PROJECT NEFOREE – TASK 1

Controlled Testing in the Non-Linear Range: Description of the Facility and Experimental Program

Lisbon, February 2007

I&D ESTRUTURAS

RELATÓRIO 25/2007 – NESDE/DE
PROJECTO NEFOREEE - TASK 1

Controlo de testes em presença de comportamentos não-lineares: Descrição das instalações e programa experimental

O presente Relatório refere-se à Task 1 do Projecto NEFOREEE (New Fields of Research in Earthquake Engineering Experimentation) e compreende a descrição da plataforma sísmica triaxial do LNEC e o programa experimental desenvolvido no âmbito do Projecto em causa.

Apresenta-se a descrição da mesa sísmica com suporte gráfico, desenhos de dimensionamento e fotografias, bem como o seu sistema de controlo. Inclui-se ainda a instrumentação disponível no NESDE e a utilizada em particular para estes ensaios.

Descreve-se o modelo ensaiado, a sequência de ensaios e por fim apresentam-se os resultados obtidos. Para finalizar é feita uma breve análise de resultados.

Lisboa, Laboratório Nacional de Engenharia Civil, Fevereiro de 2007

NEFOREEE PROJECT – TASK 1

Controlled testing in the non-linear Range: Description of the facility and experimental program

This Report corresponds to Task 1 of the NEFOREEE (New Fields of Research in Earthquake Engineering Experimentation) Project and comprises the description of the LNEC triaxial seismic platform and a presentation of the experimental program developed in the scope of this Project.

It is presented a description of the facility and the 3D seismic table with graphical support, drawings of sizing and photographs, as well as its control system. The main instrumentation available at the NESDE laboratory and used for these tests is also included in this report.

The model tested is described as well as the sequence of tests and the obtained results. Finally a brief analysis of the results is made.

Lisbon, Laboratório Nacional de Engenharia Civil, February 2007
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1. Introduction

This report provides a detailed account of a series of shaking table tests performed on a very specific specimen at the Portuguese National Laboratory of Civil Engineering (LNEC). The object of this research report corresponds to a part of TASK1 of NEFOREEE project (New Fields of Research in Earthquake Engineering Experimentation), named “Controlled Testing in the Non-Linear Range”.

The main objectives of the NEFOREE Project are to pursue research in the following six areas of earthquake engineering:

1. Controlled testing in the non-linear range of material behaviour.
2. The complementarity of shaking tables and reaction walls.
3. Reliability of qualification tests performed on shaking tables.
4. Sub-structuring methods on shaking tables.
5. Multiple support input to large structures.
6. Continuous pseudodynamic (CPsD) testing with substructuring.

Each of the referred objectives corresponded to a determined Task, being LNEC involved in TASK 1 (Controlled Testing in the Non-Linear Range), and TASK 2 (Complementary Nature of Shaking Tables and Reaction Walls. For each one of the Tasks the lead partner was responsible for setting the objectives [1].

In what concerns the TASK1, the leadership was from the responsibility of CEA Saclay and the proposed research objectives were:

1. Test the large-scale model designed by the 3 partners and constructed in France. Two non-linear energy-absorbing devices will be used, together with a variety of inputs.
2. Carry out corroborating analysis of these tests, comparing linear with nonlinear behaviour.
3. Investigate what effect the previous results may have on Design Costs, particularly in EC8.
4. To transfer the model to LNEC Lisbon and LEE Athens for the same series of tests.

The test specimen was designed taking into account the different characteristics of each shaking table facility. The main characteristic of the specimen was the simulation of the global non-linear behaviour of a structure while being damaged during an earthquake. Besides that, the specimen had to be able to change its stiffness during the seismic tests in a controlled way, whenever wanted and during an adjustable duration.

Several tests were performed with the input motion to be scaled to achieve the required peak acceleration. During testing, the stiffness of the specimen was decreased, 5 seconds after the signal has been started by slow of fast discharge of pressure air.

These tests were performed in LNEC shaking table during the beginning of January 2005 and were carried out in the transverse direction of the shaking table.
2. Earthquake testing facility at LNEC

The 3D shaking table together with a uniaxial shaking table are placed in the Earthquake Engineering Research Centre (NESDE), a LNEC division devoted to the research in the area of Earthquake Engineering. The research is being developed in NESDE in the past years addressing subjects from the seismic experimental and analytical modeling of structural systems to the issues of the seismic hazard and risk analysis [2].

