

## Dynamic Interaction between the Shaking Table and the Specimen during Earthquake Tests

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### 1 ABSTRACT

The boundary conditions between the tested structures and the platform of a large shaking table are a major parameter for the design and numerical analyses of shaking table tests. A foremost attention is given to the design of the foundation and anchorage of the structure. All analyses are made considering a completely rigid shaking table: rigid actuators and rigid platform. However, since quite a long time, the shaking table / structure interaction has been clearly observed (Blondet and Esparza, 1988) when analysing the shaking table / actuators interaction, depending on the control tuning. In CEA Saclay, during the last 15 years, decreases of mock-up frequencies between calculations and experimental tests of massive structures have been observed: CASSBA, CAMUS 1 to 4, CAMUS 2000 (Combescure and Ragueneau, 2002) and more recently SMART. For a long time it has been calculated, after tests, the global stiffness that the “Azalée” shaking table should have to explain those decreases.

This paper describes and validates the finite-element model of this shaking table platform, presents the mock-up used and finally deals with and concludes on the shaking table / mock-up interaction.

### 2 INTRODUCTION

Much advancement is on progress among the members of the European consortia of earthquake engineering laboratories (Bairrao et al., 2006) and the more important needs of the experimental facilities were already identified in detail (Taucer et al., 2005). The optimisation of leading experimental tools like shaking tables is one of the main fields of research as, for example, control systems, hybrid tests, high-speed data transfer and sub-structuring.

The improvement of shaking table technologies is clearly of paramount importance to reduce the seismic vulnerability of the building stock and also to mitigate the consequences of future, and inevitable, seismic events by contributing significantly to the amelioration of new construction techniques.

The global capacities of the biggest European shaking tables are very moderate when compared with the ones of the more recent Japanese laboratories. Therefore the shaking table test of real and very large structures is not foreseen in Europe for the near future. Consequently, the use of sub-structuring techniques must be developed in order to fix to the simulator platform just a part of the structure while all the remainder will be tested on computer, like in the pseudo-dynamic testing procedure (Bairrao, 2008).

To use this technique in shaking table tests it will be need a real-time control and an indeed very high speed of the data transfer between the control system of the shaking table and the computer system modelling the numerical part of the experiment.

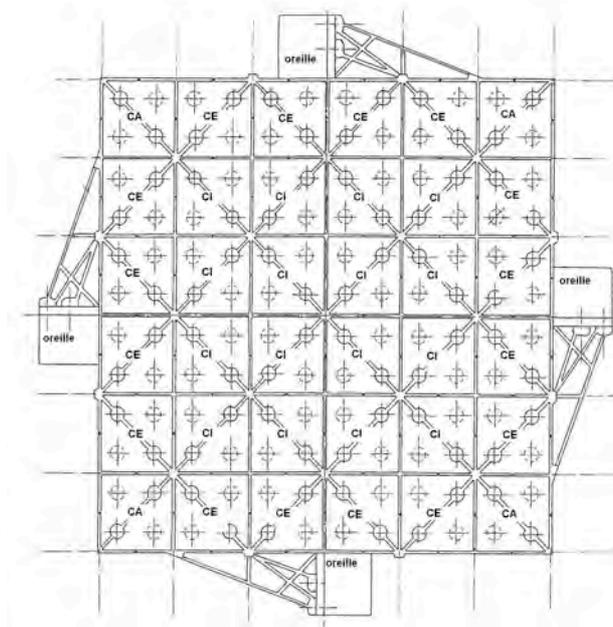
Another very important need in shaking table testing, in order to improve its performance, is a comprehensive study on the interaction between the dynamic characteristics of the facilities (the platforms and all the hydraulics systems) and the specimens during the experiments.

### 3 DESCRIPTION AND VALIDATION OF THE PLATFORM MODEL

This section describes and validates the FE model of the platform of “Azalée” shaking table of CEA Saclay.

#### 3.1 Platform model description

The Azalée platform is a square plate, 6 metres wide and 2 meters deep. It is made of 36 welded aluminium “boxes” and 4 lateral anchorages for the horizontal actuators. The mass of the platform is 23.6 tons and its maximum upload mass is 100 tons.



