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Experimental evaluation of the dynamic characteristics of Portuguese dams

Alexandre C. Portugal
Laboratório Nacional de Engenharia Civil, Lisbon, Portugal

Elsa Sá Caetano
Faculdade de Engenharia da Universidade do Porto, Portugal

ABSTRACT: For several years LNEC has been concerned with the evaluation of dynamic properties of concrete portuguese dams with the purpose of contributing to the assessment of their safety, namely towards earthquake withstanding capacity. In this context, investigation has been focused either on mathematical and physical modelling or on monitoring and testing. In this paper traditional experimental techniques, signal processing and identification methods are discussed. Emphasis is given to three case studies: a multiple arch dam (Aguieira), a gated gravity dam (Crestuma) and a double curvature arch dam (Alto Lindoso). Experimental results are compared with those obtained from finite element models. The usefulness of general information obtained from these tests is discussed and future developments in this subject are appraised.

1 INTRODUCTION

The seismic risk in the Portuguese territory makes the study of the dynamic behavior of large dams a subject to which Laboratório Nacional de Engenharia Civil (LNEC) has paid great attention for several years. For safety assessment of these structures studies have been done concerning both the prediction of structural response by means of mathematical and physical models and the monitoring and testing of structures (Pedro et al, 1987; Pedro et al, 1979; Pedro et al, 1986).

For the last five years a series of vibration tests has been performed in several of the most important Portuguese dams. More recently some joint work with Faculdade de Engenharia da Universidade do Porto (FEUP) of University of Porto has started aiming at the development of parameter identification methods.

2 EXPERIMENTAL PROCEDURES AND TESTS SET-UP

2.1 Ambient excitation tests

Ambient excitation tests are a well known technique for dynamic characterization of structures. However, attention should be called to the fact that the small level of energy from ambient excitation does not always allow the induction of measurable vibrations in all of the frequency range of interest. This is a common situation when rigid structures are considered, such as gravity or buttress dams.

Ambient excitation tests are then recognized to be a powerful tool for the identification of dynamic parameters in certain structures. Nevertheless, the impossibility of ambient noise measurement, usually overcome with the assumption of the excitation being a white noise may lead to great difficulties in interpretation of experimental data. As a consequence, ambient noise methods in dam testing are mainly applied as a preliminary phase.

2.2 Forced vibration tests

Forced vibration tests may be performed with single or multi input. The former technique has the obvious advantage of being much less demanding on equipment and control, however the results obtained with the latter yield more clearly the structural behavior. Both methods are obviously much more time consuming than ambient excitation technique.

In this context, single input stepped-sine excitation is a convenient form of excitation for a dam.

2.3 Tests set-up

The measurement system used for the dynamic testing of structures includes a set of accelerometers, seismometers and displacement meters, connected to analog anti-aliasing filters. For data acquisition a 13 bit A/D converter supported on a microcomputer is used.

Forced vibration tests are done with an eccentric mass vibrator designed and constructed at LNEC

(LNEC, 1965). This single arm vibrator produces a maximum force of about 50 kN in a frequency range of 1 to 7 Hz. The vibrator is attached to the structure by eight 30 mm steel bolts.

The main inconvenients of this equipment are the impossibility of loading with single direction forces, the narrow frequency excitation band. The development of a system to allow measurement of phase-lag between applied force and measured response is now in progress.

The usual testing sequence for a large dam has several phases. A preliminary analysis, based on existent mathematical models of the structure or experience of similar structures, allows definition of the instrumentation set-up. Usually there are limitations in number of transducers that can be used simultaneously and in positions where they might be installed on the dam.

Once measurement and data acquisition equipment are installed, a first set of ambient excitation tests is performed and Fourier analysis of the signals is done aiming at identification of important frequencies in the band that might be excited by the vibrator.

The forced vibration test is then performed with the transducers in fixed positions. The 1 to 7 Hz band is covered initially at equally spaced intervals of about 0.2 Hz. After this first run a detailed study of the zones of greater changes in response, generally associated with fundamental frequencies of the structure, is done.

The next step is a more thorough investigation of mode shapes associated with the fundamental frequencies. The vibrator is set at each fundamental frequency in study and only two transducers are used. One remains fixed in the vicinity of the vibrator and the other is travelled across the structure to the points of interest for the definition of the mode shape. Although this is quite a time consuming procedure it avoids any limitation on number of measuring points and allows frequent calibration of transducers. The procedure described generally has to be repeated for each direction as there are limitations in number of available transducers.

