Technical Sciences
Academy of Romania
www.jesi.astr.ro

Journal of Engineering Sciences and Innovation
Volume 2, Issue 4 / 2017, pp. 77-86
http://doi.org/10.56958/jesi.2017.2.4.77

E. Civil Engineering and Transporting Engineering

Received ***18 September 2017*** *Accepted* ***6 December 2017***
Received in revised from ***15 November 2017***

Safety assessment of arch dams based on dynamic in situ testing

DAN STEMATIU[*,*], RADU SÂRGHIUŢĂ[**], ALTAN ABDULAMIT[**]

[*] *Romanian Academy of Technical Sciences*
[**] *Technical University of Civil Engineering Bucharest*

Abstract. The challenge of managing dams aging became a principal focus of dam engineering throughout the world. In many practical situations damage can be reasonably interpreted and quantified as a stiffness reduction, with the significant advantage of treating a state of damage in a linear elastic context. The concrete strength reduction and the extended fissures lead to Young modulus reduction that is regarded as a damage indicator. A variation in the elastic modulus induces a change in the dynamic response of the structure.
The main tool available to reveal the changes in the dam dynamic response is the recording of the free and forced vibrations of the dam and the processing of recordings in order to identify the vibration periods and shapes and the critical damping eventually.
The dynamic tests consist in recording the vibration field in the dam induced by ambient noise excitation (free vibrations) or by the hydromechanical equipment vibrations (forced vibrations). The spectral power density and Fourier spectrum of the recordings can render evident the first vibration modes, mainly the natural frequencies.
When evaluating the dynamic behavior of concrete dams, it is reasonable in most cases to assume that the response is linear for low or moderate-intensity dynamic loading. Such an assumption of linear response simplifies both the formulation of the mathematical model used to represent the dam, reservoir water and foundation rock system and also the procedures used to calculate the response.
The present paper section deals with the field testing of dynamic response of Paltinu arch dam and the corresponding calibrated model used to assess the dam safety or its deterioration due to aging phenomena.

Keywords: arch dam, monitoring, dynamic testing, vibration mode, global modulus

*Correspondence address: stematiu@utcb.ro

1. Introduction

The role of dam monitoring within the safety management, well established nowadays. Usually, dam monitoring systems employ conventional instruments based on electrical, hydraulic or pneumatic principles, which yield important information on the changes of different physical quantities such as pressure, stress, strain, displacement or temperature.

In the case of concrete dams, the aging phenomena are usually present but cannot be directly identified by regular instrumentation. The decrease of concrete strength, the fissure development, the foundation weathering has as the end result the change of the overall stiffness of the dam structure. This change has to be early detected in order to be a starting point for further investigation concerning the actual dam safety [1].

The dam structure stiffness is directly reflected by its dynamic properties since the natural vibration properties are depending on the mass (assumed constant) and stiffness. The in situ measurements of the natural vibration modes (shape and periods) are a very convenient approach of the dam aging investigation.

The dynamic tests consist in recording the vibration field in the dam induced by a ambiental excitation (free vibrations) or by the hydromechanical equipment vibrations (forced vibrations). The spectral power density and Fourier spectrum of the recordings can render evident the first vibration modes, mainly the natural frequencies.

The field measurements are also used to define mathematical models that allow the assessing the dam behavior and the evaluation of the actual safety. When evaluating the dynamic behavior of concrete dams, it is reasonable in most cases to assume that the response is linear for low or moderate-intensity dynamic loading. Such an assumption of response linearity simplifies both the formulation of the mathematical model used to represent the dam, reservoir water, foundation rock system and also the procedures used to calculate the response. However, a linear analysis still can be very valuable in helping to understand the nature of dynamic performance [2].

This new dam monitoring technique - in situ dynamic measurements - is presented in the followings based on the Paltinu dam case study.

2. Previous studies

Early ambient vibration testing of dams was reported and highlighted the challenges of identifying natural frequencies of large stiff structures from ambient vibration testing. In 1982 Clough presented vibration tests results for Techi Dam in Taiwan. Their important results enabled an identification of first few modes and a comparison with theoretical solution [3]. In 1986 similar dynamic tests were carried out on the Monticellio dam. By these tests, the first six modes of the structure and their corresponding damping ratios were obtained. In 1990, Severn et al conducted dynamic tests of a large arch dam along with a comparison with its mathematical model. The results were in terms of stresses and hydrodynamic

pressures [4]. Darbre et al. [5] reported successful periodic ambient vibration testing of Ruskin, Fei-Tsui and Mauvoisin dams respectively. These studies indicate that there have been significant improvements in ambient vibration
testing of dams from early trials in the 1980s. The improvements can be attributed to developments in instrumentation and signal processing algorithms.
Later, in 2009, Moyo and Oosthuizen developed the dynamic testing technique as a monitoring tool for dam safety evaluation [6]. The goal of the testing program was to obtain the as built dynamic characteristics (natural frequencies & damping ratios) of the dam to be used as baseline measurements for long term monitoring of the dam. The measurements would also be used to calibrate the finite element model of the dam.

