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Julien Clement, Maria Lancieri, David Bouhjiti, J F Semblat, Benjamin Richard. In-situ characterization of Soil Structure Interaction through measurement of Impedance Functions. EUROODYN 2023 - 12th International Conference on Structural Dynamics, Jul 2023, Delft, Netherlands. pp.252011, 10.1088/1742-6596/2647/25/252011 . irsn-04890675

**HAL Id: irsn-04890675**

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Submitted on 16 Jan 2025

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To cite this article: J Clément *et al* 2024 *J. Phys.: Conf. Ser.* **2647** 252011

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# In-situ characterization of Soil Structure Interaction through measurement of Impedance Functions

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**Abstract.** In situ characterization of structural behaviour under seismic hazard provides an opportunity to acquire experimental data that improve our understanding of soil-structure interaction (SSI). Experimental programs such as Lotung and Hualien in Taiwan, EuroProteas in Greece and NUPEC in Japan, are amongst the most known. Such investigations aim at studying a structure with a rigid shallow raft and measuring the seismic impedance functions at soil-foundation interface. Indeed, impedance functions are by far the most widely used tools to study SSI. In this paper, considering feedbacks from these in situ tests, we aim at assessing the feasibility to acquire measurements of the seismic impedance functions for any structure with a rigid shallow foundation. To test the proposed methodology, we carry out a laboratory test with a small-scale device: the soil is represented by a model material (silicon rubber block) and the foundation by a cylindrical shaker inducing monitored harmonic vertical forces on the silicon rubber block. Experimental tests are paired with numerical simulations to identify, by inverse analysis, unknown parameters and to compute the order of magnitude of displacements and forces within the system. This paper presents the laboratory test setup, the experimental design, and the results of the associated simulations.

## 1. In situ experimental data acquisition of soil-structure interaction (SSI)

One of the pioneering works introducing an experimental perspective to the soil structure interaction (SSI) was established by Richart et al. in 1967 [1]. They studied the case of circular foundations of different diameters (1.5m to 4.8m) subjected to harmonic mechanical loads (horizontal, vertical, torsion). Almost twenty years later, Lin et al. [2] studied a model of a building with a square base (about 3m x 3m) subjected to incident SH type waves (S-wave that is horizontally polarized). They calculated the structural and foundation-soil impedances from the fundamental resonant frequency and mode shapes. Last Luco et al. [3] were the first to instrument a high-rise building and performed tests with the aim of isolating the response of the SSI.

In recent years, the quantification of SSI under seismic loads through in situ testing has gained an increasing interest. Particularly, one can identify four major international campaigns which are, in chronological order, Lotung [4] and Hualien [5] in Taiwan followed by NUPEC in Japan which covers three sites across the country [6][7], the Garner Valley Differential Array mockups in USA [8][9] and finally the EURO-SEISTEST [10] or more specifically the EuroProteas mockup [11][12][13] in Greece. Their objective is to benchmark assessment methods, specifically those dedicated to SSI estimation, not only by comparing numerical results to experimental data, but also to acquire, by measurement, ground



impedances. The latter are directly post-processed from recordings of the movement of the studied system during in-situ characterization tests.

