Assessing Structural Safety of an Arch Dam Using in Situ Vibration Tests

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Abstract. Safety of large dams has always been a major concern for engineers throughout the world but also for public opinion, mass-media and politicians. This is usually based on the fact that the collapse of a large dam could result in huge consequences such as fatalities, economic and/or environmental losses. Nowadays, it is well known that an important factor adversely influencing the safety of such a complex structure like a dam is represented by ageing as a process and ageing related phenomena. Since some 85% of all existing large dams are built in the last 50 years, safety influenced by different decay processes became an important issue to be analysed by dam engineers. In this regard, in situ ambient vibration measurements used to identify the dynamic response characteristics of a large dam seems to represent an appealing non-destructive technique to assess the structural and material characteristics changes and thus to monitor the safety status of the structure. The paper presents the use of the above mentioned procedure by a Romanian team of dam specialists who developed a method combining experimental and analytical techniques for the assessment of the health status of large concrete dams. The Global Elastic Modulus Method (GEMM) was initially used for analysing buttress dams, then it was extended to assess arch dams’ safety state. The most recent evaluation was made upon a 48 m height arch dam in Romania, Cincis dam, located in the central part of the country. The paper is structured into 3 main parts: Introduction, explaining the concept of the hybrid model (the mathematical model bounded to a certain in situ measurement program and calibrated using the recorded data) and of the global elastic modulus (GEM) associated with the dam structure; Experimental, presenting the used equipment, measuring scheme and the processing of the recorded data, ending with the results from spectral analyses; Analytical, presenting the mathematical model developed for the dam structure and its calibration aiming to identify the natural response frequencies and the corresponding mode shapes of the analysed structure. Final conclusions and recommendations are made.

1. Introduction
The majority of Romanian’s large dams (almost 240 according to ICOLD criteria) were built between 1950 and 1990 and ageing phenomena represents a major concern for engineers involved in dam safety and risk management activities. Ageing of dams, with all the negative associated effects, influence the safety of hydraulic structures almost as much as the factors representing loadings, environmental conditions, poor execution or faulty design. Ageing of concrete dams can be related to material degradation due to alteration processes, fatigue processes, development of cracks within the dam body, thermal fissuring, alkali-aggregate or other chemical reactions or freeze-thaw associated phenomena [1].
This material degradation may be described in terms of the change of the overall stiffness of the structure which is directly reflected by its dynamic properties since the natural vibration properties depend on structural mass (assumed constant) and stiffness.

Usual instrumentation used for dam safety monitoring is not capable to directly identify the degradation of concrete characteristics due to ageing phenomena but an appealing method to overcome this impediment is represented by Ambient Vibration Monitoring (AVM). The in-situ measurements of the natural vibration characteristics represent a quite convenient approach for dam ageing preliminary investigations [2]. This method is widely used for bridge and civil structures [3, 4], but in the last period it was also used for concrete dams – arch dams [2, 5-9] and buttress dams [1, 10-13]. This method is frequently used as a long-term monitoring procedure (ambient vibration measurements can be periodically repeated with a reasonable financial and technical effort). The fact that is carried out periodically provides an additional element tracking of structural integrity and, in case of changes in measured main modal parameters compared to the values from previous campaigns, can open the way for more complex investigations.

2. Hybrid model and Global Elastic Modulus overview

A hybrid model can be defined, according Abdulamit [1, 13, 15], Stematiu [14] and Markovic [16], as the combination between the in-situ measurement and the mathematical model associated to a certain hydraulic structure (usually a finite element model). The hybrid model allows the calibration of the mathematical model based on the recorded values of the installed monitoring systems. Hybrid models appear to be an attractive option for the evaluation of the static and/or dynamic behaviour of the hydraulic structures during their operation phases and for back analyses.