3. Paltinu Dam

Located on Doftana River, Paltinu arch dam was constructed between 1960 and 1971. The dam height is of 108 m and the crest length is of 330 m. Storage has been purposed mainly to provide the discharge for drinking and industrial water supply. Dam structure is made up of central symmetrical double curvature arch body that rests on a pulvino by means of a peripherical joint and a parabolic wing extending over the left abutment terrace (figure 1).

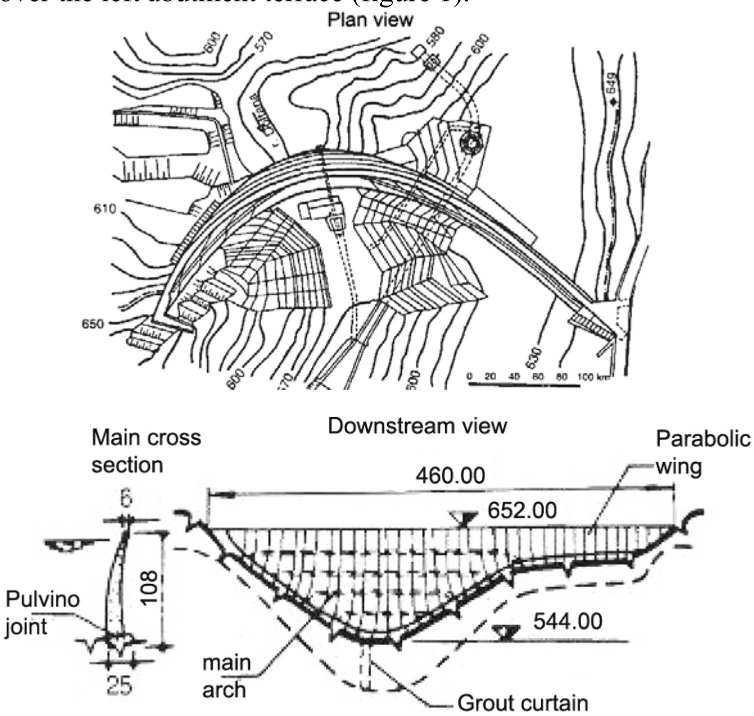

Fig. 1 Paltinu arch dam.

The cross profile of the location is characterized by a pronounced asymmetry caused by a terrace located on the left bank having a width of about 100 m along the valley. The dam foundation consists of Carpathian flish and includes detrial sedimentary rocks: sandstone, micro conglomerates and shistous clays.
The rocks present a marked bedded arrangement. The rock mass is affected by a dense cracking system, more evident in sandstone. The dam area is crossed by several faults generally located transverse on the valley. The permeability of the foundation rock was quite large (2…8 lugeons) and an extensive grout curtain was provided.
During the first 3 years after commissioning the reservoir was operated at lower levels. At the new cycle of reservoir filing in 1974 when the water levels have exceeded the previous recorded ones, an abnormal behavior of the dam was noticed: dam displacements larger than predicted, movements at the foundation level, joint openings, cracks at rock surface and significant increase of seepage (from 10 l/s to 150 l/s).
Remedial works had in view the causes of the unusual loading scheme [7]. They consisted mainly of additional rock watertightening upstream the fault, drainage downstream and additional mass on the left abutment. To reduce the seepage forces within the rock mass the upstream face of the rock was covered with concrete and a new grout curtain was performed along the left abutment. To prevent possible water pressure effects a new drainage system was provided by means of two drainage galleries located 10 m downstream the grout curtain. To increase the abutment stability a concrete cover was performed on the left bank downstream area that allowed also rock mass consolidation by grouting and controlled drainage (figure 2, 3).

