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Dynamic characteristics identification including soil-structure interaction of a strong floor reaction wall system

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Abstract. This paper presents a structural identification of a 32 m long by 13m wide strong floor with a 15m height reaction wall using ambient vibration testing. This system represents a special type of structure characterised by a very stiff reinforced concrete caisson base having overall rigid body modes and elastic deformable modes of the wall. A brief description of the facility which is housed in the earthquake engineering laboratory of the CGS (Earthquake engineering research centre in Algiers) is first introduced. Then, a three-dimensional FE model of the structure and the embedded base with spring supports to model the surrounding soil is presented in details. A series of ambient vibration testing is carried out on the structure and the free field response is also recorded to compare with the base response characterised by rigid body rocking and translation modes due to soil-structure interaction. Several important parameters affecting the accuracy of FE modeling are studied quantitatively and parameter sensitivity studies are conducted.

Keywords: Ambient vibration testing; Soil-structure interaction; Structural identification; Reaction wall

1 INTRODUCTION

Identification techniques of dynamic characteristics of civil engineering structures based on ambient vibration testing can be considered as one of the most common method, whose effectiveness is worldwide recognised by numerous cases of acceptable results of many existing buildings, bridges and other structures. This full scale testing method can be profitably used for many purposes, depending on the specified testing conditions. Numerous studies used the ambient vibration testing to validate or update numerical models. The main purpose of the model updating procedure is to minimize the differences between the analytically and experimentally determined dynamic characteristics by changing some uncertainty parameters such as material properties or boundary conditions (Altunisik et al. 2011, Jaishi and Ren 2011, Brownjohn et al. 2003). It has been applied in the field of structural integrity monitoring (SIM), which utilizes measured dynamic responses from a structural system to assess the physical properties of the structure (Salawu 1997, Wiberg 2006). Within the framework of structural identification, ambient vibration testing has also been used in conjunction with neural networks to extract structural characteristics such as building eccentricities (Bourahla and Boukhemacha 2005). Thus far, the ambient test has been applied to various types of structures including bridges, buildings, historical structures and mechanical structures. Most of these studies has focused on the superstructure assuming fixed boundary conditions and few of them which addressed the soil-structure issue for low rise and medium rise building (Tobita et al. 2000). This paper presents a detailed case study on structural identification and finite element modeling of a strong floor and a reaction wall system considered as a very stiff structure where rigid body modes plays non negligible role. Emphasis is placed on the soil-structure interface modeling techniques and existing simplified methods used in practice to estimate equivalent soil spring characteristics.

2 DESCRIPTION OF THE STRONG FLOOR AND REACTION WALL SYSTEM

The strong floor and reaction wall system is a testing facility housed in the new earthquake laboratory of the National Earthquake Engineering Research Centre CGS (Algeria). A global view of the reaction wall during the construction phase is shown on Figure 1. The overall layout, plan view and cross sections of the strong floor and the reaction wall are illustrated in Figures 2. The plan size of the strong floor is 32 m x 13 m with a clear area of 24 m x 13 m in front of the reaction wall. The height of the reaction wall is 15 m, offering the possibility of testing 4 – 5 storey buildings or large size models for taller buildings. The reaction wall is a 3–cell box-section. The thickness of the outer and inner walls is 80 cm and 60 cm, respectively. The reaction wall has three floor slabs, each 50 cm thick. The base of the reaction wall is monolithically tied into the box girder test floor. The testing floor is also a 3–cell box-section with a 100 cm thick top slab and 80 cm thick bottom slab. The inner and outer webs have a thickness of 60 cm and 80 cm respectively. Below the reaction wall, the inner webs have a thickness of 80 cm. The webs are continuous under the testing area, leaving a 4 m clear length to provide a transversal access between the corridors. In order to achieve adequate strength and stiffness performance, both the reaction wall and the strong floor are prestressed along their longitudinal axes. With regards to stiffness, pre-stressing serves the purpose of reducing the tensile stresses in concrete and thus limiting the degradation of stiffness due to tensile cracking of concrete. A sliding thin layer has been used under the base of the strong floor to reduce the friction between the base concrete and the soil in order to make the pre-stressing uniform at the base.
The structure is made of reinforced concrete class C30/37. The values of the elastic modulus, the Poisson's ratio, the mass density of the concrete were taken as 32. GPa, 0.20, and 2500 kg/m^3 respectively.