In order to fully understand a hybrid model, it is necessary to introduce the concept of Global Elastic Modulus (GEM). According to the same authors and Sârghiuță [7] and Bugnariu [12], GEM is defined as a structural parameter which can be used for safety assessment of existing dams. GEM procedure involves some assumptions: the elastic behaviour of the materials, structural continuity of the dam and the complexity of the mathematical model (different particularities of the structure which were included or not in the mathematical model). Thus, GEM value for the dam is no longer a physical parameter and it is tied by the mathematical model developed for a precise purpose and calibrated using measured data. Even if its value represents the dam body elastic modulus, the fact that is strongly depended by the structural continuity and by the complexity of the mathematical model leads to its utilization only for that specific model - GEM becoming meaningless if disconnected from the mathematical model. The same mathematical model will lead to different GEM values when used for calibration for static loads and dynamic response respectively.

GEM is also seasonal strongly depended because, for thin concrete structure such as arch or butters dams, the degree of structural continuity depends on the joint openings and the structural response and consequently GEM have different values in the cold season compared with the ones in the warm season. Therefore, the correct use of the global parameter requires that the field measurements to be acquired in a very similar thermal field within the dam. Another important condition for measuring campaigns is to use the same technique and the same measuring points.

3. Experimental Program – Cincis dam

3.1. Cincis dam – brief description

Cincis dam (figure 1) is an arch dam with a maximum height of 48 m and a L/H ratio of 4.6. The dam, located in the Western part of Romania, was erected between 1961 and 1964 and the reservoir was partially impounded in 1962. The dam, composed of 17 blocks with a width of 12 m and 2 external blocks of 8.2 m and respectively 9.4 m, has a thickness of 4.5 m at crest and 14 m at base. Medium radius at crest is 92.10 m with a corresponding centre angle of 138°.
The spillways are located within blocks no. 8 – 10 and are composed of 5 spill fields situated at elevation 297.00 masl (3 m below crest elevation) and 4 spill holes situated at elevation 293.50 masl (normal retention level). The dam storage reservoir is mainly used for water supply of industrial necessities of Hunedoara city, hydroelectricity through a small hydropower plant and flood mitigation.

The base rock from dam’s foundation is homogenous and is mainly made of quartzite shales. Geotechnical characteristics for the rock mass are: $\gamma = 26 – 28$ kN/m$^3$, $E_f = 8$ GPa and $\sigma_{adm} = 2.5$ kPa. The shales planes are orientated almost perpendicular to the valley with the angle of dip layer towards upstream, situation in which the stresses from the dam are favourable transmitted to both slopes.

According to Romanian national normative [17] regarding the seismic characteristics of Cincis dam site, peak ground acceleration for a 100 years earthquake is 0.08 g and the corner period is 0.7 s.

3.2. Ambient vibration tests
The first ambient vibration measurement campaign from the experimental program took place in 2 November 2018 between 10:00 – 14:00. The weather condition from that day were favourable for measurements – air temperature 15°C and no wind. Reservoir level was approx. 293 masl, 7 meters below dam’s crest and 0.5 m below normal retention level.

The ambient vibration measurement equipment of the Research Center for Seismic Risk Evaluation from Technical University of Civil Engineering Bucharest was used for Cincis dam tests. It consisted of a 24 bits acquisition system (GEODAS) and 1s velocity sensors (frequency bandwidth 1-20 Hz) produced by Buttan Service-Tokyo & Tokyo Soil Research Co., Ltd (CR4.5-1H). A huddle test was performed before the measurement campaign in order to check that all the sensors worked correctly. The measurement campaign consisted in two recordings of 5 minutes length with a sampling frequency of 100 Hz. The sensors were placed at dam crest and the measurement direction was radial to dam axis (downstream direction). There were used 2 layouts using simultaneously 3 sensors for each one (figure 2).