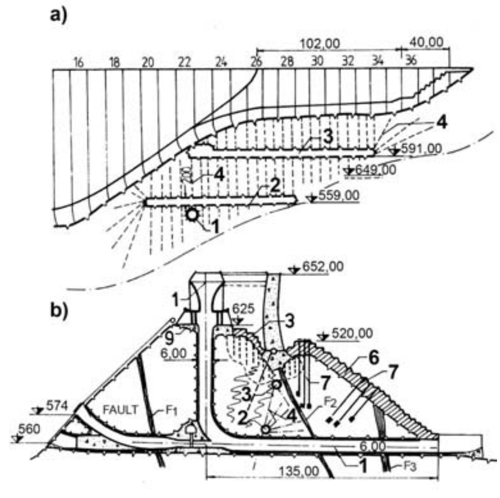

Fig. 2. Remedial works for Paltinu dam
a - longitudinal profile at the left bank; b - cross section along the bottom outlet
1 outlet gallery; 2 lower drainage gallery; 3 upper drainage gallery; 4 drainage drillings; 5 upstream concrete cover; 6 downstream concrete cover; 7 pre-stressed anchors.

Fig. 3. Downstream view of Paltinu dam.

4. Field dynamic measurements

The dynamic response of Paltinu dam was recorded by using an acquisition system Buttan Service – Tokyo & Tokyo Soil Research Co., Ltd., Japan (figure 4). The acquisition station GEODAS and CR4.5-1 sensors were used for capturing of multi-modes of vibration under low-level excitation. The positioning scheme for the transducers on the dam was adopted in accordance with the expected response [2].

Fig. 4. Positioning of equipment on dam crest.

The location of seismometers used in the October 2017 campaign is shown in figure 5. Nine sensors were simultaneously positioned at the crest level, on the radial direction, on the horizontal tangential direction and on the vertical direction. The records have been carried out taking into account vibration sources as micro tremors, together with vibrations produced by turbines of the water power station at the dam toe.

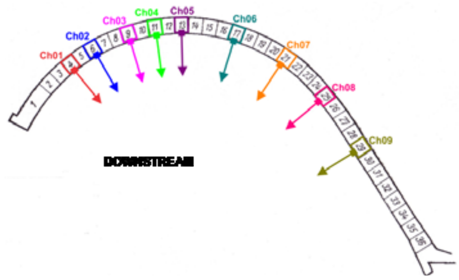

Fig. 5. Location of the sensors.

The processing of the data was carried out digitally, which allowed the determination of mean values, peak-peak values, Fourier spectra and response power spectral densities. The Fourier spectra based on the multi-channel records along the radial direction at the nine measuring points (ch01 --- ch09) are presented in figure 6.

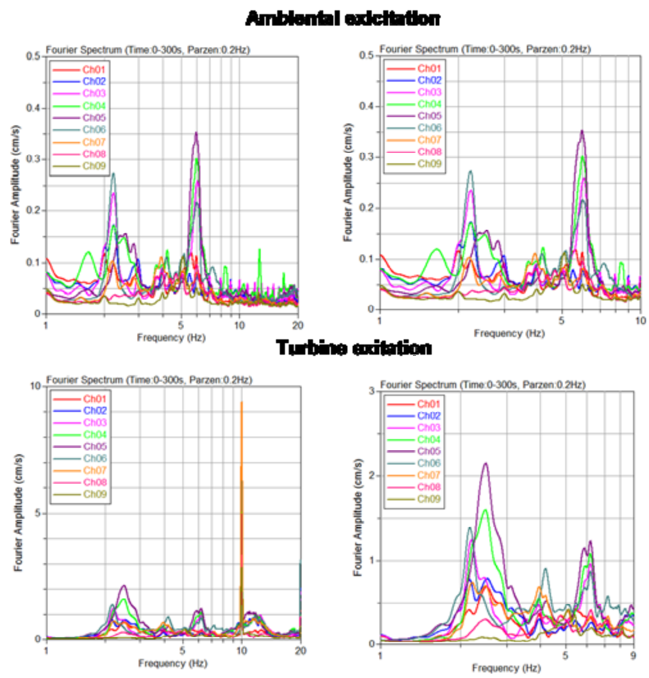

Fig. 6. Fourier spectra for some of the recorded displacements.

Based on the field measurements the first – fundamental period of vibration was identified as being T1 = 0.44 sec (f_1 = 2.26 Hz). The dynamic properties rendered evident by the previous measurements campains (see table 1) are similar, thus confirming the good structural behavior of the dam.

Table 1. Fundamental periods of vibration in the 2013 – 2017-time interval

	Block 6	Block 9	Block 11	Block 17
October 2013	0.45	0.42	0.40	0.45
October 2015	0.44	0.45	0.45	0.44
October 2017	0.45	0.45	0.44	0.45

5. Data interpretation based on the mathematical model

A 3 D finite element model of the dam – foundation system was developed using the ANSYS computer program (see figure 7). The dam-foundation interaction effects were represented by a "*standard*" massless foundation model, in which only flexibility of the foundation rock is considered but its inertia and damping are ignored. The rock foundation was modelled with 2780 solid elements connected in 3510 nodes. The arch dam was modelled as a monolithic structure represented by 574 of finite elements of appropriate types. The dam-water interaction effect was represented by the added hydrodynamic mass models according to Westergaard. The added water mass is realized by means of 173 lumped mass elements at the upstream face of the dam. The sensitivity analysis leads to a concrete elasticity modulus of 25×10^6 kPa corresponding to the measured fundamental frequency.