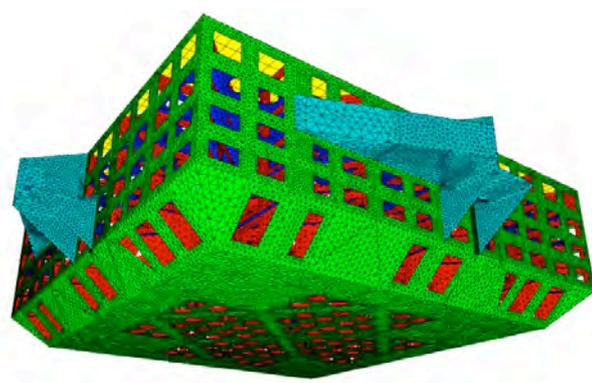
**Figure 1 : Plant view of the Azalée platform.**

Simple analytical models have been initiated initially, using common springs and plates, but that kind of models did not match correctly the more complex details of the “Azalée” geometry. So, a more detailed, but linear, FE model using thin shell elements has been made and fully simplified in order to be easily reproduced on any FE software.

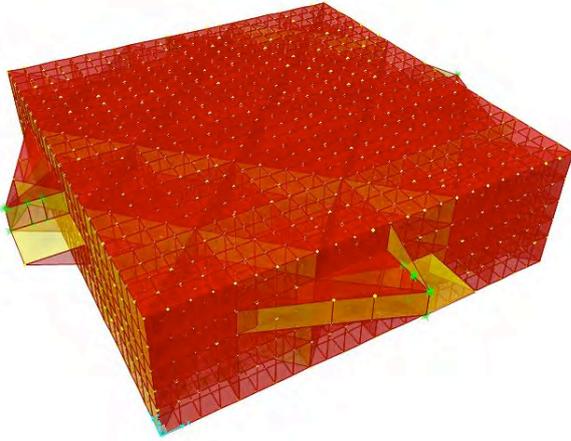
Two boundary conditions were then analysed:

For the first one, the platform was considered supported by 4 air cushions (64 springs in the model). This configuration will be used in the next section to validate the platform model.

For the second one, the platform was considered fixed to 8 rigid actuators (86 unidirectional restraints).

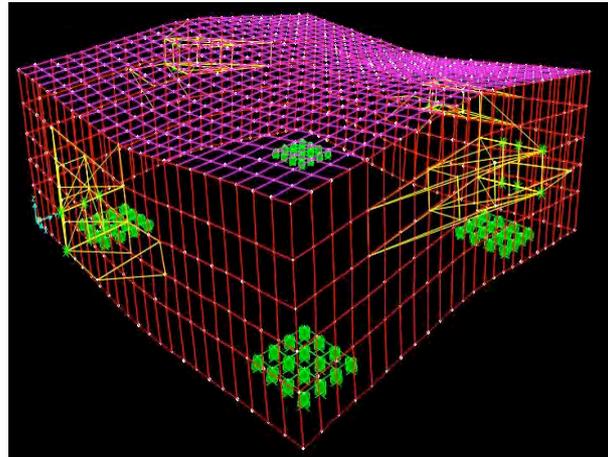


**Figure 2 : Azalée platform.**



**Figure 4 : Simplified Azalée platform model.**

**Fig. 3 : Detailed CASTEM model of the Azalée platform.**



**Figure 5 : Platform on the actuators; mode 6.**

### 3.2 Platform model validation

The validation of this linear FE model was done using 2 reference experimental tests that were performed in 1989 and 2000.

For these frequencies and modes research tests, the platform was simply supported by 4 air cushions (stiffness:  $K_{z\_cous} = 9.08 \cdot 10^5$  N/m), without any actuators. The next table presents a comparison between the calculated and the measured frequencies for each mode.

**Table 1.** Experimental and calculated frequencies with air cushions.

| Boundary conditions |                             | Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5 | Mode 6 |
|---------------------|-----------------------------|--------|--------|--------|--------|--------|--------|
| 4 air cushions      | Experimental frequency (Hz) | 80.5   | 95.7   | 116.2  | 129.2  | 129.3  | 151.1  |
|                     | Calculated frequency (Hz)   | 80.0   | 95.0   | 117.0  | 134.5  | 134.5  | 162.2  |

The platform was then analysed under its usual condition: 8 rigid actuators (hypothesis of a perfect control compensation of the oil column stiffness). Those actuators are represented by 86 unidirectional restraints. The frequencies values, for this situation, are presented in the next table. It should be mentioned that these modes are now different from the ones of the previous configuration.