LNEC seismic facility operates since 1996 and has been integrated in the “Large Scale Scientific Instalations” of the European Union since its beginning. The equipment is operated by LNEC personnel. Besides the shaking tables and their power stations, this infrastructure includes specifically dedicated rooms devoted to control, data acquisition and processing.

The use of LNEC seismic testing facility by external users has been providing significant information and important outcomes for the improvement of knowledge on the seismic response of different types of structures. The equipment and the methodologies of testing have to be frequently improved, aiming at the continuous improvement of the service provided and the increase of the field of application of the facility.

The interest of the studies performed within the use of this facility has been clearly demonstrated by the results of several large experimental studies carried out within the European funded ECOEST and ECOLEADER networks that enabled, in the framework of the Large Scale Facilities and Access to Research Infrastructures sub-programmes of TMR and IHP Programmes, the access of numerous foreign researchers to the LNEC facility and allowed the study of several key issues in Earthquake Engineering Research.

LNEC international standing has already attracted a widespread of interested scientific groups, clearly demonstrated by the quality of previous users and also by the interest shown by potential future users. It should be mentioned that LNEC 3D shaking table has unique features, which justify that some experimental research activities can only be performed in this facility.

On the National scale, LNEC holds a leading position in the fields of seismic testing and earthquake risk assessment. NESDE/LNEC has developed important activity in the framework definition of seismic scenarios for the Metropolitan Area of Lisbon (MAL) by the request of the National Civil Protection.

2.1. LNEC 3D Shaking table

The LNEC3-D shaking table is constituted by three main subgroups: (1) the body (or platform), on which the models or specimens are attached and tested; (2) the guidance system, whose main mission consists of ensuring that the platform only moves according to desired degrees of freedom; and (3) the actuating system, which includes the control systems associates and that has for mission to impose the desired action during the experimental programs [3].

The platform is a structure in welded steel plates with a triangular prism form, with the corresponding useful dimensions of 4,6x5,6 m² where are mounted and fixed, the models or specimens to be tested during the experimental programs developed in LNEC. The structure of the platform was conceived in order to present high local and global rigidity in the connection areas with the remaining subgroups of the main structure (as the actuating and guidance systems).
The guidance system constitutes an innovative element when compared to other seismic platforms. In the seismic tests carried out in LNEC 3D seismic platform the global movement of the body will be result of the combination of three translation movements (two horizontal and a vertical one). These translations correspond to the three of the six degrees of freedom of the body of the platform. In this context, the guidance system will have to eliminate (or, in the reality, adequately to restrict) the possibility of the movement of the body according to these three remaining degrees of freedom, that, as it is known, are constituted by rotations around the three orthogonal.

The experience achieved with the seismic platform shows that the performance is not away from what was expect in the design.

The actuating system is essentially constituted by oil-hydromechanical actuators and associated control systems. In a simplified way each actuator is constituted of an hydraulic cylinder of double-effect and pair-connecting rod, one or more servovalves and a set of hydraulic components, responsible for linking, command and security. The oil under pressure (normal
pressure of functioning 200 bar) is supplied by a group of hydraulic motion-bombs with a maximum debit of 690 liters/min [adapted from 2].

Figure 4: General plan of LNEC-3D shaking table.  
Figure 5: Perspective of LNEC-3D shaking table.

In the following tables are resumed the main characteristics of LNEC – 3D shaking table:

**Table 1:** General Characteristics.

<table>
<thead>
<tr>
<th>General Designation</th>
<th>MESA SÍSMICA TRIAXILAL DO LNEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Designation</td>
<td>LNEC-3G</td>
</tr>
<tr>
<td>Design/Construction</td>
<td>LNEC e INSTRON</td>
</tr>
<tr>
<td>Year</td>
<td>1995</td>
</tr>
</tbody>
</table>

**Table 2:** Type of platform.

<table>
<thead>
<tr>
<th></th>
<th>Longitudinal X</th>
<th>Lateral Y</th>
<th>Vertical Z</th>
<th>Rotation X</th>
<th>Rotation Y</th>
<th>Rotation Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiaxial</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Table 3:** Characteristics of the platform.