In situ ambient vibrations measurements were used for estimation of the most important spectral frequencies of the dam’s dynamic response at small amplitude vibrations, and for calibration of the numerical associated models. The results characterize the dams’ dynamic behaviour for linear-elastic behaviour.
A Peak-Picking procedure using Fourier amplitude spectra was used to estimate modal frequencies for the investigated dam. Examples of recorded velocities and of Fourier amplitude spectra (FAS) are given in figure 3 for layout 1.

The average values of the main frequencies and periods corresponding to the blocks on which ambient vibrations were measured as well as the average value for the entire structure are presented in table 1 and table 2.

Table 1. Average frequencies obtained from in situ records.

| Block 4 | Block 7 | Block 9 | Block 11 | Block 14 | Block 16 | Average values |
|--------|--------|--------|----------|----------|----------|----------------|
| f1     | 4.40   | 4.41   |          | 5.71     | 5.55     | 4.405          |
| f2     | 5.73   | 5.73   | 5.70     | 6.59     | 6.61     | 5.693          |
| f3     | 6.58   | 6.58   | 6.58     | 6.42     | 8.43     | 6.585          |
| f4     | 8.41   | 8.43   | 8.27     | 8.42     | 8.43     | 8.395          |
| f5     | 9.56   | 9.51   | 9.53     |          |          | 9.533          |
| f6     | 12.2   | 11.70  | 12.15    | 12.22    | 12.24    | 12.113         |
| f7     | 16.86  | 16.92  | 16.90    | 16.91    | 16.85    | 16.88          |
| f8     | 19.75  | 19.76  | 19.74    | 19.82    | 19.82    | 19.793         |
Table 2. Average periods obtained from in situ records.

|     | Block 4 | Block 7 | Block 9 | Block 11 | Block 14 | Block 16 | Average values |
|-----|---------|---------|---------|----------|----------|----------|----------------|
| T1  | 0.227   | 0.227   |         |          |          |          | 0.227         |
| T2  | 0.174   | 0.175   | 0.175   | 0.175    | 0.175    | 0.180    | 0.176         |
| T3  | 0.152   | 0.152   | 0.152   | 0.152    | 0.152    | 0.151    | 0.152         |
| T4  | 0.119   | 0.119   | 0.121   | 0.119    | 0.119    | 0.119    | 0.119         |
| T5  | 0.105   | 0.105   | 0.105   |          |          |          | 0.105         |
| T6  | 0.082   | 0.085   | 0.082   | 0.082    | 0.082    | 0.082    | 0.083         |
| T7  | 0.059   | 0.059   | 0.059   | 0.059    | 0.059    | 0.059    | 0.059         |
| T8  | 0.051   | 0.051   | 0.051   | 0.050    | 0.050    | 0.050    | 0.051         |

3.3. FEM – Mathematical models

To analyse the structural safety of the dam using the recorded data two 3D finite element models were created. These models were also used to analyse the influence of the mesh on the obtained results. In this regard, both models had the same geometry and the same extend of the foundation rock. The same element type and the same material properties were used in the analyses. The only difference between the 2 models was the mesh density for dam and foundation volumes.

The geometry of the models was based on the geometric elements presented in the design and execution drawings: tracing table, layout view, longitudinal profile through dam axis and cross sections. The extend of foundation rock was adopted approx. 2 × the height of the dam on all directions.

3D linear finite elements with 8 nodes and 3 degrees of freedom per node (ux, uy, and uz) were used to mesh all volumes in the 2 models. The aim was to obtain a regular mesh (with no pyramids) for both dam and its foundation and to assure a convenient ratio between the maximum and the minimum elements dimension.

3.3.1. Model A – This model (figure 4 and 5) is characterized by a coarser mesh for both dam and its foundation – 336 elements for dam volumes and 72758 elements for foundation rock. When meshing the dam, the joints were not modelled, the structure being considered monolithic. Another aspect considered was the number of elements in each cross section – a uniform mesh with 3 elements on the thickness of the dam resulted.