**Table 2.** Calculated frequencies with rigid actuators.

| Boundary conditions |                           | Mode 1' | Mode 2' | Mode 3' | Mode 4' | Mode 5' | Mode 6' |
|---------------------|---------------------------|---------|---------|---------|---------|---------|---------|
| 8 rigid actuators   | Calculated frequency (Hz) | 54.3    | 54.3    | 65.7    | 73.5    | 73.5    | 99.0    |

These boundary conditions have changed mainly the behaviour of the platform. Five modes have appeared between 54 and 74 Hz. The two first modes are generated by the deformation of the horizontal actuators anchorages to the platform. The other modes are due to the global flexion of the platform.

## 4 THE MOCK-UP

The evaluation of the platform with the structure is done through a study of the decrease of the mock-up frequency between the configurations “on a rigid soil” and “on the shaking table platform”. Then, this second section presents the mock-up used to check the interaction between the platform and the structure.

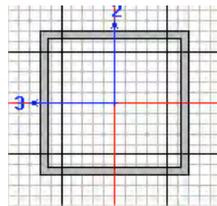
2 linear FE models of structures have been created. The next two sub sections present these FE model.

### 4.1 Simple model

This simple model can be used to make a parametric study.

A beam fixed on a very rigid square plate (Young modulus =  $2.1016 \text{ N/m}^2$ , with no local deformation at the bottom of the beam). Then, several masses and stiffness of the beam have been used to evaluate the frequency decrease of the beam between the configurations “on a rigid soil” and “on the shaking table platform”.

Square section of the beam, 2m wide, 100 mm thin, with no simulation of any torsion mode.



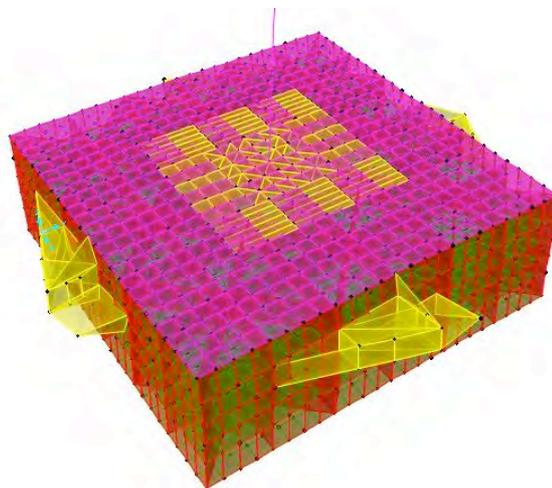
The beam should allow the simulation of flexion and vertical modes of a mock-up.

For example, it was checked that this model can correctly simulate the flexion of the CAMUS mock-up, considering these beam parameters :

Stiffness = 780.6 MN/m.

Mass = 36 ton.

Height = 3.4 m.



**Figure 6 : Azalée platform model with the simple model.**

### 4.2 More complex and realistic structures to compare with a real test.

These structures allow the analysis of different boundary conditions of the mock-up on the platform (local deformations influences).

The first structure is a non-symmetric reinforced concrete mock-up tested in 2008 during the SMART project in the CEA Saclay lab.

The mass of the mock-up is 45 tons.

Its main dimensions are 3.6m high and a surface of 2.5 m x 3 m.

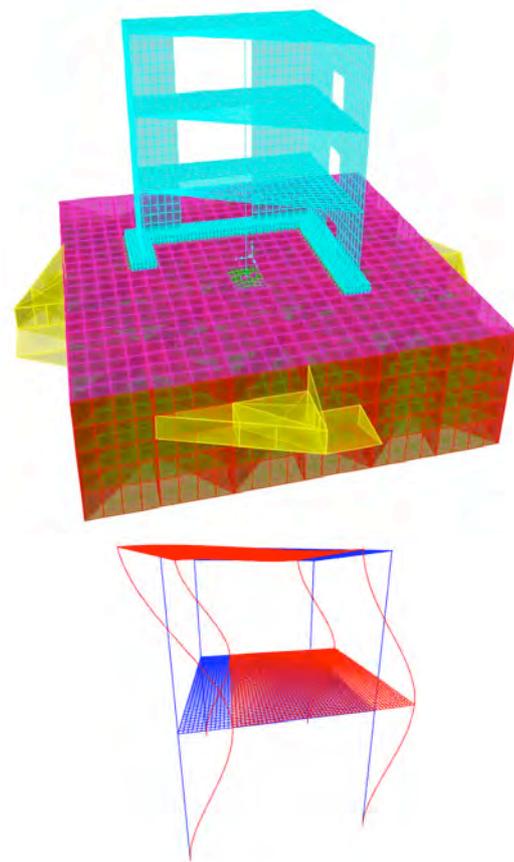
Special care has been taken to the boundary conditions between the mock-up and the platform.