Figure 1. Global view of the reaction wall during the construction phase

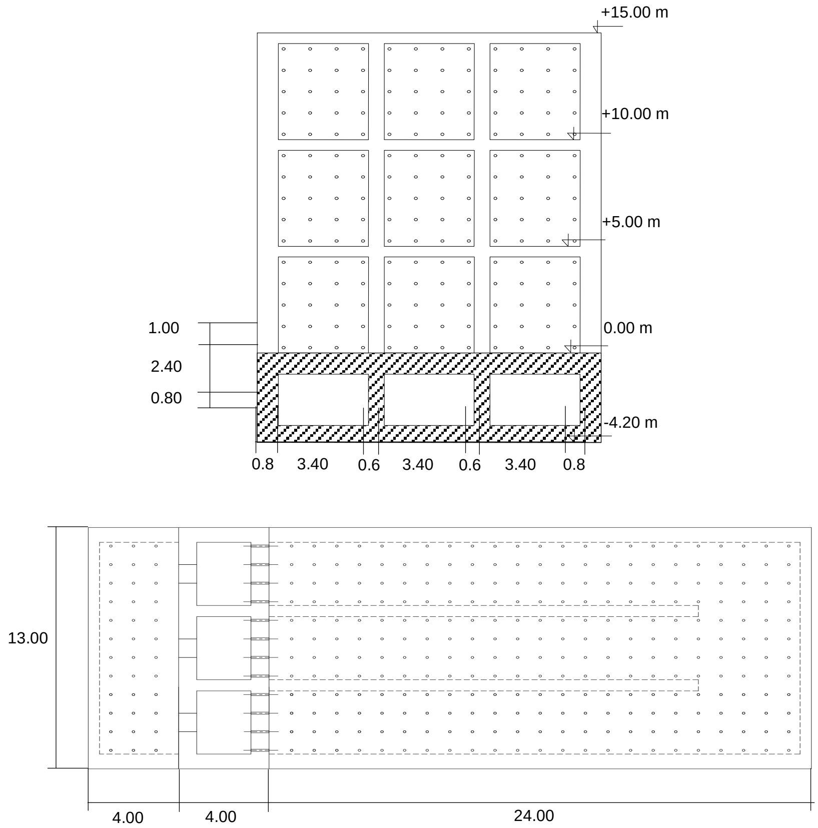


Figure 2. Strong floor and reaction wall layout.

The geotechnical and geophysical data provided by the field survey and confirmed by the excavation during the construction phase shows a soil profile having a sandy clay layer from the surface to 2.5 m depth, a hard gravel layer of about 3.5 m thick is below and the bottom layer is constituted of marl with varying characteristics. As represented in Figure 3, the soil profile is fairly homogeneous in the area of interest for this analysis. The foundation is embedded in the hard gravel layer. The shear modulus, the mass density and Poisson's for each layer are listed below.

Table 1. Geotechnical properties of the soil layers

Depth (m)	Elastic modulus (Mpa)	Density ratio (kN/m^3)	Poisson's ratio
0-1.5	400.0	17.6	0.32
1.5-2.5	1200.0	17.6	0.32
2.5-4.5	3000.0	15.9	0.34
4.5-6.0	5000.0	15.9	0.28
6.0-8.0	2700.0	16.2	0.22
Below 8.0	1000.0	16.2	0.41

Figure 3. Soil conditions under the strong floor and reaction wall system during excavation on site

3 AMBIENT VIBRATION TESTING

An ambient vibration survey of a full scale structure represents an efficient and accurate technique for detailed characterisation of its dynamic response to wind and microtremor excitation. Fully developed in early 1970's, this method now is becoming even more advantageous and convenient to use, due to the increased capabilities of personal computer (PC) and commercially available interface boards. In this paper we present briefly the main issues pertaining to this particular modal testing; frequency response function (FRF) measurement techniques, testing procedure, and modal parameter estimation method.

3.1 Test setup and procedure

The tests were performed using three degrees of freedom seismometer type Lennartz electronic (Le3Dlite) and a data acquisition system type City Shark II. The measured signals were processed using the GEOPSY program (Wathelet 2005) capable to perform most of the signal processing operations for the analysis of ambient vibration data. The sensors were located at the centre and the corner of the floors. The recording time for each sequence was set to 5 mn and found to be largely sufficient to obtain smooth FRF curves. For this particular case, nine measurements points were performed at the top and the third floor to capture the lateral and torsional fundamental frequencies.
Measurement locations representing structural behavior in the modes of interest were chosen to obtain frequency response functions. Since the rigid modes are targeted, the vertical movement of the strong floor and reaction wall system for such modes is not negligible; therefore both horizontal and vertical acceleration responses were measured. Two measurement points were performed on the top of the reaction wall to capture the lateral and torsional frequencies. Four other measurement points were carried out on different locations on the strong floor and one on the soil next to the edge of the rear part of the strong floor as depicted on Figure 4.