<table>
<thead>
<tr>
<th>Dimensions (mxm)</th>
<th>4.6x5.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kN)</td>
<td>392</td>
</tr>
<tr>
<td>Material</td>
<td>Steel</td>
</tr>
</tbody>
</table>

**Table 4:** Actuators.

<table>
<thead>
<tr>
<th>Hydraulic actuators</th>
<th>Manufacturer</th>
<th>Force (kN)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>INSTRON</td>
<td>1250</td>
<td>1</td>
</tr>
<tr>
<td>Lateral</td>
<td>INSTRON</td>
<td>750</td>
<td>2</td>
</tr>
<tr>
<td>Vertical</td>
<td>INSTRON</td>
<td>375</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 5: Platform performance.

<table>
<thead>
<tr>
<th>Frequencies</th>
<th></th>
<th>0.1/40.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max effective course</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>mm</td>
<td>290/400</td>
</tr>
<tr>
<td>Vertical</td>
<td>mm</td>
<td>290/400</td>
</tr>
<tr>
<td>Horizontal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max velocity (nominal)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>Transverse</td>
<td>70.1/121.5</td>
</tr>
<tr>
<td>Vertical</td>
<td>Transverse</td>
<td>290/400</td>
</tr>
<tr>
<td>Horizontal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max acceleration (platform without model)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>Transverse</td>
<td>70.1/121.5</td>
</tr>
<tr>
<td>Vertical</td>
<td>Transverse</td>
<td>290/400</td>
</tr>
<tr>
<td>Horizontal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max self-weight of the model</td>
<td>kN</td>
<td>392</td>
</tr>
<tr>
<td>Max compensated self-weight</td>
<td>kN</td>
<td>392</td>
</tr>
</tbody>
</table>

Table 6: Characteristics of the control system.

<table>
<thead>
<tr>
<th>Type of control</th>
<th>Compound (Analogic/Digital)</th>
</tr>
</thead>
</table>

Table 7: Characteristics of the analogic control.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>INSTRON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Uni-Variable units</td>
</tr>
</tbody>
</table>

Table 8: Characteristics of the digital control.

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Industrial Computer</th>
<th>Software Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>INSTRON 8580 Control Tower</td>
<td>INSTRON</td>
</tr>
<tr>
<td>Channels D/A</td>
<td>8 ADC channels – 16 bit</td>
<td></td>
</tr>
<tr>
<td>Channels A/D</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the testing room, where is placed the seismic platform, there are some additional structures that are described in the following tables

Table 9: Hydraulic system.

<table>
<thead>
<tr>
<th>Electric Power (kW)</th>
<th>330</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate (kN)</td>
<td>690</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>20.7</td>
</tr>
</tbody>
</table>

Table 10: Crane system inside the testing room.

<table>
<thead>
<tr>
<th>Number of cranes</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum capacity (kN)</td>
<td>392</td>
</tr>
<tr>
<td>Maximum height (m)</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 11: Access gates.

<table>
<thead>
<tr>
<th>Number of gates</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum height (m)</td>
<td>4.5</td>
</tr>
</tbody>
</table>
2.2. Instrumentation

2.2.1. Optical displacement transducers

Optical displacement transducers HAMAMATSU C5949 (comprising F50 mm lens, sensor head and led target) and HAMAMATSU conditioning device PSH Controllers C2399 can be used for measuring the displacements on the vertical/transverse plane. The following figure and table show the type of HAMAMATSUs used in LNEC-3D shaking table experimental programs and their main characteristics.

![Image of optical spot position instrumentation unit](image)

Figure 6: The optical spot position instrumentation unit (C5949 or C2399) using the semiconductor position sensing element (PSD).

<table>
<thead>
<tr>
<th>Manufacture</th>
<th>HAMAMATSU PHOTONICS (<a href="http://www.hamamatsu.com">www.hamamatsu.com</a>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>C2399-00 and C5949</td>
</tr>
<tr>
<td>Measurement points</td>
<td>1 to 7</td>
</tr>
<tr>
<td>Spectral response</td>
<td>700 to 1150 nm</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>300 Hz</td>
</tr>
<tr>
<td>Position detecting error</td>
<td>+/-1</td>
</tr>
<tr>
<td>Error due to light</td>
<td>+/-1</td>
</tr>
</tbody>
</table>

2.2.2. Inductive displacement transducers – LVDTs

RDP Electronics ACT/2000C, ACT4000C and ACT6000 inductive displacement transducers having work strokes of +/-50mm, +/-100mm and +/-150mm, respectively, can be used for measuring vertical and diagonal displacements. Figures 7 and 8 show the general aspect of the inductive displacement transducers used for the instrumentation in LNEC facility.
The following tables show some of the main characteristics of the LVDT displacement transducers that can be used during the tests performed in LNEC shaking table.