To evaluate the influence of these boundary conditions, another configuration has been tested including a very rigid square plate (Young modulus =  $2.1016 \text{ N/m}^2$ , with no local deformation at the bottom of the mock-up).

The second structure is a reinforced concrete frame with 2 storeys. This mock-up was tested in the CEA Saclay lab in 2004, being one of the mock-ups tested for the ECOLEADER European project.

The mass of the mock-up is 33 tons.

Its main dimensions are 7m high and a surface of 4m x 4m.



**Figure 7 : More complex and realistic structures.**

## 5 RESULTS

The evaluation is done by studying the frequency decrease of the mock-up between the configurations “on a rigid soil” and “on the shaking table platform”.

This study was just performed for each flexion and vertical mode of the mock-up; generally the major ones.

Two abacuses have been created to analyse these results:

- A first one for the mock-up flexion modes: with the modal mass and the centre of mass of the mock-up (flexion moment), we can read the frequency decrease between the two configurations “on a rigid soil” and “on the platform”.

- Another for the mock-up vertical modes: with the modal mass of the mock-up, we can deduce the frequency decrease between these configurations “on a rigid soil” and “on the platform”.

The experimental results of the mock-ups used for the projects SMART and CAMUS and of the ECOLEADER frame are indicated on those abacuses too.

In red are presented possible approximations of some “iso-frequency” (of the mock-up on a rigid soil) lines deduced from the “beam + rigid plate” model.

Most of these comparisons with experimental results are made for the flexion modes. For the CAMUS, ECOLEADER frame and SMART mock-ups with a rigid plate, the abacus prediction of the

frequency decrease is very correct. That means that the actuators are indeed rigid and that the frequency decrease is not due to them.