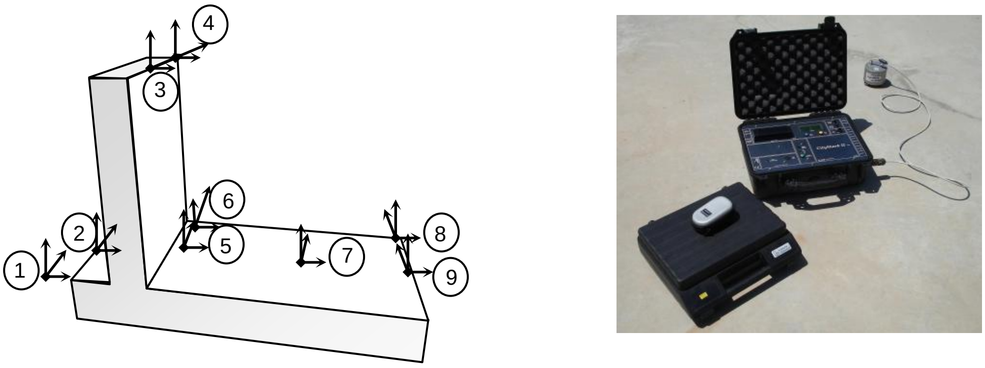


Figure 4. Sensors locations on the strong floor reaction wall system

3.2 Frequencies identification

The natural frequencies of the strong floor reaction wall system were identified using a “peak cursor” on the frequency response functions. The first curve in Figure 5 shows the FRF of the longitudinal vibrations measured on the centre of the top of the reaction wall (point 3 on Figure 4). The clearly distinct first peak at 7.90 Hz (Figure 5) corresponds to the fundamental elastic lateral mode on the longitudinal direction. The second FRF curve is obtained from a measurement on the corner of the top reaction wall (point 4) where a second peak corresponding to the elastic torsional mode can be seen at a frequency equal to 18.10 Hz (Figure 6).

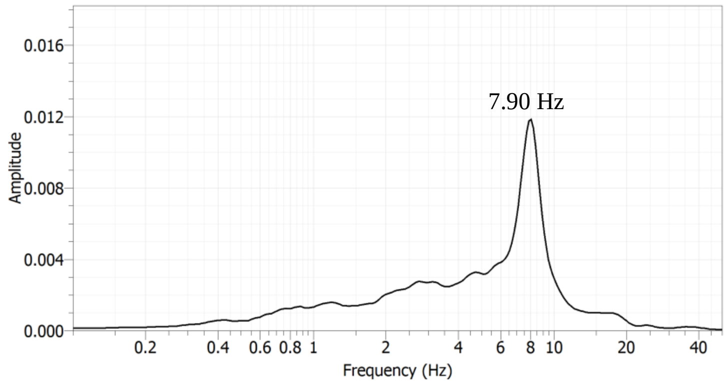


Figure 5. FRF curve in the longitudinal direction on the corner of the top floor of the reaction wall (point 3)

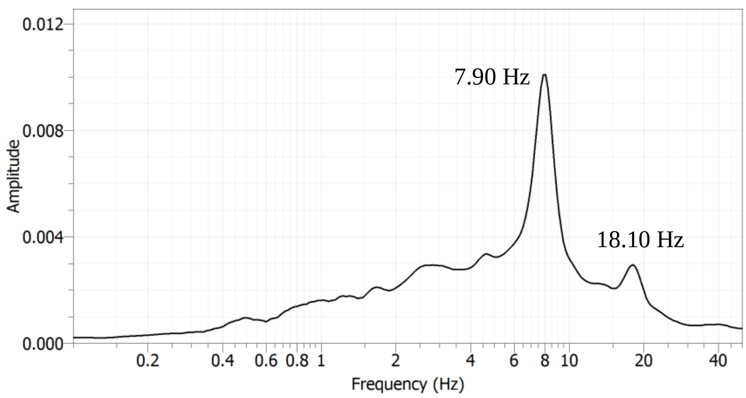


Figure 6. FRF curve in the longitudinal direction on the corner of the top floor of the reaction wall (point 4)

Lower frequencies corresponding to rigid body modes can be seen on the FRF curves measured on the top of the strong floor. The FRF curve (Figure 7) corresponding to the transverse direction of point 9 shows two main peaks at frequencies equal to 2.60 Hz and 4.30 Hz with a third one at 20.30 Hz. On the same figure a peak at a higher frequency of 35.90 Hz corresponds to the third elastic mode along the longitudinal direction. Figure 8 shows the FRF curve recorded on point 8 where in addition to a peak at frequency of 11.60 Hz along the vertical axis, the three components present a peak at 22.50 Hz.