The final task in dam testing at LNEC is a large set of ambient excitation tests to allow characterization of dynamic behavior for frequencies above the vibrator range.

3 DATA PROCESSING

Techniques used in data processing are different according to the type of excitation present. In ambient excitation tests measurement of input is not possible. Besides, input and consequently outputs, are essentially random signals, thus requiring a statistical approach, namely by smoothing and by approximate evaluation of bias and random errors associated with the obtained estimates. When dealing with forced vibration tests the level of the induced energy is much higher than the noise level permitting signals to be treated as deterministic.

When working under ambient excitation, selection of sampling frequency, number of needed averages and records length should be made prior to data acquisition so that bias and random errors do not exceed certain reasonable values. To those errors contribute the frequency content of the signals as well as structural damping factors and it can be proved (Bendat et al, 1980) that bias and random errors vary inversely with the square of the power bandwidth and the square of the number of averages taken, respectively. For structures with low damping and low natural frequencies, the total number of the required samples in the ensemble may then be very high. For a dam having a lower natural frequency at 3 Hz with 2% damping, a 10% bias and a 10% random error when sampling frequency is 40 Hz would require the averaging over 100 records of 1024 sample points.

In what concerns signal processing, the most commonly followed steps are: i) DC component removal; ii) data window application; iii) decimation; iv) extraction of overlapped series; v) raw estimation of auto and cross power spectra; vi) raw estimation of ficticious transfer functions, computed as ratios between outputs; vii) computation of smoothed estimates of ficticious transfer functions and related coherence functions.

In respect to data processing for forced vibration tests series, the assumption that these series are deterministic leads to a much simpler method. For each frequency of sine excitation a short duration series of data points is sampled. After trend removal and, when needed, i.e., if noise has some importance, a narrow band digital filter centered at the excitation frequency is applied to each series. The ratio between amplitude and phase of each series and amplitude and phase of the applied sinusoidal force, is a point of the transfer function.

4 MODAL PARAMETER IDENTIFICATION

The scheme in use at LNEC for modal parameter identification includes two steps. In the first one a single degree of freedom (SDF) algorithm is used for parameter estimation, for each transfer function (TF) individually. These first estimates are then used as initial guesses in a N degree of freedom (NDF) identification algorithm. This second algorithm computes modal parameters for sets of transfer functions simultaneously, aiming at obtaining modal parameters for the whole structure rather than for a set of different points studied separately.

The need for NDF methods comes from the limitations of the SDF approaches: i) only modes of vibration for which the TF peaks are well defined can be identified by these methods and; ii) for the same mode of vibration, frequency and damping change from point to point.

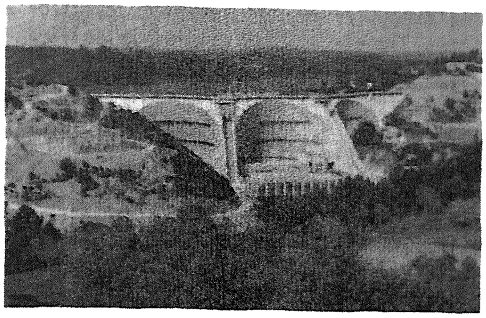

Figure 1. General view of Aguieira dam

The SDF method used at LNEC was proposed by Mau and Wang, 1989. A computer code was developed to identify modal parameters by this method, using typically 10 to 15 points for each mode.

A NDF algorithm was developed at LNEC with the purpose of solving some of the difficulties raised by the application of the SDF techniques (Câmara et al, 1991). The method lies on a non-linear minimization scheme of an error function between the values of the experimental set of TF and the values of the set of TF computed with the adjusted parameters. One of the obvious advantages of this approach is that one may now treat the structure as a whole, i.e., the frequencies and damping ratios obtained are much more meaningful. However, it must be noticed that the use of this method may bring some difficulties. In fact, the amount of time needed to achieve convergence may be strongly affected by the initial values employed.

5 CASE STUDIES

5.1 Aguieira dam

Aguieira dam, located in Mondego river in the center of Portugal, is a large-span multiple arch dam. It consists of three double curvature arches, with 89 m maximum height above foundation, resting on two buttresses whose medium planes make a 30 degree angle in plane, and a gravity crest with vertical ungrouted joints (figure 1).

The first experiences with vibration tests were tried at Cabril dam. However, as Aguieira dam is one of the most studied dams in Portugal and therefore its dynamic behavior is very well known it was chosen for the first systematic study of this kind. So, since 1980 several tests were conducted with different reservoir levels and temperature conditions, aiming mainly at development of methods and techniques of forced vibration testing. It must be emphasized that these tests first started with on paper recording of signals and suffered great development which led through tape recordings to the actual digital acquisition systems.