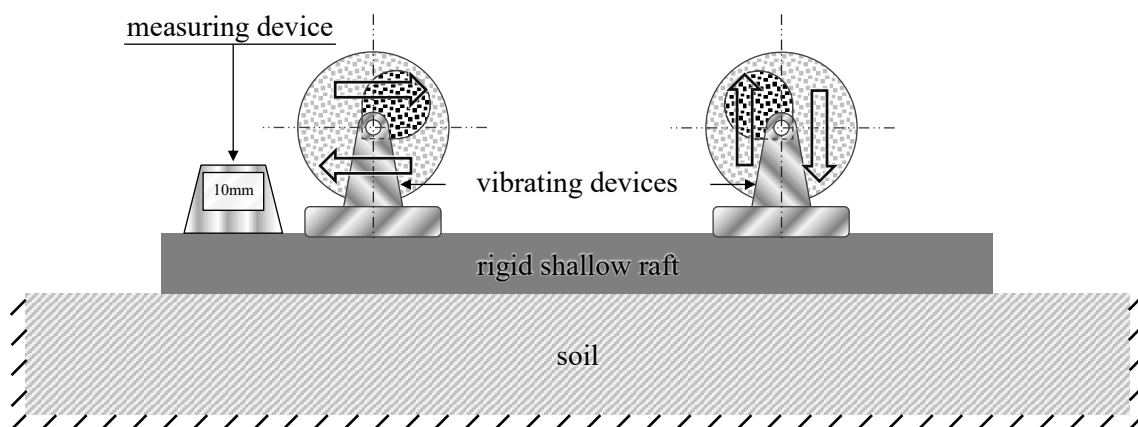
The most common technique to activate artificially SSI is the Forced Vibration Test (FVT) which consists in placing one or more shakers on the structure or the structure foundation to apply harmonic forces. As stated in Hadjian et al. [14], this type of tests allows us to easily obtain the natural frequencies and impedances of the SSI. An interesting example is provided in Morisita et al. [15] during the Hualien tests where the anisotropy of the soil's behavior was identified and characterized based on FVT SSI measurement of the soil and the circular foundation (the site having been flooded during the construction of the model, a part of the ground under the foundation has collapsed, which is presumed to be the main cause of this anisotropy). Concerning NUPEC experimental campaign, FVT was used [16] to highlight the impact of the embedment and [17] to study the differences between hard and soft soil. Finally, regarding the EuroProteas model [18], FVT experimental results were used to benchmark and validate numerical modelling strategies. It is necessary to specify that the implementation of FVT is not limited to experimental programs but is also of interest for industrial applications mainly aiming at the characterization of SSI of existing structures, especially in the case of high-rise buildings [19][20]. In this regard, we should mention the work by Star et al. [21], which reviews several methods of processing FVT results to characterize in situ ISS.

The objective of this paper is to present a new approach to measure the impedance function of buildings with a shallow rigid foundation. To do so, the paper is organized as follows: in section 1 we present a brief review on the matter of SSI in situ measurements, in section 2 we present the proposed methodology and the associated experimental protocol to SSI characterization and in section 3 we propose a proof of concept based on a laboratory scale experiment.

## 2. Towards a practical methodology for the measurement of seismic impedance functions

### 2.1. Scientific purpose

The previous literature review shows that the methods for in situ measurement of the seismic impedance function through FVT are mature. However, one can argue that their implementation at this stage is yet limited to experimental mock-up scale and that the industrial application is still foreseen. Therefore, we propose to go one step further with this approach by exploring the deployment of a methodology for the measurement of the seismic impedance function for any structure with a rigid shallow foundation. To achieve this, it is necessary to quantify continuously (during the measuring process) the forces at the soil-foundation interface. For that, we propose a FVT using vibrating devices or shakers disposed on a rigid shallow raft as illustrated in figure 1.



**Figure 1.** Principle of a measurement of the impedance functions for a shallow foundation using vibrating devices/shakers.

We propose to carry out the measurement at the end of the construction of the foundation by applying sinusoidal monotonic inertia forces using shakers. Vibrating devices/shakers are placed upon the foundation so that the total torque is a horizontal force or vertical force or a tilting moment. Measurement is performed without the structure. However, in accordance with the assumptions of the methodology, it should be verified that the raft is sufficiently rigid compared to the soil layer. If not, the measurement might be performed when parts of the structure are built so that the foundation is stiffened.

It is preferable to have straightforward and analytical post-processing of the experimental data allowing the identification of seismic impedance function. To do so, we assume that the foundation is non-deformable. Then, rigid body mechanics lead to the following mechanical equilibrium at the surface foundation (1):

$$\mathcal{T}_G(\mathcal{F}/\mathcal{N}) = \mathcal{R}_{G, \text{sol} \rightarrow F} - \sum_i \mathcal{T}_G(S_i/\mathcal{N}) \quad (1)$$