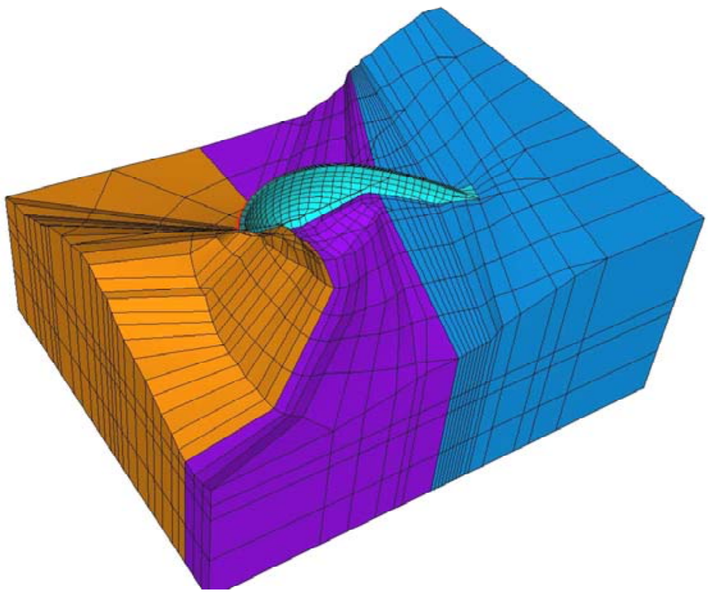

Fig. 7. The finite element model.

The computed eigenfrequency of the system with the impounded reservoir and the added mass approach for structure reservoir interaction are presented in table 2. From the frequency response analysis, it can be seen, that the first 5 eigenmodes are sufficient to represent the structural response.

Table 2. Vibration periods

Eigenmode	1	2	3	4	5
Frequency [Hz]	2.25	2.45	2.86	3.23	3.69
Period [s]	0.44	0.41	0.35	0.31	0.27

In order to acquire advance knowledge of the dynamic behavior of the dam and also to examine the accuracy of the results, the computed natural

modes of vibration were presented in the form of deflected shapes (figure 8).