**Table 13:** Characteristics of the RDP displacements transducer.

<table>
<thead>
<tr>
<th>Manufacture</th>
<th>RDP ELECTRONICS (<a href="http://www.rdpe.com">www.rdpe.com</a>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>ACT2000, ACT4000 and ACT6000</td>
</tr>
<tr>
<td>Stroke</td>
<td>+/-50mm (ACT2000); +/-100mm (ACT4000); +/-150mm (ACT6000)</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>15mV/V/mm (ACT6000) to 3030mV/V/mm (ACT2000)</td>
</tr>
<tr>
<td>Energising supply</td>
<td>5 Vrms, 5 Hz</td>
</tr>
<tr>
<td>Linearity deviation</td>
<td>0.08% (ACT2000) to 0.3% (ACT6000)</td>
</tr>
</tbody>
</table>

Besides the RDP Electronics, and for displacement measurements, are also available in LNEC facility inductive displacement transducers from the type HOTTINGER BALDWIN M. Their main characteristics are presented in the following table.

**Table 14:** Characteristics of the Hottinger displacement transducer.

<table>
<thead>
<tr>
<th>Manufacture</th>
<th>HOTTINGER BALDWIN M (<a href="http://www.hbm.com">www.hbm.com</a>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>WA300 and WA500</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>80mV/V</td>
</tr>
<tr>
<td>Linear deviation</td>
<td>700 to 1150 nm</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>+/-0.1% to +/-0.2%</td>
</tr>
<tr>
<td>Frequency range</td>
<td>5 to 65 Hz</td>
</tr>
</tbody>
</table>
2.2.3. Accelerometers

High frequency ENDEVCO, model 7290-A with variable capacitance, CROSSBOW LF series with high precision and PCB Piezotronics, model 337A26, can be used for acceleration measurements in the experimental programs in development in LNEC facility. Figures 9, 10 and 11 show the general aspect of the referred accelerometers.

Figure 9: High frequency ENDEVCO, model 7290-A.

Figure 10: CROSSBOW LF series.

Figure 11: PCB Piezotronics, model 337A26.

The following tables show some of the main characteristics of the accelerometers existing in LNEC facility.

Table 15: Characteristics of the ENDEVCO accelerometers.

<table>
<thead>
<tr>
<th>Manufacture</th>
<th>MEGGITT SENSORS (<a href="http://www.endevco.com">www.endevco.com</a>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>7290A-2 and 7290A-10</td>
</tr>
<tr>
<td>Range [g pk]</td>
<td>+/-2 and +/-10</td>
</tr>
<tr>
<td>Sensitivity (at 100Hz) [mV/g]</td>
<td>1000 +/-20 and 200 +/-10</td>
</tr>
<tr>
<td>Amplitude Response +/-5% [Hz]</td>
<td>0 to 15 and 0 to 500</td>
</tr>
<tr>
<td>Mounted Resonance and frequency [Hz]</td>
<td>1300 and 3000</td>
</tr>
<tr>
<td>Transverse Sensitivity [% Max]</td>
<td>2</td>
</tr>
<tr>
<td>Zero Measurand Output [mV Max]</td>
<td>+/-50</td>
</tr>
<tr>
<td>Damping Ratio [-]</td>
<td>4.5 and 0.7</td>
</tr>
</tbody>
</table>
Table 16: Characteristics of the CROSSBOW LF accelerometers.