where  $G$  is the point of the Newtonian reference frame where the impedance matrix is sought,  $\mathcal{R}_{G, \text{sol} \rightarrow F}$  is the resulting torque at  $G$  of the forces applied by the soil to the underside of the foundation,  $\mathcal{T}_G(\mathcal{F}/\mathcal{N})$  and  $\mathcal{T}_G(S_i/\mathcal{N})$  are the respective dynamic torques of the motions of the foundation and of the shaker  $i$ , expressed in  $G$  with respect to the Newtonian reference frame. Knowledge of the dynamic torque of both the foundation movement and the shakers is granted by the measurement of the foundation movement as well as the setpoint effort applied by the shakers. The measurement of the movement of the foundation consists in identifying the amplitude and the phase shift with respect to the shakers. In addition, since the solids are non-deformable, the unknowns can be reduced to three translations and three rotations characterizing the movement of the foundation: the post-processing of the data can be done analytically, which significantly simplifies the realization of the measurement.

## 2.2. Proposal of a laboratory test

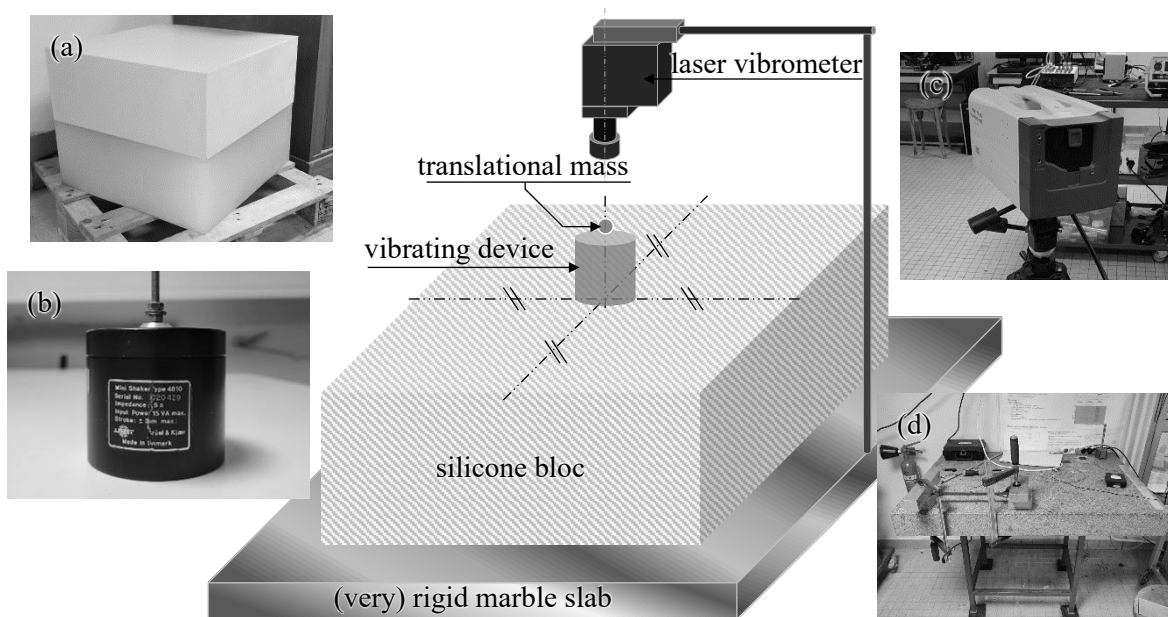
Before aiming at a full scale in-situ measurement setup, it is necessary to carry out laboratory tests on small-scale prototypes with a simple geometry, using homogeneous and well characterized materials and with well monitored experimental boundary conditions.

First, it is necessary to list the limits of such laboratory tests to avoid drawing wrong conclusions. It involves having a soil block limited in size. This is not consistent with the SSI propagation mechanism of radiating waves through thick and multiple soil layers. Moreover, if the scale is reduced, it is not the case for the wavelengths of the soil block. These two remarks imply that the results of the measured seismic impedance functions will not be representative of a real soil column case. Consequently, it is not necessary to restrict the test to using a realistic material to represent the soil. On the contrary, it is better to favour the use of a well characterized and homogeneous material with limited inherent uncertainties. In this work, elastomers are selected as model materials.

