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Dynamic behaviour of an asymmetric building: Experimental and numerical studies

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ABSTRACT

The paper presents a study on the seismic assessment of a 21-story building having an asymmetrical plan. The study applies the approach using in-situ measurements to assess the building's seismic performance. According to preliminary observations on site, the soil may have a significant influence on the building's behaviour. That is why it is important to isolate the behaviour of the building from the soil effect (fixed-base structure). First, in-situ dynamic measurements are conducted to identify dynamic characteristics of the building. The Frequency Domain Decomposition (FDD) method is used to determine the vibration modes of the building in three dimensions (3D). First three vibration modes with close frequencies and unusual mode shapes were identified, which shows the relevance of the used method in the case of buildings having complex behaviour. Second, the relevance of the applied approach was checked by using 3D Finite Element (FE) modelling, in both cases: *fixed-base structure* and *soil + structure system*.

1. Introduction

Assessing the seismic vulnerability of existing buildings is actually an important subject in France and in Europe (Boutin et al., 2005 [2], Hans et al., 2005 [15], Michel et al., 2010 [21]). This paper presents a study on a 21-story building in Guadeloupe (Overseas France). The building plan is asymmetric and the foundation is on piles. The building experienced several earthquakes in recent years (up to 6 Richter magnitude) without significant damage. A priori, according to observations on site [20], high effect of soil is likely. The question which arises is did this building perform so well during earthquakes because of its structural design or owing to a positive contribution of the soil? Then, in the future, which maximum intensity of earthquake could this building endure without significant damage?

To assess the seismic behaviour of the structure itself ("fixed-base"), it is necessary to isolate the dynamic behaviour of the structure from the influence of soil (Todorovska and Trifunac, 2008 [25], Kumar and Prakash, 2004 [17]). This paper presents how the dynamic characteristics of the fixed-base structure are identified. The ideal of this strategy was presented in Luco et al. (1988) [19] for forced vibration tests. The present investigation is an application of this strategy on a usual structure (asymmetric), by "ambient" vibration tests and supported by a more recent technique of data processing.

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2. Principles of in-situ dynamic measurements and data processing

In-situ dynamic measurements are directly performed on real structures (e.g. buildings or bridges). Accelerometers or velocimeters are used as sensors to measure respectively the accelerations of the vibration or the velocities of the structure (Hans et al., 2005 [15], Bui et al., 2011 [4]). With the help of these measured data, dynamic characteristics of the structure such as its natural frequencies, mode shapes and damping ratios can be identified. There are several methods for the in-situ dynamic measurements in the elastic domain of material (Hans et al., 2005 [15]). Among these methods, the "ambient vibrations" measurements is commonly used. In this method, excitations are human or natural activities at low amplitude around the structure under study, such as vehicles, micro-earthquakes, waves, wind, etc. The action of these excitations is assumed to be a "white-noise" (Clough and Penzien, 1995 [5]).

2.1. General soil + structure system

Consider a general soil + structure system that undergoes a displacement at the base $v_g(t)$. At a point on the structure, call:

- $v_{SS}(t)$, the *relative* displacement of this point on the soil + structure system, compared to the base of the system (position of the source $v_g(t)$);
- $v^t(t)$, the *absolute* displacement of the considered point on the soil + structure system;

we have:

$$v^t(t) = v_g(t) + v_{SS}(t) \tag{1}$$

In general for civil engineering structures, the excitation $v_g(t)$ is considered to be a white-noise. In that case, the usual relationship between the power spectral densities of the response ($\boldsymbol{S}_v$) and the excitation ($\boldsymbol{S}_p$) can be used (Clough and Penzien, 1995 [5]):

$$\boldsymbol{S}_v(\varpi) = \left|\boldsymbol{H}(i\varpi)\right|^2 \boldsymbol{S}_p = \left|\boldsymbol{H}(i\varpi)\right|^2 \boldsymbol{S}_0 \tag{2}$$

where, $\boldsymbol{S}_0$ is constant. Consequently, to determine the frequencies of the soil + structure system (ϖ), the curve of $\boldsymbol{S}_v(\varpi)$ is drawn and then the natural frequencies can be identified at peak positions on the curve.

2.2. Extracting dynamic characteristics of the fixed-base structure

With a sensor on the building (at a height H), the following equation can be obtained:

$$v^t(t) = v_f(t) + H.\theta_f(t) + v(t) \tag{3}$$

where $v(t)$ is the horizontal displacement of the fixed-based structure; $v_f(t)$ and $\theta_f(t)$ are respectively the foundation horizontal displacement and rotation ("rocking"). $v_f(t)$ can be measured by a sensor being on the foundation and $\theta_f(t)$ can be calculated by the relation (Luco et al., 1988 [19]):

$$\theta_f(t) = \left[z_2(t) - z_1(t)\right]/b_f \tag{4}$$

where $z_1(t)$ and $z_2(t)$ are the vertical displacements of two sensors on the foundation and b_f is the distance between these two sensors. Eq. (4) is acceptable in the case of a rigid base.