Figure 4. 3D view for Model A (a – view from downstream, b – view from upstream)
3.3.2. Model B – For Model B (figure 6 and 7) a finer mesh for dam volumes was considered. The arcs of the dam were divided in 25 equal parts when the size of the elements was imposed. As in the case of Model A, the structure was considered monolithic. A uniform mesh resulted, with 3 elements on the thickness of the dam. Model B is composed of 198125 elements from which 3600 are associated to dam’s volumes.

The initial material properties assigned to dam volume are: Young modulus – $E_{\text{init}} = 21$ GPa, Poisson coefficient - $\nu = 0.18$, density - $\rho = 2.4$ t/m$^3$. The material properties for rock foundations were adopted based on the geotechnical studies realized during the design phase of the dam. For field rock foundation the assigned values are: Young modulus – $E_f = 8$ GPa, Poisson coefficient - $\nu = 0.25$. In order to analyse
the dynamic properties of the dam structure, the mass density of the rock foundation is assumed equal to zero. Both the concrete and the foundation rock were considered linearly elastic, homogeneous and isotropic materials.

The influence of the water level in the lake was included in the modelling by introducing additional water masses on all nodes situated on the upstream face. The values of these concentrated masses were determined using the Westergaard relationship for a parabolic distribution of hydrodynamic pressure. The concentrated masses of water were modelled in the dam-reservoir-foundation assembly by introducing mass concentrated finite elements, for which was taken into account only the translational inertia, ignoring the rotation inertia. Hydrodynamic pressure values were calculated considering the water level from the day when the measurement campaign took place.

4. FEM results
Comprehensive analyses using the two FE models were performed. The first phase of the analysis consists of verification of the modelling accuracy, performing a modal analysis in the empty reservoir case (using the initial material properties). The first 3 vibration mode shapes are presented in figure 8.

As it can be observed, the modal analyses with empty reservoir led to quite comparable results for both models. Mode shapes are very similar (first is antisymmetric, the second and the third are symmetrical) and the difference between the computed natural periods for the first 3 vibration modes are approx. 10%. This behaviour is maintained also in the analyses with reservoir at normal retention level.

![Figure 8](image)

**Figure 8.** The first 3 modes (mode shapes and periods) for empty reservoir (Model A – left; Model B – right)

Next step was to calibrate the two models. The calibration of the FE Models was performed for the full reservoir case and was based on the recorded values of the in situ ambiental vibrations. Natural periods for the first 3 vibration modes were used, computed for different values of concrete elastic modulus $E_c = 21$ GPa ... $52.5$ GPa. The material properties for rock foundations were kept unchanged ($E_f = 8$ GPa). To calibrate the models, it was used the least squares method.
For Model A calibration the best fit was obtained for $E_c = 36.75$ GPa. For Model B calibration the best fit was obtained for $E_c = 47.25$ GPa. Therefore, Model B performs like a more flexible structure and an artificial increase of the global stiffness was necessary to lead to comparable results with the measured ones. The corresponding results for the full reservoir case were also comparable between the two models (an average of 11% difference between the computed natural periods for the first 3 vibration modes). The results of the calibration phase can be observed in tables 3 and 4 and in figure 9.

### Table 3. Results of parametric analyses for Model A.

| $E_c$ | $E_{\text{init}}$ | $1.5 \times E_{\text{init}}$ | $1.75 \times E_{\text{init}}$ | $2.0 \times E_{\text{init}}$ | $2.5 \times E_{\text{init}}$ | Measured average values |
|-------|-------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-------------------------|
|       | $[s]$             | $[s]$                       | $[s]$                       | $[s]$                       | $[s]$                       | $[s]$                   |
| T1    | 0.300             | 0.245                       | 0.227                       | 0.212                       | 0.190                       | 0.227                   |
| T2    | 0.280             | 0.229                       | 0.212                       | 0.198                       | 0.177                       | 0.176                   |
| T3    | 0.199             | 0.163                       | 0.151                       | 0.141                       | 0.126                       | 0.152                   |
| T4    | 0.162             | 0.133                       | 0.123                       | 0.115                       | 0.103                       | 0.119                   |
| T5    | 0.140             | 0.115                       | 0.106                       | 0.099                       | 0.089                       | 0.105                   |