**2.2.1. Presentation of the experimental device.** We propose to build the mock-up of the device shown in figure 2: The silicone rubber block  $50 \times 50 \times 20 \text{ cm}^3$  (the soil) ground is placed on a rigid marble (the bedrock). The shaker (the nondeformable foundation) is placed in the centre of the upper face of the silicone rubber block. A mass is fixed on the translation axis of the shaker: when the shaker is put into action, the movement of the mass generates inertia forces. These are known from the weight and the movement of the mass in translation which ultimately depends both on the setpoint applied and the movement of the shaker. The displacement of the shaker is known using the laser vibrometer which is arranged vertically to the shaker. The different pictures show the material used and correspond to (a) the silicone rubber block (b) the shaker (c) the laser vibrometer, and (d) the rigid marble slab.

The objective is to acquire measurements of the vertical impedance function of a circular interface with a soft and homogeneous silicone rubber block (inset (a) in figure 2). It has a square section of  $50 \times 50 \text{ cm}^2$ , a height of 20 cm and a mass around 60 kg. To study the variability of the measurement depending on the stiffness of the material, two blocks are built, and mechanical characterizations are carried out

during laboratory tests to identify the Young's modulus and the Poisson's ratio. The diameter of the foundation is limited to 1/5 of the diameter of the soil block as recommended by the common practice for SSI calculation. The equipment chosen to represent the shallow foundation is a cylindrical shaker, Mini-shaker 4810 from BRÜEL & KJÆR (inset (b) in figure 2); his diameter is 7.8cm which is consistent with the criterion on the maximum diameter size of the foundation. Moreover, given the circular shape of the contact surface, it is possible to compare our experimental results of impedance functions with the ones provided by the literature for similar circular case [22][23][24]. The measurement of the vertical displacements is carried out with a laser vibrometer (inset (c) in figure 2). Finally, the equipment acting as rigid boundary conditions and Newtonian reference frame is a flat marble slab (inset (d) in figure 2) on which the rubber silicon block rests and to which the laser vibrometer is embedded. The device is assembled by setting the shaker in the center of the silicone rubber block.



**Figure 2.** Diagram of the experimental device.

The geometry of the mock-up as well as the applied forces have two vertical symmetry planes. Hence, under the effect of a vertical solicitation, the observed response is theoretically a vertical movement. Using the formalism of (1) where  $G$  is the impedance function calculation point at the middle of the underside of the shaker, the analytical equation of the system in the Fourier domain is (2):

$$-\omega^2 m_F \underline{u}_G = \underline{K}_{uz} \underline{u}_G + \omega^2 m_P \underline{u}_F - \underline{F} \quad (2)$$

where  $m_F$  and  $m_P$  are respectively the masses of the shaker and the translating mass,  $\underline{u}_G$  is the measured vertical displacement of the vibrating pot,  $\underline{K}_{uz}$  is the vertical impedance function and  $\underline{F}$  the applied loading.

*2.2.2. The experimental and numerical design plans.* The objective is to acquire measurement of the vertical impedance at the interface between the shaker and the silicone rubber block. To do so, laboratory tests are paired with numerical tests. As some specific parameters of the behaviour of the silicone rubber used are not well known, particularly its capacity to dissipate energy (damping), the realization of numerical simulations by exploring different hypotheses shall provide us with the right insights on what to expect whilst running the experiments.

The first step consists of running numerical simulations which aim at identifying the frequency range of interest of the silicone rubber block/shaker system along with the maximum displacements as a function of the amplitude of the sinusoidal loads. Several modelling assumptions linked to the energy dissipation (various damping ratios) and the interfaces conditions (with and without sliding) are explored.

The second step is rather experimental and aims at applying a vertical impact loading with a shock hammer on the vibrating rod of the shaker. The results are to be compared with the previous blind numerical simulations. The objective of such comparison is to verify the ability to model the physics of this test and then to identify by inverse analysis the damping ratio as well as the nature of the sliding conditions at the interfaces.