<table>
<thead>
<tr>
<th>Manufacture</th>
<th>CROSSBOW (<a href="http://www.xbow.com">www.xbow.com</a>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>CXL02LF3</td>
</tr>
<tr>
<td>Input Range [g pk]</td>
<td>+/-2</td>
</tr>
<tr>
<td>Sensitivity [V/g]</td>
<td>1</td>
</tr>
<tr>
<td>Transverse Sensitivity [%FS]</td>
<td>+/-5</td>
</tr>
<tr>
<td>Non-Linearity [%FS]</td>
<td>+/-2</td>
</tr>
<tr>
<td>Alignment Error [deg]</td>
<td>+/-2</td>
</tr>
<tr>
<td>Noise Density [μg/Hz½ ]</td>
<td>140</td>
</tr>
<tr>
<td>Noise [mg rms]</td>
<td>1</td>
</tr>
<tr>
<td>Bandwidth [Hz]</td>
<td>DC-50</td>
</tr>
</tbody>
</table>

Table 17: Characteristics of the PCB accelerometers.

<table>
<thead>
<tr>
<th>Manufacture</th>
<th>PCB PIEZOTRONICS (<a href="http://www.pcb.com">www.pcb.com</a>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>337A26</td>
</tr>
<tr>
<td>Sensitivity [mV/g]</td>
<td>100</td>
</tr>
<tr>
<td>Measurement range [g pk]</td>
<td>100</td>
</tr>
<tr>
<td>Broadband resolution [g rms]</td>
<td>0.0001</td>
</tr>
<tr>
<td>Frequency range [Hz]</td>
<td>0.5 to 5000</td>
</tr>
</tbody>
</table>

3. Description of the specimen tested

In general the specimen tested is composed by: a) footing plate which allows the perfect connection to CEA, LNEC and NTUA shaking tables, b) rigid steel frame, c) oscillation mass attached with more or less rigidity to the steel frame and corresponding to an initial excitation frequency of about 7Hz, d) system of four pressurized airbags which allows the modification of the frequency during any seismic test. In Figures 12 and 13 are presented, respectively, the front and the lateral view of the model.

The oscillation mass, above referred, is characterized by its stiffness and its damping, which roughly allows the simulation of the response of a model equivalent to a building. The main characteristics are able to change in a controlled way, whenever wanted and during an adjustable duration, in order to simulate the degradation due to seismic inputs. The mobile mass of the specimen corresponds to an important percentage of the shaking tables masses, particularly for the smallest table considered (NTUA) for which corresponds to 70%. The mass, composed by a set of several identical plates has a maximum of 7ton and allows the use of a smaller number of plates if convenient. Transversely the mass is guided in order not to disturb the longitudinal motion during the tests. Vertically the mass is maintained by a bearing device that was designed to have a vertical frequency higher than 20Hz [4].
The frequency was able to be adjusted by the air bags pressures and the damping was ensured by a set of Gerb shock absorbers. The changing of frequency, from about 7Hz to 3Hz during the tests, was obtained by a partial depressurization through specific gauged diaphragms. Two diaphragms of larger (60mm) and smaller (10mm) openings were tested for validation of the discharges duration.

4. Instrumentation of the specimen and shaking tables

The instrumentation on the table and on the specimen consisted only in one displacement transducer to measure the displacement of the additional masses, one optical transducer to measure two displacements on the table and five accelerometers to measure the accelerations on the bottom and top of the specimen, on the centre of the additional masses and at two different points of the shaking table platform to check the level of rotations that were generated. In Figure 14 is presented the instrumentation plan of the specimen and of the shaking table proposed for the NEFOREE – Task 1 Project. In what concerns the LNEC experimental program the accelerometers az2tab, az1tab and axtab were not used.
The different input signals and the condition of the valves were also recorded: a) velocity, force and displacement of the table, b) displacement and force from roll and pitch degrees of freedom, c) displacement, intensity and delta pressure on the level of a servo valve of one actuator, d) driver signal sent to the servo valve, e) opening and closing commands of the valves and e) opening and closing response of the valves.

5. Experimental Program

5.1. Input signal
Preliminary tests have been performed to calibrate the pressure in each pair of airbags to obtain the required frequencies. With the referred pressurized airbags the frequency of the moving mass is 6.7Hz while without pressure the minimum frequency measured was 3.4Hz.

The base signal was filtered for a frequency band ranging from 0.1 to 33 Hz and adapted to achieve a table acceleration of 0.6g. During the tests this signal was scaled to achieve the desired peak acceleration level. In all tests the trigger action to open the relief valves has occurred 5s after the start of the input signal. The slow discharges (approximately 5s) were obtained by using a diaphragm with a 10mm opening; while the fast discharges (approximately 0.1 s) were obtained by using a diaphragm with a 60 mm opening.