### Table 4. Results of parametric analyses for Model B.

| $E_c$ | $E_{\text{init}}$ | $1.5 \times E_{\text{init}}$ | $2.0 \times E_{\text{init}}$ | $2.25 \times E_{\text{init}}$ | $2.5 \times E_{\text{init}}$ | Measured average values |
|-------|-------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-------------------------|
|       | $[s]$             | $[s]$                       | $[s]$                       | $[s]$                       | $[s]$                       | $[s]$                   |
| T1    | 0.339             | 0.277                       | 0.240                       | 0.226                       | 0.215                       | 0.227                   |
| T2    | 0.305             | 0.249                       | 0.216                       | 0.203                       | 0.193                       | 0.176                   |
| T3    | 0.230             | 0.188                       | 0.163                       | 0.153                       | 0.145                       | 0.152                   |
| T4    | 0.191             | 0.156                       | 0.135                       | 0.127                       | 0.121                       | 0.119                   |
| T5    | 0.146             | 0.120                       | 0.104                       | 0.098                       | 0.093                       | 0.105                   |

**Figure 9.** Calibration process for Model A (left) and Model B (right) (the first 3 modes for full reservoir)
Comparing the measured processed results and the corresponding values produced by the computation calibrated models, it can be seen that the 1\textsuperscript{st} (fundamental) and 3\textsuperscript{rd} vibration modes show a remarkable good fit between recorded and calibrated values, while the 2\textsuperscript{nd} vibration mode shows some minor differences between the 2 values – approx. 15%.

Model A, with a coarser mesh, leads to satisfactory results for the purpose of the study. An increase in mesh density (model B) did not lead to fundamentally different results, the differences between models being approx. 10-11%. On the other hand, the time required to develop and calibrate model B was much longer compared to that required for the model with a coarser mesh.

As it can be observed each model calibrated on a different value for elastic modulus of concrete. In this regard, one can conclude that each mathematical model bounded to the recorded values represents a hybrid model and the elastic modulus of concrete used for calibration represents a global elastic modulus. GEM is a parameter that has a meaning only connected to the calibrated model and it cannot be used on a different model even if the only difference is the mesh.

5. Conclusions
An appealing and non-invasive method to monitor the safety of concrete dams is the periodic determination of dynamic characteristics of the structure using in situ ambient vibration measurements. The recorded data is compared with previous values and with the ones obtained from the attached mathematical model in order to detect possible changes. While preserving the dynamic characteristics represents a confirmation of structural integrity maintenance, the growth of vibration periods can be a symptom of structural degradation. An essential condition for measuring campaigns is to use the same technique and the same measuring points.

The mathematical model attached to the structure is a hybrid model realized using the finite element method and calibrated based on the first measurement campaign values. During the calibration process GEM value is determined and this parameter is strongly depended by the structural continuity and by the complexity of the mathematical model and it can be used only for that specific model - GEM becoming meaningless if disconnected from the mathematical model.

Even though the method is not quantitative – cannot provide values related to structural characteristics – its simplicity and the fact that it is carried out periodically, provides an additional element tracking of structural integrity and, in case of differences between the values, can open the way for more complex investigations.

The monitoring of the Cincis arch dam behaviour by periodic determination of the structure’s dynamic characteristics aims the early detection of the structural integrity degradation due to aging phenomena. The instrumental/ experimental investigations refer exclusively to overall behaviour of the dam in the elastic range and it considers as a source of vibration the ambient vibrations.

Acknowledgment
The authors wish to acknowledge The Romanian Waters Authority “Apele Romane” - ANAR, owner of Cincis dam, who kindly assured the access of the research team to the monitored dam and provided all the required information and documentation.

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