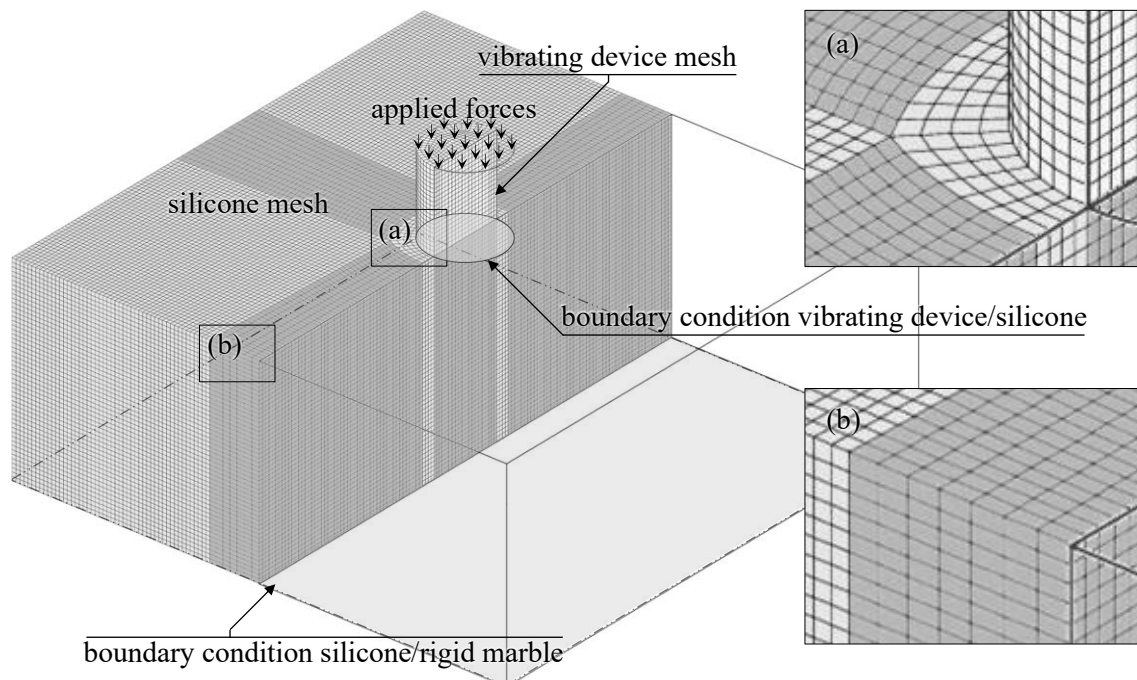
The third step consists of applying sinusoidal inertia loading with the vibrating device, at the frequency response peaks. The objective is to accurately measure the impedances at the frequency peaks, in particular the damping ratio corresponding to these specific frequencies.

### 3. Numerical simulations preceding the experiments

#### 3.1. Description of the model

Elastic transient calculations are performed with the finite element software CAST3M (version 2020). The used mesh is of volumetric nature (8-nodes cubic elements). As previously discussed, the system (geometry, loads and boundary conditions) has two vertical planes of symmetry, so the calculations can be performed on the quarter of the geometry.

3.1.1. Description of the mechanical model. Figure 3 shows the mesh developed with CAST3M.



**Figure 3.** Model used to simulate the test described in Figure 1. It includes meshes of the shaker and the silicone rubber. The marble is not modelled as it is considered a rigid medium into which waves do not propagate. (a) The transition zone between circular and square mesh is optimised to avoid the concentration of irregularities in a small number of elements. (b) The ratio of dimensions between the edges of an element does not exceed 0.5. Special attention is paid to the regularity of the mesh. The average size of the finite elements is 4 mm.

Mechanical loads are applied uniformly on the top of the shaker's surface. At the interfaces (shaker/silicone rubber and silicone rubber/rigid marble), nodes are doubled to allow the modelling of sliding (with no friction). Three different configurations are explored for the boundary conditions named Model 1 to 3:

- Model 1: no sliding in both interfaces (a perfect kinematic condition between doubled nodes)
- Model 2: authorized sliding at silicone rubber bloc/rigid marble interface and no sliding at shaker/silicon bloc interface.
- Model 3: authorized sliding at both interfaces.