2.3. Data processing

In this paper, a recent technique – Frequency Domain Decomposition (FDD), Andersen et al., 2007 [1], Brincker et al., 2001 [3] – is used for data processing. The FDD is known as one of the most user friendly and powerful techniques for operational modal analysis of structures in the recent years (Ventura et al., 2002 [26]). This technique was applied with success on several studies (Bui et al., 2011 [4], Michel et al., 2010 [20], Michel et al., 2012 [22]).

Any displacement vector $\boldsymbol{v}$ (static or dynamic) for this structure can be developed by superposing suitable amplitudes of the normal modes:

$$\boldsymbol{v}(t) = \Phi_1 q_1(t) + \Phi_2 q_2(t) + \ldots + \Phi_N q_N(t) = \boldsymbol{\Phi q}(t) \tag{5}$$

In time domain, the covariance matrix of the responses:

$$\boldsymbol{R}_{vv}(\tau) = E\left\{\boldsymbol{v}(t+\tau)\boldsymbol{v}(t)^T\right\} \tag{6}$$

$$\Rightarrow \quad \boldsymbol{R}_{vv}(\tau) = E\left\{\boldsymbol{\Phi q}(t+\tau)\boldsymbol{q}(t)^H \boldsymbol{\Phi}^H\right\} = \boldsymbol{\Phi C}_{qq}(\tau)\boldsymbol{\Phi}^H \tag{7}$$

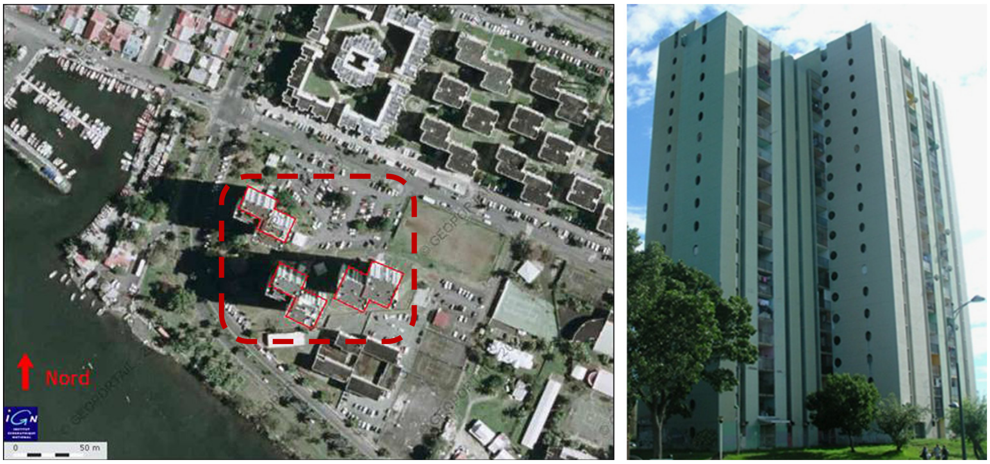

Fig. 1. (a) Left: aerial view of the three studied buildings; (b) Right: general view of a building.

^{H} is the Hermitian transposed operator. The equivalent relation in the frequency domain is obtained by using the Fourier transform:

$$\boldsymbol{S}_{vv}(\omega) = \boldsymbol{\Phi} \boldsymbol{S}_{qq}(\tau) \boldsymbol{\Phi}^H \tag{8}$$

If the modal coordinates $(q_1, q_2, \ldots)$ are uncorrelated, then the power spectral density (PSD) matrix $\boldsymbol{S_{qq}(\omega)}$ is diagonal (Clough and Penzien, 1995 [5]). And if the mode shapes are orthogonal, then the above equation is a singular value decomposition (SVD) of the response matrix $\boldsymbol{S}_{vv}(\omega)$.

Therefore, FDD is based on taking the SVD of the spectral density matrix:

$$\boldsymbol{S}_{vv}(\omega) = \boldsymbol{U}(\omega)[\boldsymbol{s}_i]\boldsymbol{\Phi}(\omega)^H \tag{9}$$

The matrix $\boldsymbol{U}(\omega)$ is a matrix of singular vectors and the matrix $[\boldsymbol{s}_i]$ is a diagonal matrix of singular values. As it appears from this explanation, plotting the singular values of the spectral density matrix will provide an overlaid plot of the auto spectral densities of the modal coordinates. Note that here the singular matrix $\boldsymbol{U}(\omega)$ is a function of frequency because of the sorting process that is taking place as a part of the SVD algorithm (see Fig. 5 for more details).

3. Case of Gabarre asymmetric building

3.1. Building descriptions

Three identical towers were built side by side (Fig. 1a), in Pointe à Pitre, Guadeloup Island (Overseas France). They are called Gabarre1, Gabarre2 and Gabarre3 respectively. Fig. 1b shows an example of Gabarre2 building.