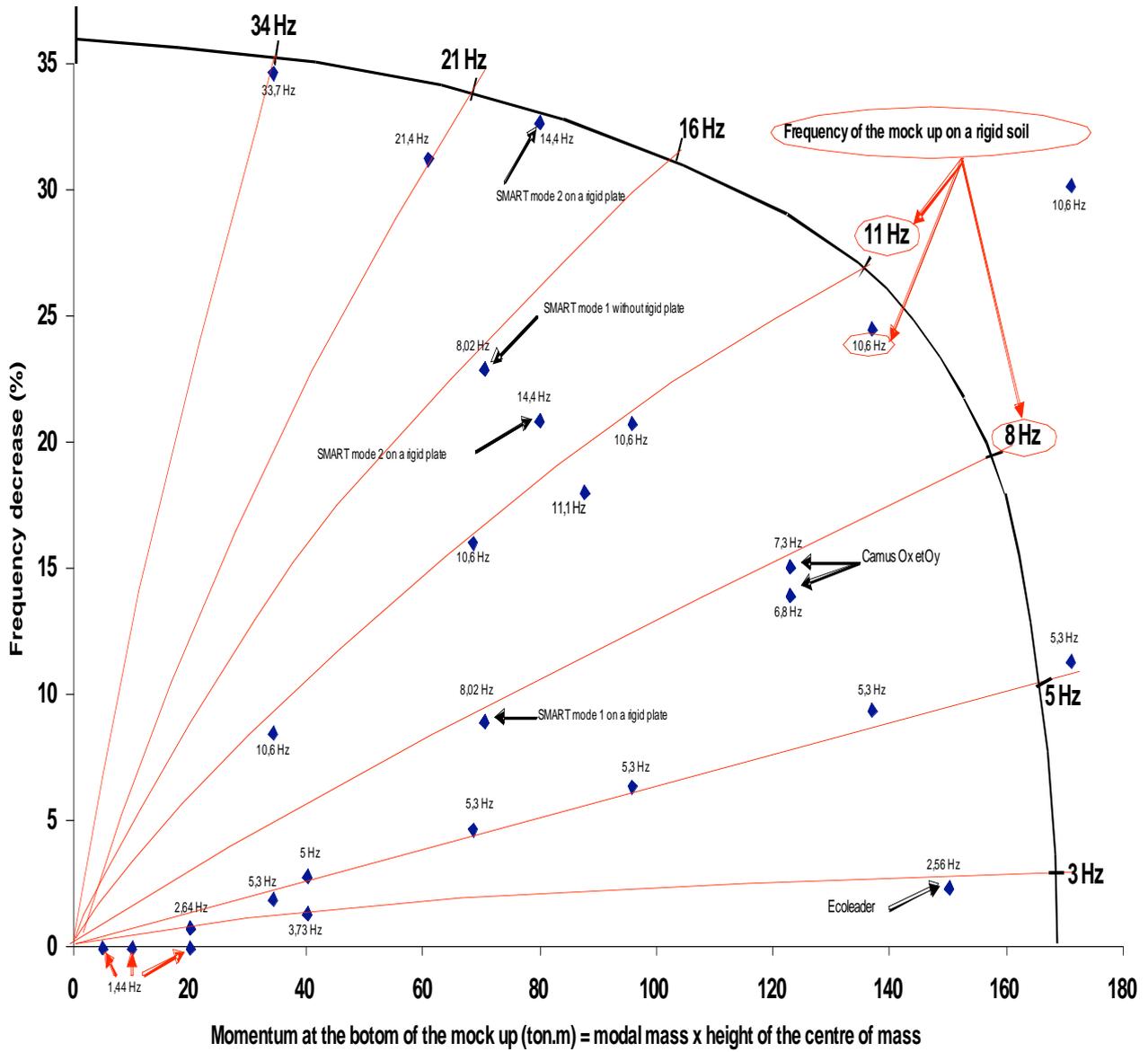
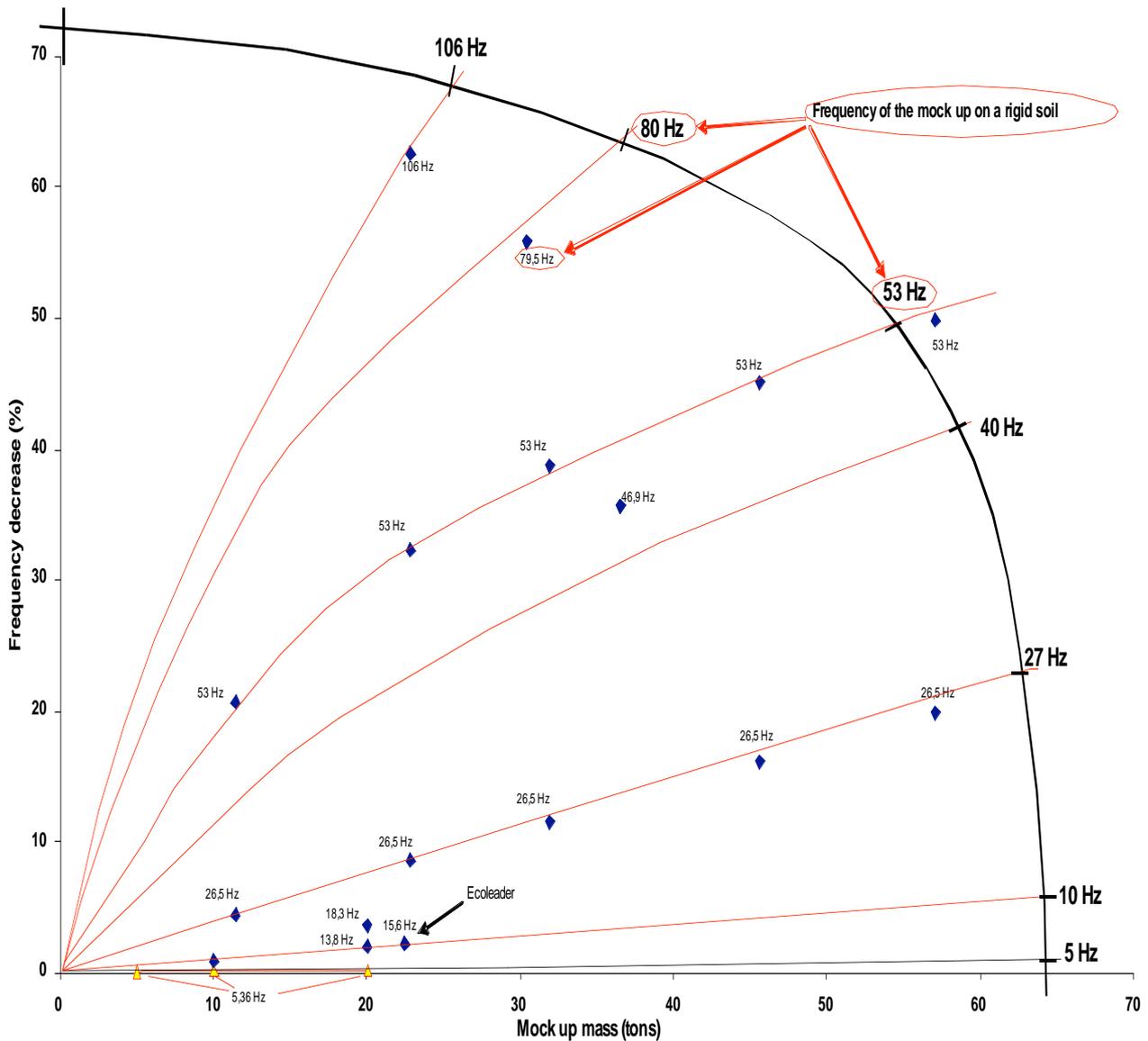


