USE OF AMBIENT VIBRATION TESTS FOR STRUCTURAL IDENTIFICATION: 3 CASE STUDIES

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Abstract

In this study we summarize the results of Ambient Vibration Testing on 3 different structures: the Portuguese Telecom Tower; the Cabril concrete dam; and the “nuns” church a masonry structure in Lagos, south Portugal.

Ambient vibration testing was conducted in order to determine natural frequencies, mode shapes and damping ratios. An Finite Element Model updating of each structure was developed and updated with experimental results. The experimental results and the analytical results are presented, in this paper, and compared.

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1 Introduction

Instrumental monitoring of engineered structures is an essential tool for hazard mitigating programs. Dynamic characterization is important for dynamic behavior prediction, finite element modal updating and structural health monitoring.

The work presented here was carried out under the framework of the Dynaseis and Caravela projects, funded by FCT, Portugal and IPL, Portugal respectively.

Ambient vibration tests are frequently applied to on-site dynamic tests for structural engineering and present several advantages: they are nondestructive, they do not require expensive devices for artificial excitation of the structures, so the experimental cost is fairly low.

In this paper we present 3 cases studies of application of output-only modal identification used in civil engineering structures in Portugal. The first structure is a concrete reinforced tower building, the second is a large concrete arch dam and finally the third is an historical construction a masonry church.
2 PT Tower

The PT Tower is a 16-storey reinforced concrete structure, with two cores in the extremities, which concentrates most lateral and torsional resisting elements. Ambient Vibration Tests were conducted in order to obtain the dynamic parameters of the structure, including the fundamental lateral and torsional natural frequencies of the building, as well as the corresponding damping ratios and mode shapes, to calibrate a finite element model of the structure.

2.1 Finite Element Model

A Finite Element Model was developed using the computer program SAP 2000 version 7.10. This program can be used for linear and non-linear analysis, static and dynamic analysis of three-dimensional structure model of structure [3]. In our study the program was used to determine the fundamental frequencies and the corresponding mode shapes of structure, based on its physical properties.

The Finite Element Model, includes 14 533 shell elements and 957 frame elements. It is assumed that is a reinforced concrete structure with the following characteristics: i) the material is homogeneous and isotropic; ii) modulus of Elasticity, \( E = 36.5 \text{ GPa} \) (determined on the basis of base in the initial conditions of project; and admitting the increase of its value with base in the determination in Portuguese code – [9]); iii) Poisson’s ratio 0.2; iv) linear elastic behavior is admitted. The connection between the contention walls and the foundations soil it is simulated by an elastic restriction.

\[
\begin{align*}
  f_1 &= 1.05 \text{Hz} \\
  f_2 &= 1.19 \text{Hz} \\
  f_3 &= 1.90 \text{Hz} \\
  f_4 &= 4.22 \text{Hz} \\
  f_5 &= 5.21 \text{Hz}
\end{align*}
\]

Figure 1: Mode shapes obtained from the finite element model.

FEM was used for calibration calibrate it such that its frequencies and modes shapes, correspond to those obtained from experimental results.

2.2 Ambient Vibration Tests

Analysis based on ambient vibrations is a popular method to characterize the dynamic behavior of a structure during low amplitude vibrations [2]. The information obtained could be very useful to calibrate finite element models of the building, or can be used for the health monitoring of the building. The results of FDD peak picking and the stabilisation diagram were presented below in next figures.
In Figure 4 we present isometric views of the mode shapes of the first five vibration modes.

\[
\begin{align*}
  f_1 &= 1.05\text{Hz} & 1\text{st} \text{transversal} \\
  f_2 &= 1.28\text{Hz} & 1\text{st} \text{longitudinal} \\
  f_3 &= 1.89\text{Hz} & 1\text{st} \text{torsional} \\
  f_4 &= 4.27\text{Hz} & 2\text{nd} \text{transversal} \\
  f_5 &= 5.25\text{Hz} & 2\text{nd} \text{longitudinal}
\end{align*}
\]

Figure 4: Experimental mode shapes.

It is particularly important to note that the first five modes obtained experimentally are in the same sequence as those obtained in the analytical study.

### 3 Cabril Dam

The Cabril dam, the highest Portuguese arch dam, 132 m height. The results observed are compared with those of a numerical model of 3D finite elements, based on the hypothesis of linear elastic behaviour and assuming that the hydrodynamic water pressure is properly simulated through associated water masses, in accordance with Westergaard’s formula.

Figure 5: Elevation and cross-section by the central cantilever.

The recent development of modal identification techniques – FDD and SSI, and the dynamic range of the sensors enable the establishment of an effective continuous monitoring system for large
concrete dams. These systems are intended to continuously record and analyse, with acceptable accuracy, the dynamic response of these structures under the action of ambient noise and under seismic actions of different intensity levels. Within the framework of dam safety control, these systems may be highly important, namely to identify the variations in the dynamic characteristics (natural frequencies and vibration modes) of the dam-foundation-reservoir set. These are associated with: i) variations in the reservoir level, and with annual thermal variations; as well as with ii) structural alterations accidentally induced, as is the case of intensive earthquakes, or gradually induced as a result of deterioration processes.