Fig. 2 shows the plan of a regular storey. The black lines represent the reinforced concrete walls. The other walls are brick masonry walls.

Such architecture with asymmetric plan is usually not recommended in the seismic design. However, these three buildings are not the only ones using this architectural type. In Guadeloupe, other buildings with the same type of asymmetric plan can be observed. Therefore, a dynamic study on one of these buildings may help to also understand the behaviour of the other similar buildings.

The foundation of the studied building consists of piles of diameters ranging from 0.65 m to 0.80 m, down to a depth of 33 m. Horizontal beams with great height (2 m), linking the heads of the piles were designed to withstand large horizontal loads (Paumelle, 1972 [23]). The implementation of this type of beam can effectively strengthen the behaviour of piles in earthquakes, even when their intensity is high (Finn, 2005 [12]).

3.2. In-situ measurements

The sensors used are Tromino triaxial velocimeters that can measure the vibration velocity in three orthogonal directions, two horizontal directions (NS and EW) and one vertical direction. In total, five sensors were used thus giving each time 15 data sets.

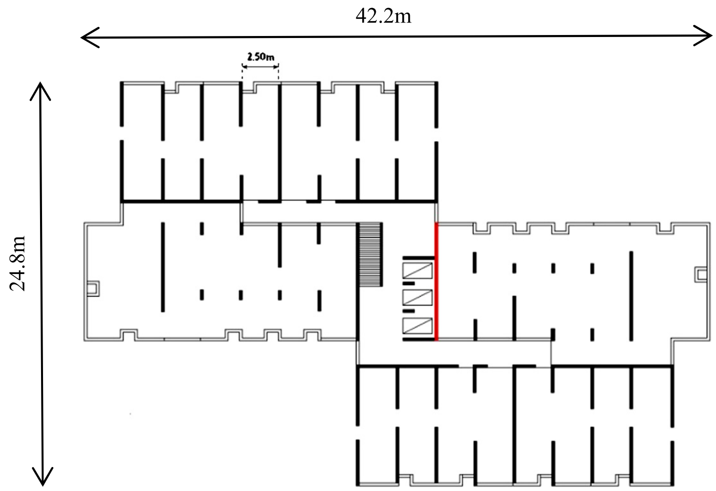

Fig. 2. Plan of a current story of the studied building.

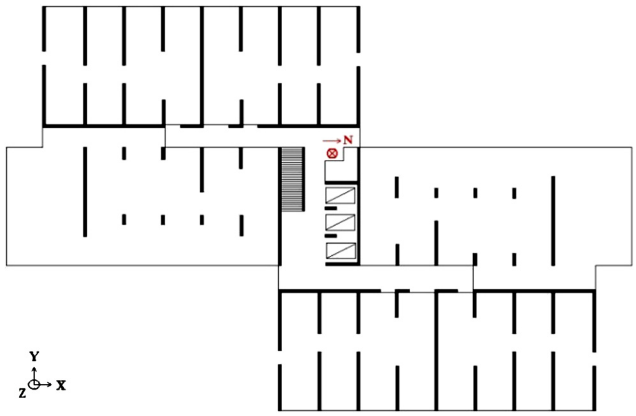

Fig. 3. Configuration for the "deformed" configuration: sensors are placed at floor center.

With a limited number of sensors, several configurations were needed to "capture" all the vibration modes of the building. Two main types of configuration were applied:

- "Deformed" configuration is used to detect the axial "bending" deformation (transverse and longitudinal) of the structure. In this configuration, all sensors are placed on the vertical axis passing through the geometric center of the building (Fig. 3). Two sensors are used as reference, one on the foundation (sensor 20) and another on the 19th floor (sensor 21). Three other sensors are moved from one floor to another on the geometric central axis of the building with the purpose of obtaining "bending" deformation on each floor of the building.
- "Torsional" configuration is used to detect the torsional movements of the structure. The reference sensor "20" is always at the 1st level. Four other sensors are put on the 18th story, one at the floor center and three other are on the floor perimeter to better detect the torsional movements (Fig. 4).

3.3. *Results of the soil + structure system (flexible base)*

Fig. 5 shows an example of the first singular values obtained from a torsional configuration. In this figure, following the principle of the FDD method, three first modes can be detected at frequencies respectively 1.25, 1.37 and 1.53 Hz.

From the observations on these figures, it is suggested that there is a torsional mode at 1.37 Hz. To confirm this hypothesis, verification was done: the floor is considered as a rigid body; the rotational velocity of the sensors on the building perimeter, relative to the geometric center of the rigid body is calculated and then, its power spectral is plotted. An example is shown in Fig. 6. On this figure, two torsional frequencies can be determined and are respectively 1.37 and 6.46 Hz.