*3.1.2. Mechanical characteristics of silicone rubber.* Silicone rubbers are polymers belonging to the category of elastomers. They are highly deformable materials with a great capacity of recovery of their mechanical characteristics if the time between two consecutive loads is sufficient [25]. Their behaviour is then viscoelastic with the particularity of having an elastic modulus and a recovery modulus strongly depending on the temperature and the strain level [26]. In the present study, we limit the strains at low values (less than 0.1%) and we consider that the related elastic modulus is constant. Table 1 summarizes the material properties of the two blocs of silicone rubber used in our experiments. We note that the values of the Poisson's ratio are higher than 0.5. This can be explained, in part, by the loading rate. For the calculation of the first series of tests, we will retain a value of 0.49.

**Table 1.** Results of the mechanical characterisation tests of the two silicones for deformations of less than 0.25%.

Shore A 42 silicone			Shore A 55 silicone		
Young Modulus <sup>a</sup>	Poison's ratio <sup>a</sup>	Density <sup>b</sup>	Young Modulus <sup>a</sup>	Poison's ratio <sup>a</sup>	Density <sup>b</sup>
4252 KPa	0.62	1.08 g.cm <sup>-3</sup>	5595 KPa	0.74	1.28 g.cm <sup>-3</sup>

<sup>a</sup> Average value according to tests on 5 specimens

<sup>b</sup> Value calculated from the technical specification of the mixture proportions

Regarding the modelling of the energy dissipation, and given the low strain level, the conditions at interfaces and materials used, we expect a system with limited dissipation. Amongst the approaches proposed in [28], we choose the Rayleigh viscous damping model. Its formulation is recalled in equation (3):

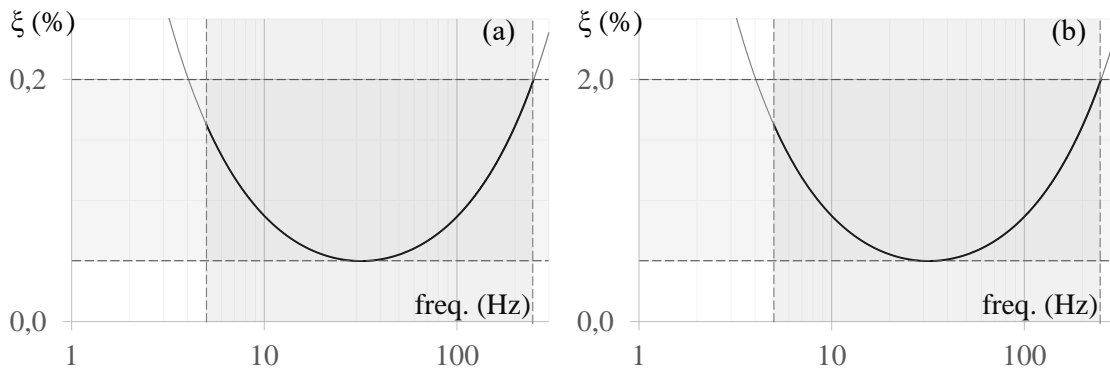
$$[C] = \alpha[M] + \beta[K] \quad (3)$$

where  $[C]$  is the viscous damping matrix,  $[M]$  and  $[K]$  are respectively the mass and stiffness matrices of both the shaker and silicone rubber block, and  $(\alpha, \beta)$  two positive real numbers to be determined, based on the values of the targeted damping ratio for the frequency range of interest. This is mainly a practical choice given its simplicity of implementation in simulations. The lack of experimental data and information in the literature leads us to explore several damping values. Three sets of coefficients  $(\alpha, \beta)$  are determined under these assumptions:

- No viscous damping meaning  $\alpha$  and  $\beta$  zero.
- Low viscous damping between 0.05% and 0.2% over the frequency range of interest.
- High viscous damping between 0.5% and 2% over the frequency range of interest.

The purpose of performing the calculation without viscous damping is to identify the frequency range of interest, which is between 5Hz and 250Hz for the present case. Figure 4 shows the curves of the damping ratio as a function of the frequency chosen for each of the two hypotheses with non-zero damping.