Figure 8 : Abacus for flexion modes.



**Figure 9 : Abacus for vertical modes.**

These simple abacuses are a first approximation allowing a quick evaluation of the frequencies decrease for a mock-up fixed to the Azalée platform.

When a very high decrease is expected, it is now possible to perform a numerical analysis with the mock-up placed on the simplified model of the Azalée platform.

On the abacus for flexion modes, 4 points for the SMART mock-up are considered. Two of them are related to the SMART mock-up with a rigid plate between it and the platform. The two other are related to the SMART mock-up directly fixed to the platform of the Azalée shaking table. The comparison between these configurations “with a rigid plate” and “without a rigid plate” gives an estimation of the decrease generated by the boundary conditions between the mock-up and the platform:

- 9 % to 23 % for the first mode. Then, for this mode, more than half of the decrease is generated by local deformations between the mock-up and the platform.
- 21 % to 33 % for the second mode. For this mode, more than 30 % of the decrease is generated by the same local deformations.

## 6 CONCLUSION

In shaking table studies, a main attention is paid to the design of the foundation and to the anchorage of the structure. All analyses are made considering a completely rigid shaking table: rigid actuators and rigid platform. However, since quite a long time, an interaction between the shaking table and the structure has been clearly observed for massive structures: a decrease of frequency between the structures “on the shaking table” and “on a rigid soil” has been calculated. This article presented the study of the validity domain of a rigid “Azalée” shaking table of the CEA Saclay laboratory (France).

This study demonstrates that, for this large shaking table, most of this interaction is due to the platform deformation during the tests. Two abacuses have been obtained using a simplified structure for flexion and vertical modes, without local deformations between the mock-up and the platform. Those two abacuses have been validated with three large experimental tests performed in the last 10 years at Saclay (CAMUS, ECOLEADER and SMART projects). Using those abacuses, it's now easy to get an evaluation of the minimum decrease of frequency that will have a mock-up fixed on the platform. If this first evaluation shows an important interaction, a more precise study is needed: a simplified FE model of the platform is available and allows a definite evaluation of the interaction. A second evaluation takes into account the local deformations between the mock-up and the platform. For large mock-ups, these local deformations can induce about 50% of frequency decrease.

In previous Azalée shaking table tests, a major attention has been taken during the design of the foundation and anchorage of the structure. Some evaluations of the interaction were made, after test, using simplified models. This study will permit experimental and numerical engineers to better take care, before tests (during the design), of the boundary conditions between the platform of the shaking table “Azalée” and the mock-up. On the Azalée shaking table, more precise comparisons to numerical analyses of large shaking table tests will now be possible too.

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