5.2. Loading sequence
A common sequence of tests was proposed for the three shaking tables (CEA, LNEC and NTUA) under the NEFOREEE Project. In LNEC were also performed some additional tests. Next table resumes the experimental program performed at LNEC
Table 18: Experimental program performed on LNEC-3D shaking table.

<table>
<thead>
<tr>
<th>PGA [g]</th>
<th>Description</th>
</tr>
</thead>
</table>
| 0.1     | Test 1 - without discharge  
Test 2 - with a 5 seconds discharge (10mm diaphragm)  
Test 3 - with a 0.1 seconds discharge (60mm diaphragm) |
| 0.4     | Test 4 - without discharge  
Test 5 - with a 5 seconds discharge (10mm diaphragm)  
Test 6 - with a 0.1 seconds discharge (60mm diaphragm) |
| 0.6     | Test 7 - without discharge  
Test 8 - with a 5 seconds discharge (10mm diaphragm)  
Test 9 - with a 0.1 seconds discharge (60mm diaphragm) |
| 0.8     | Test 10 - without discharge  
Test 11 - with a 5 seconds discharge (10mm diaphragm)  
Test 12 - with a 0.1 seconds discharge (60mm diaphragm) |
| 1.0     | Test 13 - with a 0.1 seconds discharge (60mm diaphragm) |
| 1.2     | Test 14 - with a 0.1 seconds discharge (60mm diaphragm) |

6. Data acquisition

The model tested was instrumented with accelerometers and inductive displacement transducers (LVDTs) similar to the ones already referred. The corresponding physical units used all along the present Report are g and mm, respectively. The shaking table acceleration and displacement were recorded during the experimental program. The list of channels, with the corresponding identification numbers and simplified description of the measurement parameters, is following presented.

Table 19: List of channels used during the experimental program.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Acceleration in shaking table (EW)</td>
</tr>
<tr>
<td>1</td>
<td>Acceleration in shaking table (NS)</td>
</tr>
<tr>
<td>2</td>
<td>Acceleration in A1 (EW-bottom)</td>
</tr>
<tr>
<td>3</td>
<td>Acceleration in A2 (NS-bottom)</td>
</tr>
<tr>
<td>4</td>
<td>Air Bag Pressure Trigger</td>
</tr>
<tr>
<td>5</td>
<td>Acceleration in A4 (EW-Mass)</td>
</tr>
<tr>
<td>6</td>
<td>Acceleration in A5 (NS-Mass)</td>
</tr>
<tr>
<td>7</td>
<td>Acceleration in A6 (Vert-Mass)</td>
</tr>
<tr>
<td>8</td>
<td>Acceleration in A7 (EW-Top)</td>
</tr>
<tr>
<td>9</td>
<td>Acceleration in A8 (NS-Top)</td>
</tr>
<tr>
<td>10</td>
<td>Acceleration in A9 (Vert-Top)</td>
</tr>
<tr>
<td>11</td>
<td>Displacement in D1 (Mass)</td>
</tr>
<tr>
<td>12</td>
<td>Displacement D2 in shaking table (EW)</td>
</tr>
<tr>
<td>13</td>
<td>Displacement D3 in shaking table (NS)</td>
</tr>
</tbody>
</table>
7. Tests Results

The frequencies of the specimen were obtained by means of the FRFs for each of the tests. The values obtained are summarized in the following table and graphically presented in Annex IV.

Table 20: Frequencies obtained during the experimental program.

<table>
<thead>
<tr>
<th>Test</th>
<th>Frequency of specimen [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.65</td>
</tr>
<tr>
<td>2</td>
<td>7.02</td>
</tr>
<tr>
<td>3</td>
<td>7.02</td>
</tr>
<tr>
<td>4</td>
<td>6.53</td>
</tr>
<tr>
<td>5</td>
<td>6.41</td>
</tr>
<tr>
<td>6</td>
<td>6.53</td>
</tr>
<tr>
<td>7</td>
<td>6.71</td>
</tr>
<tr>
<td>8</td>
<td>6.30</td>
</tr>
<tr>
<td>9</td>
<td>6.53</td>
</tr>
<tr>
<td>10</td>
<td>6.41</td>
</tr>
<tr>
<td>11</td>
<td>6.35</td>
</tr>
<tr>
<td>12</td>
<td>6.47</td>
</tr>
<tr>
<td>13</td>
<td>6.53</td>
</tr>
<tr>
<td>14</td>
<td>6.53</td>
</tr>
</tbody>
</table>

During discharge tests, the change of the frequency of the tests specimen was always triggered 5 seconds from the beginning of the seismic time history. In the case of slow discharge, the change of the frequency of the specimen took place within 5 seconds, while in the case of fast discharge the change of the frequency happened within 0.10 seconds. More detailed results are presented in Annex IV.