3.1 Numerical Model

A finite element model was developed to analyse and predict the dynamic response of the Cabril dam. The discretisation adopted for the dam and for an adjacent foundation block was the one consisting of isoparametric 3D finite elements with 20 nodal points. A higher refinement at the upper zone (cracking zone) was chosen, which led to a mesh with 174 elements and 1296 nodal points. The hydrodynamic effect of the reservoir water has been considered through Westergaard’s associated water masses.

For the behaviour of materials, it has been assumed that the foundation rock mass could be considered, in a simplified way, as an elastic isotropic medium having a 32.5 GPa modulus of elasticity and a 0.2 Poisson’s ratio, with a null mass so as to simulate an elastic support.

The structure of the dam was assumedly made of concrete, and it has undergone the normal maturation processes, having presently achieved a static modulus of elasticity ranging from 21 to 22 GPa [4]. Both the hypothesis of isotropy and of linear elastic performance has been assumed for the whole dam structure, except for the cracked zone. For the latter, an orthotropic material has been assumed, in which the modulus of elasticity adopted for the vertical direction was about 10% of the one considered for the other directions (0.9 damage factor). In quantitative terms, a 32.5 GPa modulus of elasticity has been considered for the whole dam and in every direction, except for the previously mentioned zone where a 3.25 GPa modulus of elasticity has been assumed for the vertical direction.

![Figure 6: 3D View of finite element model.](image)

![Figure 7: Variation of the first three natural frequencies as function of water level.](image)

Based on the previous assumptions, a graph was prepared in the form of influence lines, which represent the variation of frequency according to the reservoir water level. The figure 7 shows the evolution of the first natural frequencies.
3.2 Ambient Vibration Tests

Three ambient vibration tests were conducted with two different types of equipment using two slightly different test procedures [6, 7].

3.3 Modal Identification

The computer program ARTeMIS Extractor, release 3.4, was used to perform the modal identification of the structure [11]. Two different techniques were used for modal identification: the Frequency Domain Decomposition (FDD) and the Stochastic Subspace Identification (SSI). This two modal identification techniques are used to cross-validate the results. The joint analysis of the signals measured in various strategic points of the structure makes it possible to identify the modal configurations and the corresponding natural frequencies [6, 7].

Figures 8 and 9 show the FDD peak picking and the stabilisation diagrams of the Cabril dam, respectively.

3.4 Analysis of Results

The results experimentally obtained from ambient vibration tests are compared with the results numerically calculated using the finite element model, as Figure 10 shows. The same figure also presents the results of two forced vibration tests. The experimental results are represented as points for the same three first natural frequencies, in each test performed.

The modal configurations identified for the three first modes previously analysed coincide with those calculated from the mathematical model [7, 9]. The 4th vibration mode identified do not
coincide with the calculated value obtained with elastic numerical model. In order to simulate the
dynamic behaviour due to the influence of the horizontal cracks the vertical modulus of elasticity
was changed to 10% of the value considered in the other directions. Figures 11 and 12 show an
obvious agreement between the modal configuration identified and the numerically calculated.

![Figure 11: Experimental mode shape influenced by horizontal cracking.](image1)
![Figure 12: Numerical mode shape influenced by horizontal cracking.](image2)

4 The Nuns Church - Lagos

The “Nuns” church, it is one of the most important structures in the Lagos historical centre, built in
the 16th century and partially destroyed by the catastrophic earthquake of 1755.11.01 – known as
the Lisbon earthquake. It was partially rebuilt after that event but since then no significant retrofit
was performed. This is a masonry structure with a central nave covered with a cylindrical vault, a
structural form quite common in religious European heritage; a spherical dome is located over the
high-chapel. The external walls discharge directly on the soil. In each case experimental results as
well as the analytical results are presented in this paper and compared.

![Figure 13 Plan view of the church.](image3)
![Figure 14 Frontal view of the church.](image4)

4.1 Numerical model

A three-dimensional model of the church was implemented using SAP2000® [3] and the
fundamental frequencies and the corresponding mode shapes of the structure, based on its physical
and mechanical properties, were determined.

![Figure 15 3D View of the model.](image5)

In the preliminary phase, it is assumed that all the materials of the structure have the following
characteristics: i) they are homogeneous and isotropic; ii) the modulus of Elasticity, \( E = 0.7 \) GPa
(based on a preliminary ambient vibration test); iii) the Poisson’s ratio is 0.2; iv) a linear elastic behaviour is assumed. The geometry of the structure is idealised considering the structure to be made of shell elements [1].

4.2 Experimental tests

Acceleration data was recorded for 30 minutes; the sampling frequency used was 250 Hz. The location of the accelerometers is shown on figure 17.

![Power spectral densities](image)

Figure 16: Power spectral densities on: (T) transversal direction; (L) longitudinal direction; (V) vertical direction.

![Sensor location](image)

Figure 17: Sensor location.

5 Conclusions

Dynamic analysis based on ambient vibration tests provides an accurate estimate of modal parameters. Concerning the PT Tower and the Cabril dam a good agreement in identified natural frequencies has been found with FDD based on the peak picking method and time domain – based on stochastic subspace identification.

A good correlation was achieved between results obtained by ambient vibration tests and the finite element modelling in all case studies and the experimental results were used to update the finite element models. Modal parameters obtained for each structure may be used for future health monitoring.

6 References