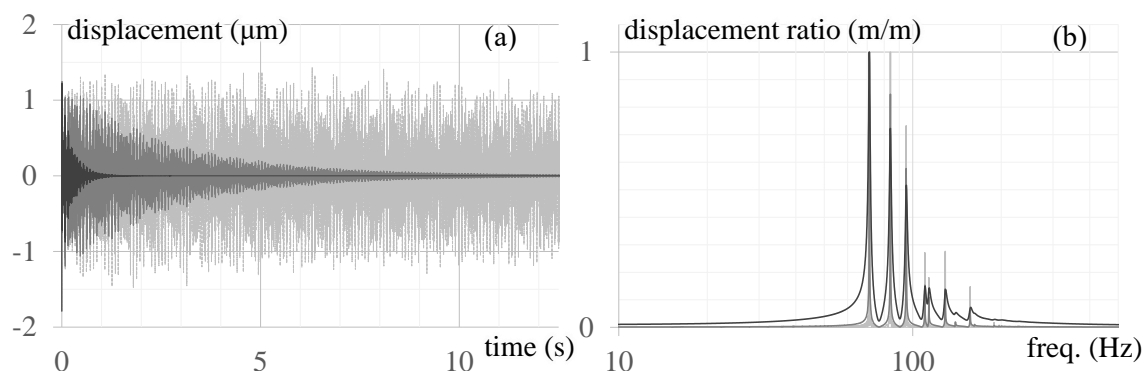
**Figure 4.** Curves of the damping ratio versus frequency for the two assumptions of damping. The frequency range of interest is between 5Hz and 250Hz. (a) Curve corresponding to a low damping ratio between 0.05% and 0.2% with  $\alpha = 0.099$  and  $\beta = 2.5 \cdot 10^{-6}$ . (b) Curve corresponding to a high damping ratio between 0.5% and 2% with  $\alpha = 0.99$  and  $\beta = 2.5 \cdot 10^{-5}$ . The two curves are homothetic by a factor of 10.

*3.1.3. Description of the mechanical loads.* The applied mechanical load consists of a quick displacement release test. In a first step, a static calculation with the loading (for a value of 100gr) described in figure 3 is carried out. In a second step, a dynamic calculation without loading on the shaker but with initial conditions taken from the static calculation is performed following the instantaneous remove of the mass (Heaviside loading function).

*3.2. First series of numerical tests*

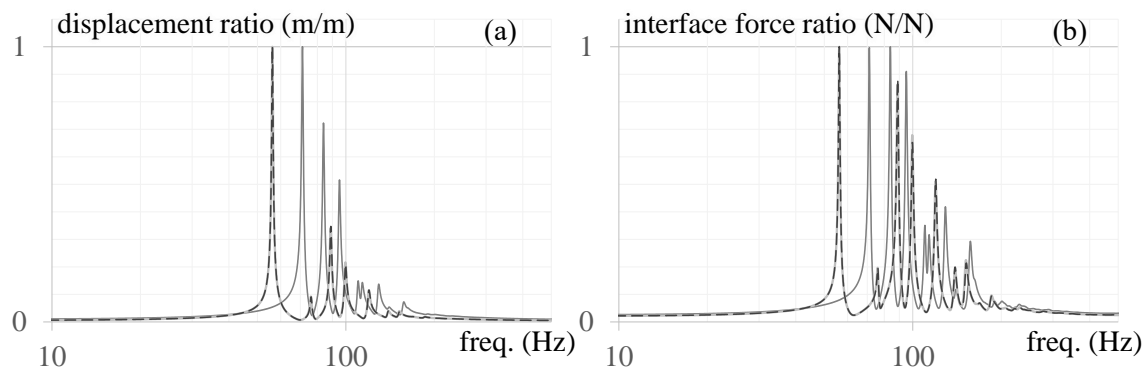
Calculations are performed with three different models, each with a particular boundary condition and a damping hypothesis. Therefore, a total of nine calculations per rubber type is achieved.

*3.2.1. Results.* Results shown are related to the Shore A 42 type of silicone rubber. Since, we aim at measuring the vertical impedance function at the interface between the shaker and the silicone rubber block, the results of the calculation that we present are the vertical displacement and the vertical interface forces between both. Figure 5 shows a comparison of the vertical displacement results for the different damping assumptions. The results are related to model 1, which corresponds to the hypothesis where sliding is prevented at both interfaces.