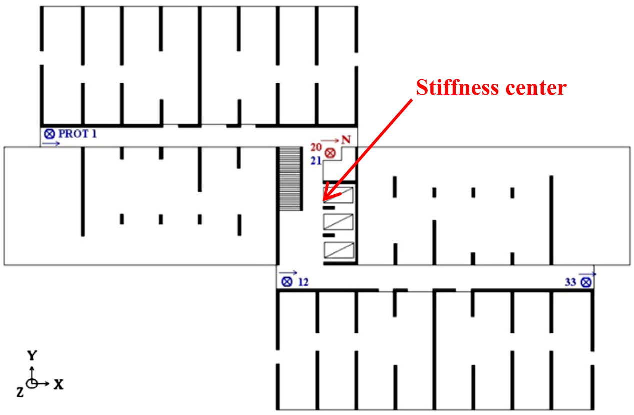

Fig. 4. Configuration for the "torsional" configuration.

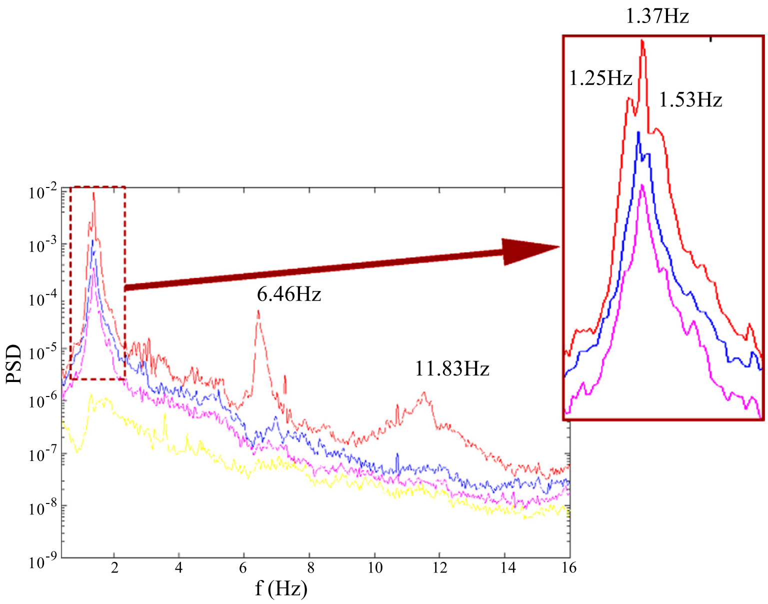

Fig. 5. The first singular values obtained from a measurement of torsional configuration. Right: a zoom on the first three peaks.

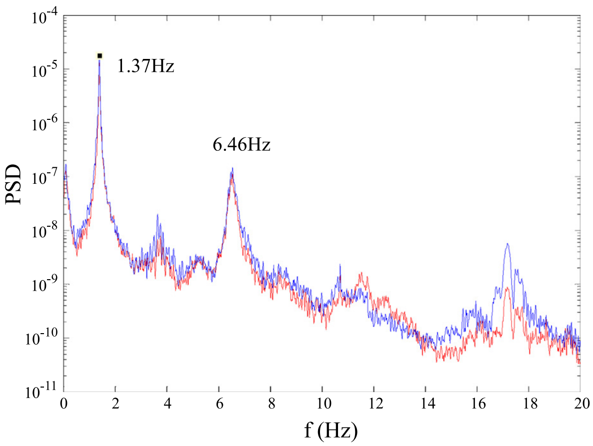

Fig. 6. Two spectra of two different sensors in a "torsional" configuration, relative to the floor's geometric center, to determine the frequencies of torsional modes.

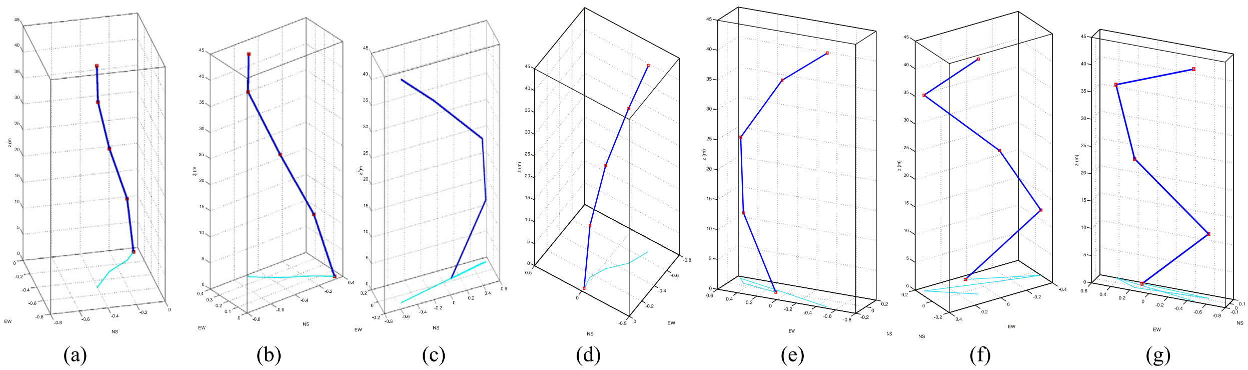

Fig. 7. First vibration modes of the Gabarre soil + structure system: (a) 1.25 Hz, (b) 1.54 Hz, (c) 4.90 Hz, (d) 6.46 Hz, (e) 8.45 Hz, (f) 11.83 Hz, (g) 14.80 Hz.