Figure 2 presents the location of excitation and measuring points for the vibration tests. For the forced vibration tests about 40 different samples were taken for each direction (radial and transverse horizontal and vertical), corresponding to different exciting frequencies. For each record 40 Hz sampling frequency and 256 points were used, meaning about 6.4 s time series.

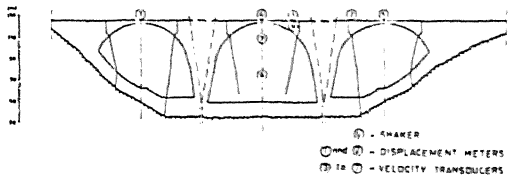

Figure 2. Aguieira dam. Excitation and measuring points.

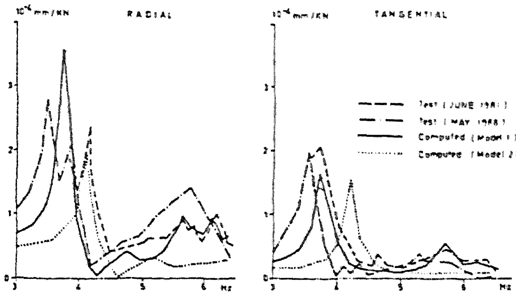

Figure 3. Aguieira dam. Experimental and computed transfer functions.

Table 1. Aguieira dam. Frequencies and damping coefficients.

TEST	1st mode (AS)		2nd mode (S)		3rd mode (AS)		4th mode (AS)	
	f(Hz)	μ(%)	f(Hz)	μ(%)	f(Hz)	μ(%)	f(Hz)	μ(%)
April 1980 empty reservoir	4.0	-	4.5	-				
June 1980 empty reservoir	4.2	-	4.8	-				
June 1981 full reservoir	3.8	-	4.2	-				
May 1988 full reservoir	3.5	2	3.9	2	5.2	-	5.9	
Computed FEM empty reservoir	4.0		4.2				6.3	

Note: S-simetrical. AS-Antisimetrical

Table 1 presents the most important results of the several tests performed at Aguieira dam. These results were obtained by the HPB method.

Figure 3 presents transfer functions obtained in these tests compared with results from mathematical models analyzed by the finite element method.

5.2 Crestuma dam

Crestuma is a multi-purpose plant in Douro river near Porto mainly intended for hydroelectric power, water supply to the city and improvement of navigability conditions (CPE, 1972). The main parts of the plant are: a gated movable dam, a navigation lock located near the river left bank, a 120 MW power station and a fish lock.

The movable gated dam (figure 4) consists on 8 double-fixed roller-gates (hook type), 28 m clear span, 13.7 m in height, supported by 6 m thick, 49 m large concrete piers, founded by the concrete-wall technique on the schist bedrock, 40 m below the alluvium river bed. The stilling basins are in plain concrete poured directly on the alluvium and are structurally independent from the piers. The piers also support a road bridge connecting the river banks and two beams on which the rails for the gantry crane lie.

The tests were performed in July 1988 and in March 1990. These tests were repeated because problems in the vibrator occurred during July 1988 campaign, which lead to several modifications in it's structure, specifically in order to make it stiffer and to eliminate problems in the attachment system. Ambient excitation (wind, hydraulic flow and turbine operation) and forced vibration tests were done. The vibrator was located on pier 2D and velocities were measured at several points (figure 5). About 80 different samples were taken, corresponding to different exciting frequencies. For each sample 120 Hz sampling frequency and 512 points were used, meaning about 4 s time series.

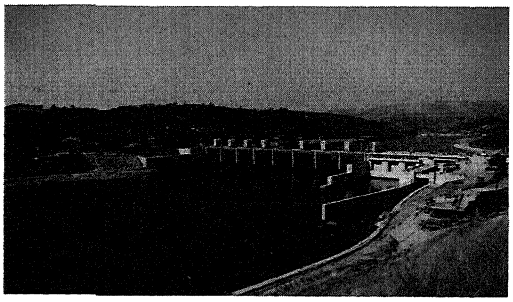

Figure 4. General view of Crestuma dam.

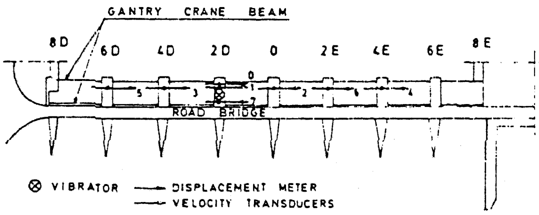

Figure 5. Crestuma dam. Measurement and exciting points.