For each test, the acceleration time histories (Annex III) and the corresponding response spectrum are plotted, as well as the hysteretic loops of the force-displacement relations (Annex IV) in which may be observed the stiffness reduction from the situations without discharge to the situations with discharge. The comparison between required and achieved peak accelerations is presented in Table 23.

Table 21: Required and achieved peak acceleration.

<table>
<thead>
<tr>
<th>Test</th>
<th>Required peak acceleration [g]</th>
<th>Achieved peak acceleration [g]</th>
<th>Difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>0.082</td>
<td>-18.00</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>0.096</td>
<td>-4.00</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>0.098</td>
<td>-2.00</td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
<td>0.396</td>
<td>-1.00</td>
</tr>
<tr>
<td>5</td>
<td>0.4</td>
<td>0.386</td>
<td>-3.50</td>
</tr>
<tr>
<td>6</td>
<td>0.4</td>
<td>0.392</td>
<td>-2.00</td>
</tr>
<tr>
<td>7</td>
<td>0.6</td>
<td>0.563</td>
<td>-6.17</td>
</tr>
<tr>
<td>8</td>
<td>0.6</td>
<td>0.548</td>
<td>-8.67</td>
</tr>
<tr>
<td>9</td>
<td>0.6</td>
<td>0.555</td>
<td>-7.50</td>
</tr>
<tr>
<td>10</td>
<td>0.8</td>
<td>0.861</td>
<td>7.63</td>
</tr>
<tr>
<td>11</td>
<td>0.8</td>
<td>0.865</td>
<td>8.13</td>
</tr>
<tr>
<td>12</td>
<td>0.8</td>
<td>0.861</td>
<td>7.63</td>
</tr>
<tr>
<td>13</td>
<td>1.0</td>
<td>1.152</td>
<td>15.02</td>
</tr>
<tr>
<td>14</td>
<td>1.2</td>
<td>1.297</td>
<td>8.08</td>
</tr>
</tbody>
</table>
The comparison between the acceleration series for each one of the different PGA steps (0.1, 0.4, 0.6 and 0.8) is also presented in Annex IV. The differences observed correspond to the performance of the table for the different steps of the experimental program and considering the different discharges.

8. Conclusions

The tests carried out on the LNEC shaking table, and the analysis of their results, showed that the control of the LNEC 3D shaking table was not affected by the fast decrease of stiffness of the mock-up. It should be mentioned that the mass of the specimen tested was relatively small when compared with the mass of the shaking table (40 ton).

Comparing the achieved and desired time histories of input motion (Annex II) and the relevant response spectra (Annex IV) for all the performed tests it can be concluded that the tests performed in LNEC have demonstrated an excellent performance achieved by the control system of the shaking table during the performance of the tests. In both cases (slow or fast changes) the frequency of the response did not show a significant difference.

The stiff reduction observed was larger for fast discharges. It was also observed the increasing of the force in the mass during the tests as well as the measured displacements, as expected.

9. Acknowledgements

The studies described in the present paper were financed by the European Union (contract HPRI-CT-2001-50023) under the NEFOREEE Project (New Fields of Research in Earthquake Engineering Experimentation) in the aim of the “Specific Research and Technological Development Programme” of the “Human Research Potential and Socio-Economic Knowledge Base”.

The cooperation of LNEC personnel, namely Engº Campos Costa, Engº Paulo Morais, Artur Santos, Ana Marques, Paulo Semedo and Dulcina Marecos, during the preparation and the performance of the shaking table tests, was deeply appreciated.

The authors wish to thank also Ana Marques, for her careful help concerning the tables and figures preparation and the word processing of this report.

10. References

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Figure 20: Mass EW acceleration (A4).
Figure 21: Mass NS acceleration (A5).

Figure 22: Mass vertical acceleration (A6).

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