3.4. Result analysis

There are three first vibration modes, whose frequencies are respectively 1.25, 1.37 and 1.53 Hz. Among these three modes, the second is a torsional movement (1.37 Hz). Another torsional mode occurs at 6.46 Hz.

3.4.1. Interpretation of results

The building is not symmetric, this is why neither the transversal nor the longitudinal direction is the main direction of the structure.

The principal axes of the building will be determined following the formula in the theory of Strength of Materials:

$$\tan(2\theta) = 2I_{xy}/(I_x - I_y) \tag{10}$$

where I is the moment of inertia, θ is the angle of the first main axis from the horizontal (or building longitudinal direction).

Calculating the moment of inertia of each floor (Fig. 2), the principal axes of the building are determined. The first main axis makes an angle about 40° from the building longitudinal direction.

3.4.2. Analyse in three dimensions

An analysis of the building vibration was performed in 3D by the FDD technique. Fig. 7 shows examples of 3D mode shapes obtained, data from a "deformed" configuration. The lines on the horizontal plane are the projections of the structure deformation on this plane, which indicate more clearly the vibration directions in each mode. For example, the first mode at 1.25 Hz evidences a vibration direction which makes an angle θ_1 approximately 40° from the longitudinal direction of the building (NS). The mode at 1.54 Hz shows a vibration direction forming an angle θ_2 about 130° from the longitudinal direction of the building (NS), i.e. perpendicular to the first mode (at 1.25 Hz).

3.4.3. Confirmation of the principal axes

In order to verify the performance of FDD method in the case in which frequencies of three modes are very close, the above results were checked. To confirm the vibration angles θ_1 and θ_2 determined from the mode shapes in 3D, data processing was done in these directions. Indeed, by using data measured in two longitudinal (NS) and transverse (EW) directions of the building, data for a vibration in a direction inclined θ from the horizontal direction can be established, as follows:

$$v_\theta = v_{NS} \cdot \sin\theta + v_{EW} \cdot \cos\theta \tag{11}$$

For the first mode: $\theta \approx 40°$; for the second mode: $\theta \approx 130°$. When processing data v_θ, vibration spectrum in these directions can be obtained. Fig. 8 shows two spectra of vibration in both directions forming respectively 40° and 130° from the longitudinal direction of the building (NS). This figure confirms that the vibrations are indeed *decoupled* in these two directions, which are also the two main axes of the building.

3.4.4. Summary of results of soil + structure system

Summary of results of *soil + structure* system is presented in the second column of Table 1.

3.5. Fixed-base structure

The technique identifying dynamic characteristics of fixed-base structure was used in the study of Luco et al. (1988) for forced vibration tests. In the present study, the dynamic characteristics of the fixed base structure were identified in the case of ambient vibration tests.

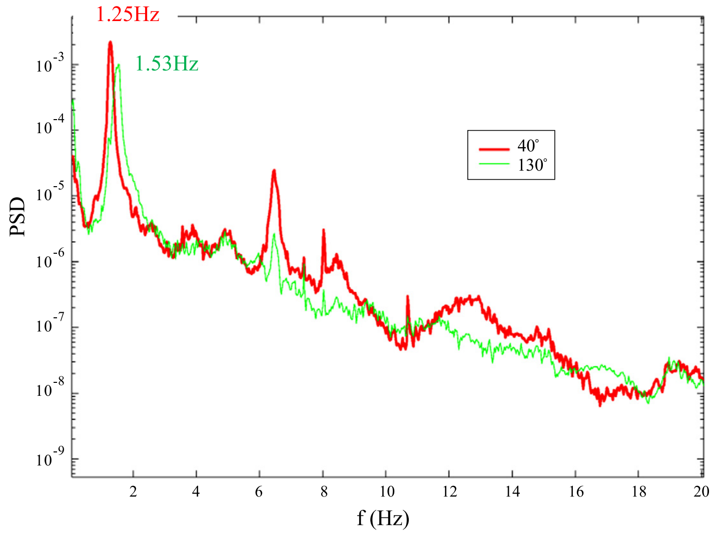

Fig. 8. The first singular values in two directions 40° and 130° respectively, compared with NS.