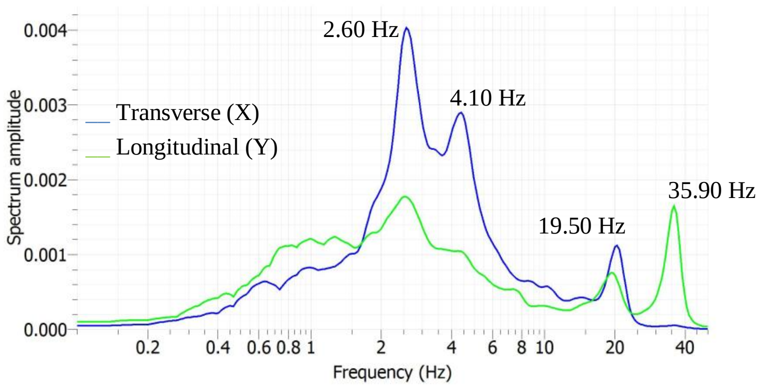


Figure 7. FRF curve for transverse and longitudinal direction on the strong floor (point 9)

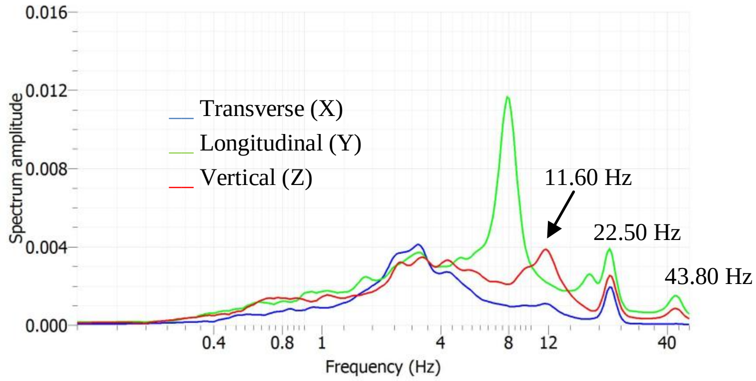


Figure 8. FRF curve for three directions on the strong floor (point 8)

3.3 Identification of the modal damping ratios

The ambient vibration output-only data is commonly used to estimate the damping ratios of structures at low amplitudes of vibration. For each identified frequency, a damping ratio has been determined using the random decrement technique. Figure 9 shows typical free decay fitting using Geopsy software. The values of the damping ratios corresponding to the rigid body modes tend to be higher compared to those of the elastic modes (Table 2).

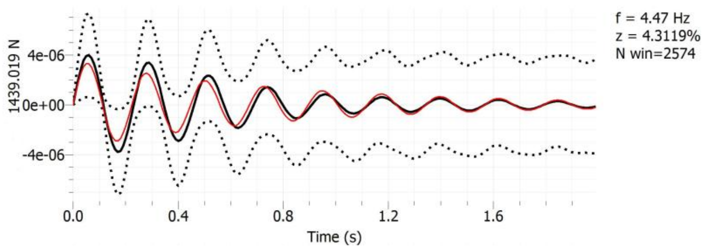


Figure 9. Typical free decay fitting for damping estimate using GEOPSY

4 FINITE ELEMENT MODEL WITH SOIL SPRINGS

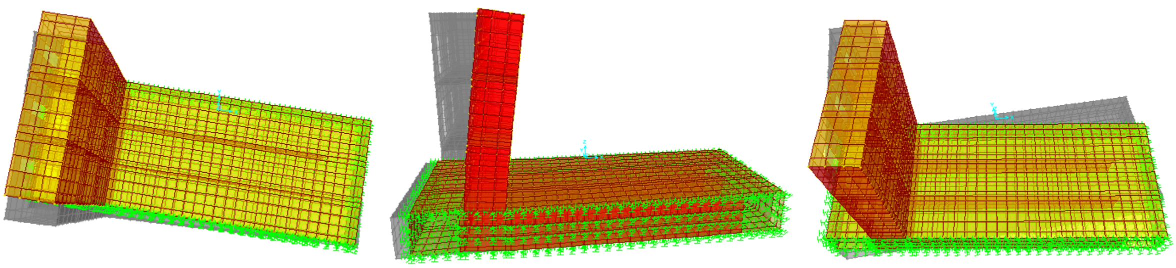
For the purpose of this study, a model has been elaborated where the RC strong floor and reaction wall system is modeled using thick shell elements and the surrounding soil is represented by a set of three translational springs, attached at each node at the base and the lateral faces in contact with the soil.