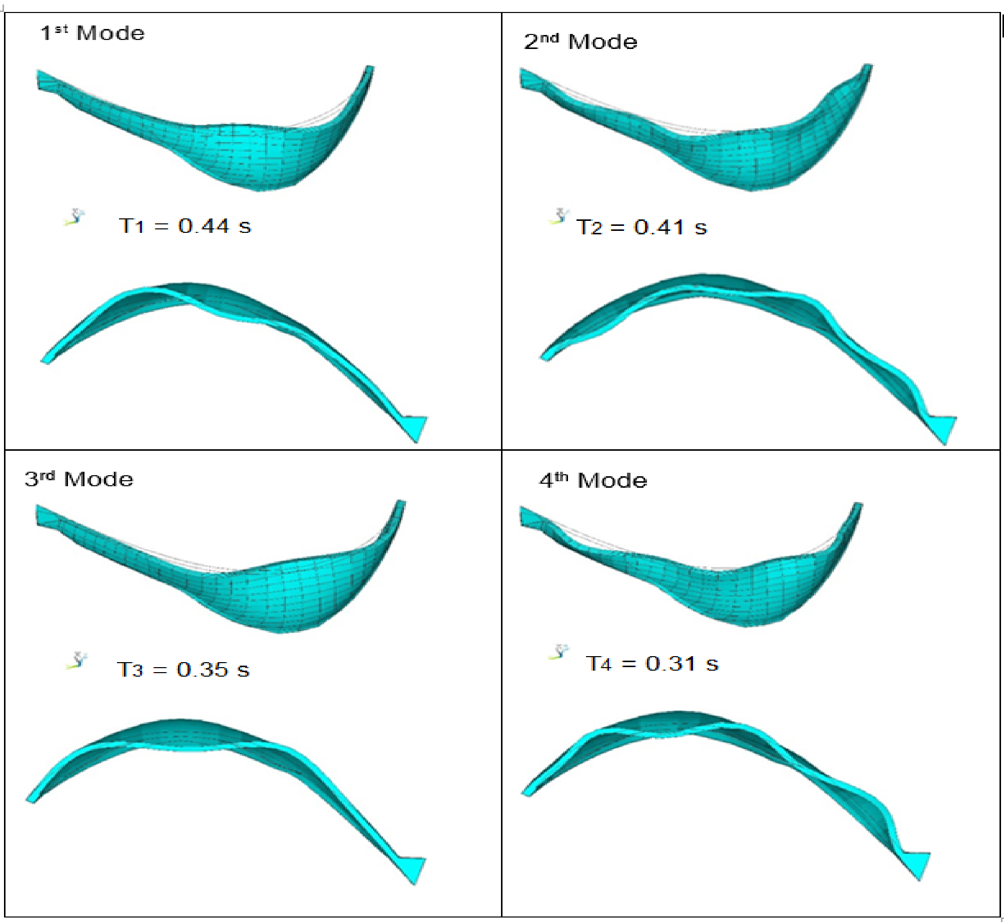

Fig. 8. The first four vibration modes of the FE model.

Performing several modal analyses on the basis of a finite element model of the dam, each of them for a proposed value for the elastic modulus of concrete one can establish a graphical correlation.
In the case of Paltinu dam the calibration leads to a concrete elasticity modulus of 25×10^6 kPa corresponding to the measured fundamental frequency (figure 9).

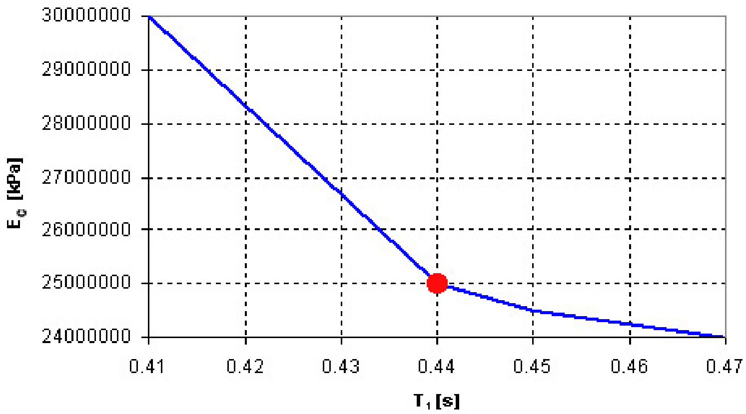

Fig. 9. Calibration of the mathematical model by the fundamental period.

Based on annual campains of field measurements the calibration process is renewed. If the new values of the elastic modulus do not differ significantly from the previous value one can conclude that the dam has preserved its structural properties. If this is not the case, further investigation are required.

6. Concluding remarks

The dynamic testing of dams is a very interesting nondestructive test to add to common existing monitoring systems, such as piezometric measures, pendulums, differential settlement gauges, etc.
It provides valuable information about dam global structural behavior, as well as a tool to track possible structural damage. Dynamic testing can offer insight into the behavior of dams and the calibration of dam structural models. The results of dynamic tests are used to establish baseline measurements for long term dynamic monitoring of the dam in order to assess the structural integrity along the years of operation.

References
[1] Stematiu, D., Popovici, A., Sarghiuță, R., Abdulamit, A., Popescu, C., Gaftoi, D., *Advanced Monitoring of Romanian Dam Portfolio*, Third congress on dams, Struga, 2013.
[2] Sarghiuță, R., Abdulamit, A. *Diagnosis of the structural evolution of dams using dynamic monitoring data,* Proc. International Symposium Dams in a Global Environmental Challenges, Bali, Indonesia, 1-6 June 2014.

[3] Clough, R.W., Stephen, R.M., and Kuo, J.S-H. *Engineering Research Center Report*, No UCB/EERC 82/11, University of California Berkeley, 1982.
[4] Severn, R.T., Taylor, C.A., and Brownjohn, J.M.W. *Full Scale Dynamic Testing and Mathematical Model Validation of Dams*, Dam Engineering, **1**(2), 1990.
[5] Darbre, G.R. and Proulx, J. *Continuous ambient-vibration monitoring of the arch dam of Mauvoisin.* Earthquake Engineering and Structural Dynamics, 31, 2002, p. 475-480.
[6] Moyo, P., Oosthuizen, C. *Dynamic testing of a concrete arch dam.* 3rd International Operational Modal Analysis Conference: 95-100. Portonovo, 2009.
[7] Stematiu, D., Popovici, A., Covaceanu, D. Foundation Aging Phenomena for some Romanian Dams. Transactions of 24 Congress on Large Dams, Q95, R10, Kyoto, June, 2012.