Table 1
Comparison between the natural frequencies of soil + structure system and fixed-base structure.

f (Hz)	*Soil + structure*	*Fixed-base structure*	f_0/f_{SS}	Mode of vibration
f_1	1.25 ± 0.01	1.38 ± 0.01	1.10	1st X_0
f_2	1.37 ± 0.03	1.40 ± 0.03	1.02	1st torsion
f_3	1.53 ± 0.02	1.70 ± 0.03	1.11	1st Y_0
f_4	4.90 ± 0.03	5.10 ± 0.03	1.04	2nd X_0
f_5	6.46 ± 0.06	6.46 ± 0.06	1.00	2nd torsion
f_6	8.43 ± 0.1	9.16 ± 0.2	1.09	2nd Y_0
f_7	11.83 ± 0.4	12.34 ± 0.40	1.04	3rd torsion

Note: (1) f_0 and f_{SS} are respectively the frequencies of the structure alone and of the soil + structure system, (2) X_0 and Y_0 are respectively the 1st and 2nd main axes in the building plan, which are respectively 40° and 130° compared to the longitudinal direction of the building.

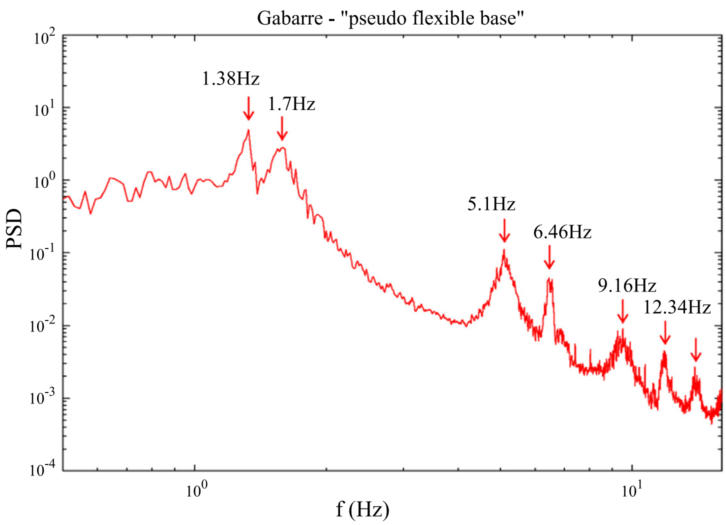

Fig. 9. Spectrum $S(\omega)$ in the NS direction, the case of the fixed-base structure.

Fig. 9 is an example of a result of *fixed-base structure*, calculated following the theory in Section 2.2. The results of identified frequencies are presented in the third column of Table 1. From this table, it is observed that the frequencies of translation modes of the *soil + structure* system are lower than when the structure is on fixed base; which shows the influence of soil in the *soil + structure* system response, even with low-intensity excitations in ambient measurements.

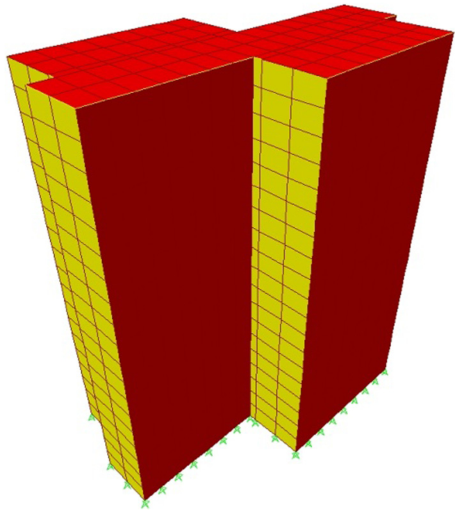

Fig. 10. Model of a Gabarre building in FE modelling, with fixed-base.

4. FE modelling

The FE modelling of the building aims to fulfil two main objectives. Firstly, to verify the mode shapes identified in the previous section where an unusual dynamic behaviour was observed. Secondly, once the model is calibrated to correlate with in-situ measurements, an assessment of the seismic capacity can be performed with the model.

4.1. Fixed-base structure

Modelling was done with the SAP2000 software, which was successfully applied in the study of Liu et al. (2005) [18]. The FE model was firstly built for the superstructure corresponding to the fixed base (Fig. 10). The materials' characteristics were calibrated in modelling to reproduce the in-situ dynamic behaviour. Indeed, the current value of the Young's modulus of concrete in France is 32 GPa (Eurocode 2 [9]), but this corresponds to a concrete tested at 28 days. This value decreases in the times due to the creep phenomena. Following the empirical formula gave in Eurocode 2, this Young's modulus of concrete can decrease until 12 GPa. Therefore, a calibration of concrete modulus was necessary in an interval from 12 to 32 GPa.

For Young's modulus of masonry, to surmount the inhomogeneity of masonry panels, the *in-situ* values found in the study of De Sortis et al. (2005) [8] were noted in which the mean modulus of masonry varied from 1.5 to 3 GPa. The volumic mass and the damping ratio of concrete were taken of 2500 kg/m^3 and 4% respectively. The modulus of steel was taken of 200 GPa. To assess as accurately as possible the mass of the building, the mass of each floor was calculated taking into account the permanent and live loads according to Eurocode 8 [10].