Table 2 presents the most important results of these tests. These results were obtained by the NDF method referred to in point 4 of this paper.

Figure 6 presents transfer functions obtained from the test results compared with those obtained from a FEM model of the structure (Portugal et al, 1991).

Table 2. Crestuma dam. Frequencies and damping coefficients.

MODE	Frequency (Hz) FEM	Frequency (Hz) Meas.	Damping (%)
1	2.78	2.78	3.6
2	3.39	3.31	5.0
3	4.52	4.41	3.9
4	5.50	5.36	14.2

5.3 Alto Lindoso dam

Alto Lindoso dam, located in river Lima, in the northern Portugal-Spain border, is a double curvature arch dam, with 110 m maximum height above foundation, 300 m length crown arch, founded on a sound granitic foundation (figure 7). Construction of the dam ended in May 1990, and first impounding of the reservoir started in January 1992.

The monitoring of the dam included a in situ study of its dynamic characteristics. Two sets of tests were considered: the first one, with empty reservoir, has already been done; the second one will take place as soon as the water in the reservoir raises to a convenient level.

The first set of vibration tests took place in October 1991. At that time the reservoir was completely empty. Both ambient excitation and forced vibration tests were done. Figure 8 presents the measuring points and the vibrator's location.

Table 3 presents the most important results obtained in these tests.

Figure 9 presents mode shapes obtained both from ambient excitation and forced vibration tests. For the latter tests mode shapes were investigated by the travelling transducer technique.

Figure 10 presents transfer functions obtained from the forced vibration tests.

This study was the first one in which ambient excitation tests allowed identification of an important number of fundamental frequencies and associated mode shapes and damping coefficients. Usually, in dams, the ambient excitation is very complex as there is generally the influence of the rotating machinery of the power-houses associated with these structures. This machinery generates vibrations of relatively high amplitude whose spectrum covers a wide band and is very different from a

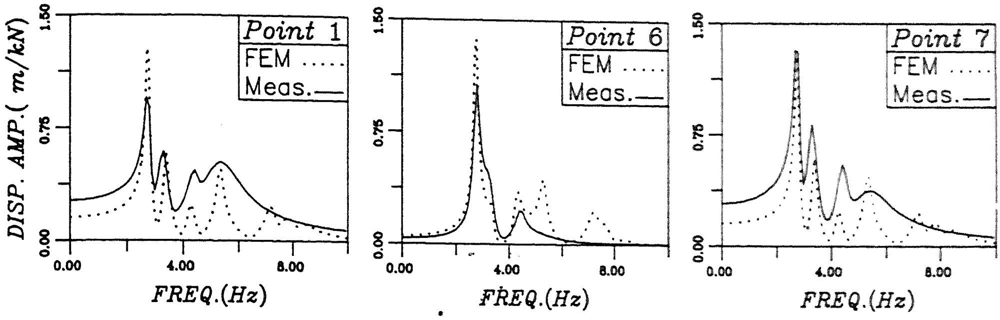

Figure 6. Crestuma dam. Experimental and computed transfer functions.

Table 3. Alto Lindoso dam. Frequencies and damping coefficients.

TEST	1st mode (AS)		2nd mode (S)		3rd mode (S)		4th mode (AS)		5th mode	
	f(Hz)	μ(%)	f(Hz)	μ(%)	f(Hz)	μ(%)	f(Hz)	μ(%)	f(Hz)	μ(%)
Ambient	3.8	2.1	4.1	2.2	5.1	2.3	6.4	1.0		
Forced	3.7	1.4	3.9	1.7	4.9	1.3	6.1	2.2	6.9	3.4