**Figure 5.** Comparison between calculations with different damping values, with model 1. In dark grey results for high damping, in medium grey results with low damping and in light grey results without damping. (a) Vertical displacement of the shaker versus time. (b) Normalised modulus of the Fourier transform of the vertical displacement of the shaker.

Figure 6 shows results of the vertical displacement and the forces at the interface between shaker and the silicone rubber for the three models of interface conditions. The results are shown for the high damping assumption.



**Figure 6.** Comparison between calculations with different interface conditions, for the high damping assumption. In medium grey results with model 1, in dotted dark grey results with model 2 and in light grey results with model 3. (a) Normalized modulus of the Fourier transform of the vertical displacement shaker. (b) Normalized modulus of the Fourier transform of the interface vertical force.

Based on results shown in figures 5 and 6, the following observations are made:

- Figure 5 (a) shows that, for a high damping assumption, the system goes back to rest within 2s whereas it requires 10s for low damping. By achieving a simple qualitative shock test, one can evaluate how long it takes to dissipate the energy of the shock. For the present case, the vibrations can be felt for about 2s to 3s, which indicates that high damping assumption is more accurate. However, this remains a qualitative result and shall be compared with measurements done with the laser vibrometer while applying controlled forces with the shaker.
- In figure 5 (b), results without damping shows 7 amplification peaks between 50Hz and 200Hz. It is from these results that the frequency range from 5Hz to 250Hz was identified to choose both sets of  $(\alpha, \beta)$  coefficients for the Rayleigh viscous damping. The calculation without damping has the same peaks as the calculations with low and high damping. This evidences, that the 5Hz to 250Hz range of frequencies covers all the peaks regardless of the damping hypothesis.
- Figure 6 (a) and (b) show that the results with model 2 and model 3 are identical. For the record, the difference between both lies in the interface condition between the shaker and the silicone rubber block (model 2: authorized sliding at silicone rubber bloc/rigid marble interface and no sliding at shaker/silicon bloc interface vs. model 3: authorized sliding at both interfaces). On the other hand, results are different whereas sliding between the silicone rubber block and the rigid marble is allowed (model 2) or not (model 1). This is of practical interest whilst running the experimental tests. At the silicone rubber/rigid marble interface, the contact stress related to the effect of the deadweight is high; so it is unlikely that vertical uplift occurs during the test. This is not the case at the shaker/silicone rubber interface where that kind of non-linearities may occur. A treatment of the interface between the shaker and the silicone block, by generating a suction cup effect for instance, might be necessary. This will help limit vertical uplift. With regards to sliding, numerical calculations with model 1 (no sliding at shaker/silicon bloc interface) and model 2 (with sliding at shaker/silicon bloc interface) suggest the uncertainty regarding this boundary condition will have limited impact on the measurements.

#### 4. Conclusions

There is a growing interest on the international scientific community in quantifying SSI through direct in situ testing. Several experimental platforms and programs have emerged since the 1990s. The most used technique to activate SSI is the FVT by applying harmonic forces using dynamic shakers. Following the same path, we proposed in this paper a methodology for measuring the seismic IF of rigid superficial foundations, using shakers, and based upon the assumptions of the dynamics of the non-deformable solid.

For the sake of proof of concept, the test will be carried out, first, at a laboratory scale on a model with idealized materials. The soil is represented by a 50x50x20 cm<sup>3</sup> silicone block, the foundation by a shaker and the harmonic loading is vertical. It should be noted that the objective is not to be representative on a scale but to verify the possibility of measuring IF using adapted tools. In this regard, it was necessary to characterize the frequencies of the vibrating block-pot system upstream. Therefore, several numerical simulations of the experiments were carried out to calibrate the laboratory test before conducting it.

The main blind numerical result with that regard covers the expected spectral amplifications within the 50hz and 200hz with relatively high sensitivity to the damping capacities regardless of the nature of boundary conditions between the silicone bloc and its support. As a follow-up, we quantified by experimental means the damping ratio of our material which is between 0.5% and 2% for the frequency range of interest. Another issue raised by our proof-of-concept numerical work is the risk of having uplift between the silicone rubber and the shaker to which we must be very careful by limiting the amplitude of the applied forces and then, still being able to have a response of interest that can be measured by our sensors.

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