Following several preliminary simulations, it was observed that the natural frequencies of the studied structure depended predominately on the stiffness of concrete. However, the stiffness of infill masonry played a significant role on the torsional modes. Indeed, by changing the stiffness of masonry, the 1st torsional mode may pass from 2nd mode to 1st or 3rd mode of the structure. This is understandable because infill masonry panels are in the building's perimeter, so they have an important influence on the building's torsional stiffness.

To calibrate the Young's modulus of concrete, firstly, the model was tested with a modulus $E_{c,trial}$, the first natural frequency (called $f_{1,trial}$) obtained from the model was noted. According to the theory of Dynamic of Structures, the following relationship can be derived:

$$E_{c,measured} = (f_{1,measured}/f_{1,trial})^2 E_{c,trial} \tag{12}$$

Then, the Young's modulus of masonry was calibrated by the same way, by using the first torsional mode (3rd global mode).

$$E_{m,measured} = (f_{3,measured}/f_{3,trial})^2 E_{m,trial} \tag{13}$$

After the calibration, the identified modulus of concrete and masonry were of 25 GPa and 1.5 GPa respectively. The comparison of the FE results and those of in-situ measurements is presented in Table 2.

Table 2
Results of natural frequencies of the fixed-base structure of a Gabarre building, obtained from in-situ measurements and FE model.

f (Hz)	In-situ measurements	FE model	Mode of vibration	Difference (%)
f_1	1.38 ± 0.01	1.38	1st X_0	0
f_2	1.4 ± 0.03	1.43	1st torsion	2.1
f_3	1.70 ± 0.02	1.72	1st Y_0	1.2
f_4	5.10 ± 0.03	5.16	2nd X_0	1.2
f_5	6.46 ± 0.06	6.30	2nd torsion	−2.5
f_6	9.16 ± 0.20	8.95	2nd Y_0	−2.3
f_7	12.34 ± 0.40	11.25	3rd torsion	−8.8

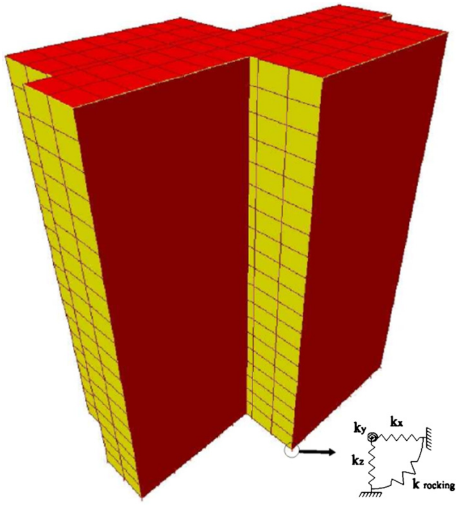

Fig. 11. Modelling of soil + structure system in EF. The Soil + Foundation system is simplified and modelled by springs.

4.2. Soil + structure system

To this day, there are several possibilities to introduce the "soil" in the model (in the present case, it means piles + soil), Finn et al. (2011) [13]. The first possibility is to model the superstructure on the piles and then the soil will be modelled by springs (linear or nonlinear) around the piles. This model is known as the Winkler model.

The second possibility is to use the "substructures", meaning that only the superstructure is modelled and boundary conditions between the superstructure and the foundation are added (Han, 2002 [14], Clouteau et al., 2012 [6]). In this case, the piles + soil will be replaced by springs at the level of the foundation which is supposed to be super-rigid (Fig. 11). The second approach is applied here because it is simpler.

During earthquakes, there is an interaction between soil and structure (including the piles). Soil stiffness in this case varies according to the nature of excitations (intensity, frequency), Finn (2005) [11]. To take this effect into account, the springs representing the soil should have a nonlinear behaviour and should vary according to excitation nature (e.g. frequency).

In the case of ambient measurements, the intensity of excitation is very low and therefore the soil behaviour can be considered as elastic linear. The soil stiffness in ambient measurements corresponds to the "starting point" (excitation intensity near zero) of the curve representing the variation of the soil stiffness following the intensity of earthquakes (Finn et al. [12,13]). The finding of this "starting point" is very important for SSI study during earthquakes.

For the calibration of the spring stiffness, series of simulations were carried out, from the values found in a bibliographic study (Jeremic et al., 2004 [16]). In the present investigation, a code was added for the optimisation of the model. For each spring, the stiffness was varied from 10^4 to 10^7 kN/m, with a step of 50 kN/m. The spring stiffness giving a minimum error were selected, where:

$$Error = \text{sqrt}\big(\Sigma(f_{i,num} - f_{i,exp})^2\big) \quad i = 1:7 \tag{14}$$

with $f_{i,num}$ and $f_{i,exp}$ were respectively the numerical and experimental frequencies of the modes from 1 to 7.

The spring stiffness after the calibration are presented in Table 3.

The first three mode shapes of the calibrated FE model are illustrated in Fig. 12. Comparison of the consistency between the results of the FE model and in-situ measurements is presented in Table 4. It is observed that the natural frequencies and the mode shapes of the model correspond well with results of in-situ measurements, this shows a good representation of

Table 3
Spring stiffness for elastic foundation system in the present study.