Note: S-simetrical, AS-Antisimetrical

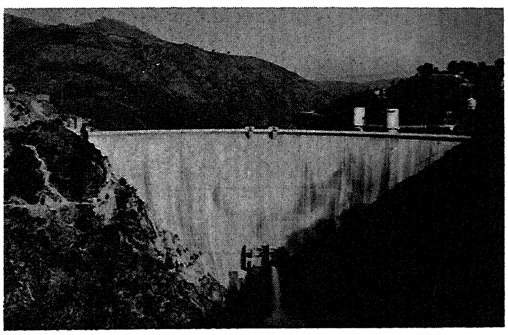

Figure 7. General view of Alto Lindoso dam

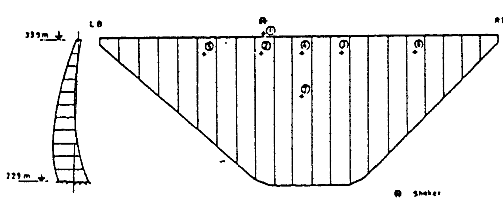

Figure 8. Alto Lindoso dam. Measuring and excitation points

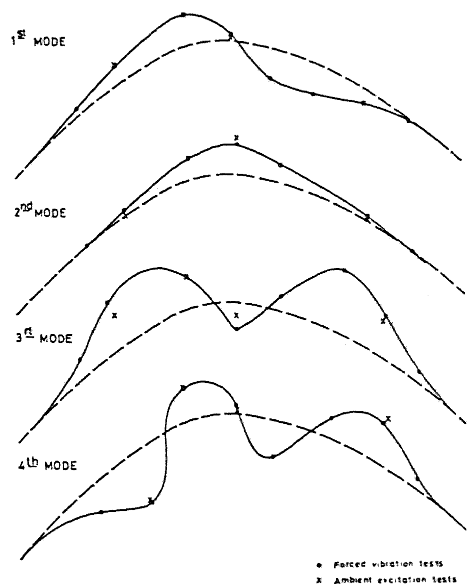

Figure 9. Alto Lindoso dam. Experimental mode shapes

white noise, making interpretation of the structural response a very difficult task. The case of Alto Lindoso dam is a particular one as the power station wasn't on service when the tests took place. Therefore the main source of ambient excitation was the wind, and though the vibration level was very low, it was possible to use methods initially developed at LNEC for the processing of bridge test data (Ritto-Corrêa et al).

No mathematical model results are presented as the study is still in progress.

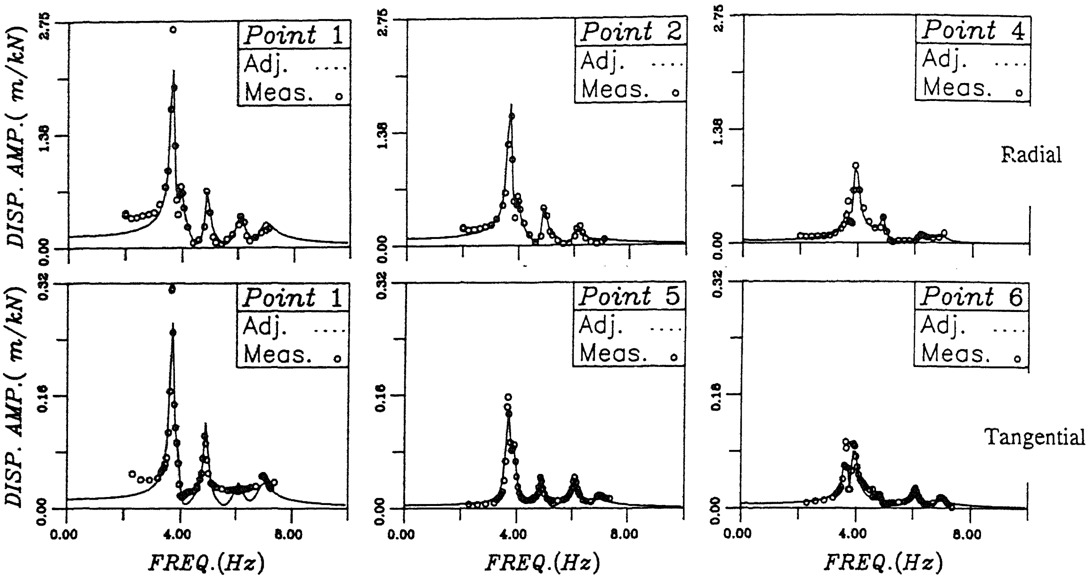

Figure 10. Alto Lindoso dam. Transfer functions from forced vibration tests.

6 FINAL REMARKS

The generally good quality and consistency of dynamic parameters derived from experimental analysis and the amount of information it provides show that dam testing has become a reliable everyday technique.

Probably the most important role actually played by experimental analysis is the contribution to mathematical models calibration. Also of great importance is the evolution of dynamic characteristics along time, which may be used in safety assessment.

Future FEUP-LNEC joint work will focus on the development of the excitation system and of system identification techniques. In fact, FEUP is in the final stage of development of an exciting system (Caetano) which will allow application of single direction forces and measurement of force response phase-lag. The identification methods will be adapted to consider the new information provided.

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