The characteristics of the spring elements are derived from the axial stiffness values of the equivalent springs k_x, k_y and k_z which are calculated as per Richart and Lysmer model and modified by the embedment factors (Chowdhury et al. 2009). The lateral stiffness in each direction is uniformly distributed on the five faces of the model in contact with the soil. However, the values of the lateral stiffness at the base of the strong floor k_x and k_y have been reduced because the base of the strong floor rests on a thin layer which reduces the friction between the strong floor base and the soil to make the pre-stressed of the concrete more efficient and uniform. The calculated frequencies for this distribution have been used as a first try and have been slightly refined to give a reasonable match with the experimental frequencies. The best fit has been obtained for a distribution of 70% of the total stiffness at the base and the remaining 30% on the lateral faces. The rigid body and the elastic modes are shown on Figure 10 and 11.

For comparison purposes, a modal analysis has been carried out assuming that the structure is fixed at the base. For this model, only the elastic modes of the reaction wall are obtained. Obviously the rigid body modes of the structure cannot be obtained, yet the frequencies are close to the corresponding elastic modes of the model with an equivalent soil springs (Table 2).

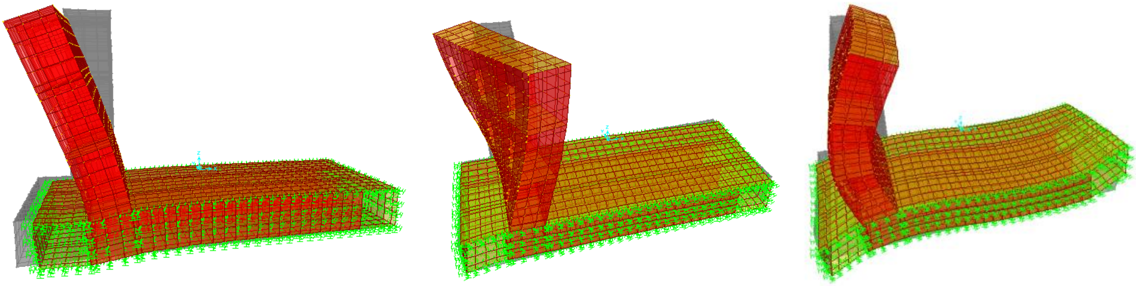
Table 2. Analytical and experimental frequencies with corresponding damping ratios

Mode	Type of mode shape	Elastic Soil Model	Fixed base Model	Experimental Frequency (Hz)	Error %	Modal Damping ratio (%)
1	Rigid body (Y-RZ)	2,72	--	2.60	4.5	7.40
2	Rigid body (X)	4,11	--	4.10	0.2	6.10
3	Rigid body (RZ)	4,21	--	4.40	4.3	4.31
4	Elastic 1 (X)	7,41	8.10	7.90	6.2	1.18
5	Rigid body (RX)	8,41	--	--	--	
6	Rigid body (Z)	12,32	--	11.60	6.2	2.73
7	Elastic (RZ)	16,92	16.68	18.10	6.5	0.56
8	Elastic (Z-X)	18,61	19.80	--	--	
9	Elastic (RX)	23,28	--	22.50	3.5	1.40
10	Elastic (RY)	26,28	--	--	--	
11	Elastic 2 (X)	32,38	35.23	35.90	9.8	0.48



a- Rigid body mode (Y-RZ) b-Rigid body mode (X) c- Rigid body mode (RZ)

Figure 10. Rigid body modes of the reaction wall strong floor system



a- Elastic mode (X) b-Elastic mode (RZ) c- Elastic mode (RX)

Figure 11. Elastic modes of the reaction wall strong floor system

5 CONCLUSION

Identification techniques of dynamic characteristics of civil engineering structures based on ambient vibration testing can be considered as one of the most effective method. In the present particular case, the identification concerns a strong floor and a reaction wall system characterised by a very stiff reinforced concrete caisson base having overall rigid body modes and elastic deformable modes of the wall. The measured frequencies of the rigid body modes were identified and used to update the FE models. The best fit has been obtained for a distribution of 70% of the total soil spring stiffness at the base and the remaining 30% on the lateral faces. It has been noticed that the elastic modes are less sensitive to the soil spring stiffness distribution on the faces. The measured modal damping, however, is found to be higher for the rigid body modes compared to those corresponding to the elastic deformation.

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