Degree of freedom	Spring stiffness
Axial (vertical, z direction)	5e6 kN/m
Transversal (horizontal x and y directions)	1e5 kN/m
Torsional (around vertical z axes)	6.5e6 kN/m
Rocking (around horizontal x and y axes)	7.8e6 kN/m

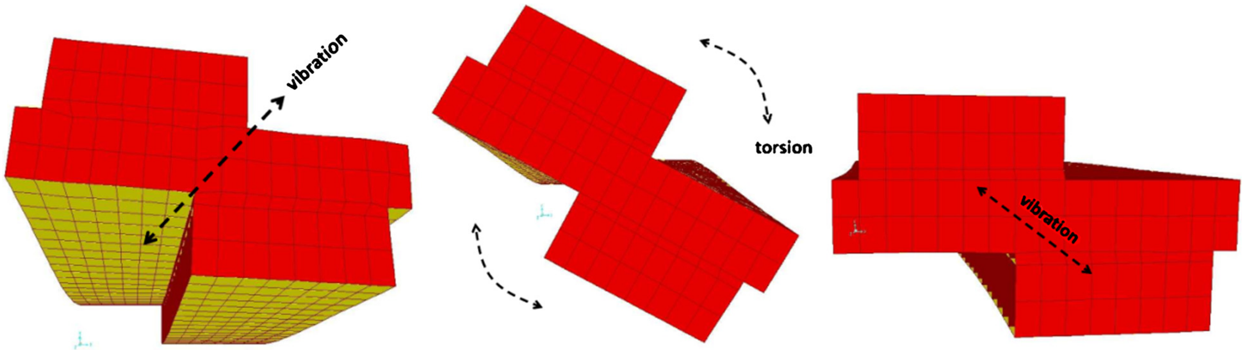

Fig. 12. First (left), second (middle), and third (right) mode shapes of the building, in the model taking into account the effect of the foundation and the soil. The vibration in the first mode is the first translation mode in the first main axis of the building. The vibration in the second mode corresponds to the first torsion mode. The vibration in the third mode is the first translation mode in the second main axis of the building.

Table 4
Results for natural frequencies of the soil + structure system of a Gabarre building, obtained from in-situ measurements and finite element model.

f (Hz)	In-situ measurements	FE model	Mode of vibration	Difference (%)
f_1	1.25 ± 0.01	1.27	1st X_0	1.6
f_2	1.37 ± 0.03	1.34	1st torsion	−2.2
f_3	1.53 ± 0.02	1.59	1st Y_0	3.9
f_4	4.90 ± 0.03	5.15	2nd X_0	5.1
f_5	6.46 ± 0.06	6.30	2nd torsion	−2.5
f_6	8.43 ± 0.1	8.62	2nd Y_0	2.3
f_7	11.83 ± 0.4	10.93	3rd torsion	−7.6

the numerical model. This good correlation enables to conduct a future assessment on the studied building, by introducing simulated excitations in the model (for example Cornell and Vamvatsikos, 2002 [7], Villaverde, 2007 [27]).

5. Conclusions and prospects

The paper presents an investigation on the dynamic behaviour of an asymmetric building and the effects of its soil. First, in-situ dynamic measurements were conducted to identify the building's dynamic characteristics. The FDD method was successfully used to identify the building vibration modes in three dimensions, which enables to identify the dynamic behaviour of the building. For the torsional modes, verification was performed using the technique of rotation of a rigid body. This technique associated with the FDD method enables to understand the actual dynamic behaviour of the complex studied building. Then, the soil effect was isolated to obtain the dynamic behaviour of the fixed-based structure which will be useful for the seismic assessment of the structure.

Then, numerical models were performed to, on one hand, verify the validity of the dynamic characteristics identified, specially the existence of the unusual mode shapes; and on the other hand, to calibrate the soil characteristics. These last were derived from information obtained from the *fixed-base structure*.

The numerical *soil + structure system* model reproduced the natural frequencies and the mode shapes of the in-situ measurements results, which showed a good representativeness of the numerical model. This good correlation enables to conduct investigations on the seismic capacity of the studied building with the "regulatory" method (Clouteau et al., 2012 [6]). The "regulatory" method is a simplified method which consists of soil springs. Its drawback is the inability to account for the frequency dependence of the foundation impedance since the springs must have constant stiffness characteristics with respect to frequency. But its advantage is its simplicity still allowing for complex nonlinear model of the structure together with all types of nonlinear behaviour of the soil springs (Gerolymos and Gazetas, 2006 [11]).

Calibrating analytical and physical models by the approach used in this paper is interesting for research on the soil effect. This approach is even more promising in the case of instrumented buildings located in frequent earthquake areas.

The advantage of this approach is that data are measured on site, which provides valuable information for a complex phenomenon like earthquake (Rovithis et al. 2009 [24]).

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