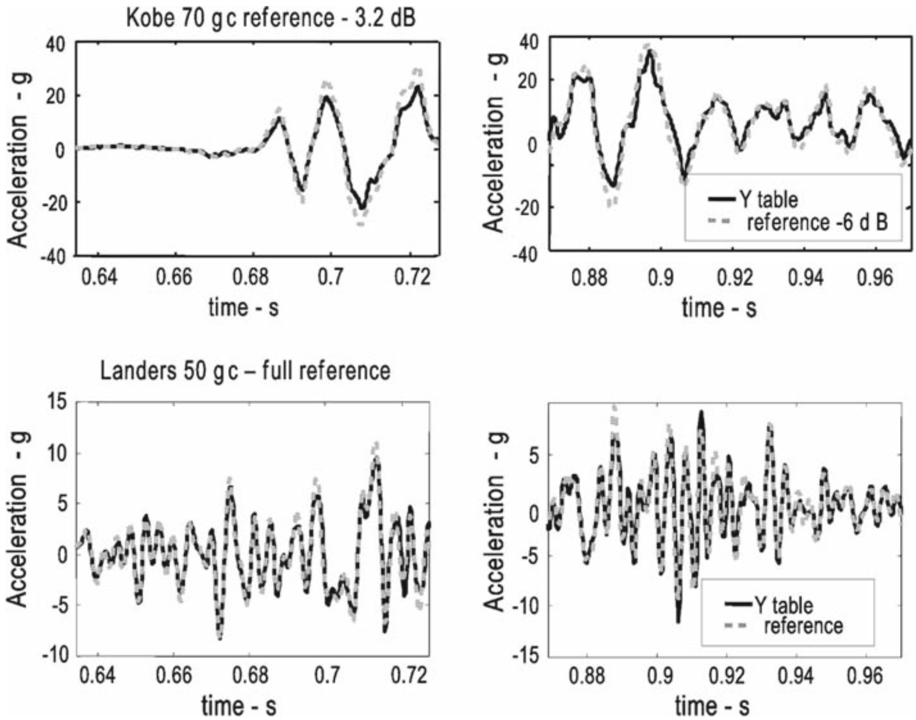

Fig. 3 Detail records of the simulation of reference earthquake: left, beginning of the signal; right, end of the signal. Up, Landers – 50 gc; down, Kobe 70 gc

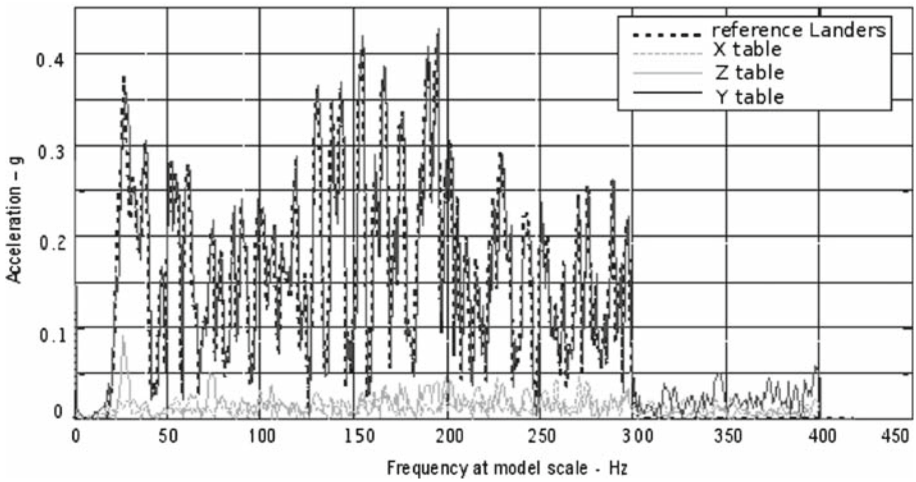

Fig. 4 Frequency analysis of the simulation of a record of the 1992 Landers earthquake. Centrifuge acceleration 40 gc

performances and the high level of fitting of the input motion recorded on the shaking table to the scheduled input opens a wide range of research approaches and will enable fine studies on the effects of the different types of inputs on the earthquake engineering problems.

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