SEISMIC LEGISLATION AS A RESULT OF QUANTIFICATION OF THE STRUCTURAL EVOLUTION OF LARGE CONCRETE DAMS IN ROMANIA

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ABSTRACT :

A large dam represents a notably important type of seismic risk evaluation problem. Not only is the dam in itself a relatively expensive project, but it is intimately involved in the whole economy, through power generation, flood control, irrigation etc. In addition, structural failure of a dam may lead to a major disaster because large populations may be exposed to sudden flooding. The actual situation in Romania is such that it is necessary to deal mostly especially with existing dams and their safety in the future. The first reason is due to the fact they were built in compliance with regulations that are generally not in force present days, the second one being the major changes of the climate that led to an increasing volume of water in the reservoirs. The age of dams is, without doubt, a third logical reason. The paper is focused mainly on the results of a research program entitled "Quantification of the Structural Evolution of Large Dams Based on Numerical and Instrumental Investigations" and on a Romanian new code entitled „Seismic instrumentation of dams", recently elaborated by the authors.

KEYWORDS: ambient vibration, dam, instrumental investigations, seismic instrumentation

1. BRIEFLY ON THE SEISMICITY OF ROMANIA

„*A safe dam is one that provides people and property with a required level of protection against dam failure and which meets safety criteria commonly used by engineering profession*". The basic principle in safety control recognizes that all people are entitled to the same level of protection against a potential hazard and to the same level of emergency preparedness, independently of the size of the dam, or reservoir. Up to present, one can consider the safety record of the Romanian dams as being very good. The only one failure was produced by an exceptional flood, much larger than the predicted ones. Some other dam behavior incidents have been encountered but their causes were traced and clarified and thus the required remedial works were performed (Stematiu, 2000).

Subcrustal earthquakes of moderate to large magnitudes ($6 < M_W < 7.5$), with depth of focus ranging between 60 and 170 km, occurred quite frequently in Romania. A few shallow focus earthquakes of smaller magnitude ($M_W < 5.5$) also occur, especially towards its southern part. Another contribution to the seismic hazard of Romania is the *crustal contribution* that comes from various, less active and less intensive, shallow seismogenic zones that are distributed over the entire territory of the country. In terms of earthquake risk, the second most important seismicity zone in Romania is the Fagaras zone placed in the Meridional Carpathians, where the earthquakes are of shallow focus. The seismic risk of this zone should not be underestimated, as shallow earthquakes of $M_W = 6 \div 6.5$ occurring have a considerable potential of destruction. In the Banat region, situated in the S-W of the country, shallow earthquakes occurred on July 12 ($M_S = 5.7$), July 18 ($M_S = 5.6$) and on December 2 ($M_S = 5.6$), 1991, and produced significant damage. In conclusion, the seismicity of Romania is mainly due to activity from within the Vrancea region that delivers in the average, per century, more than 95% of the entire seismic energy for the country. This source zone has direct influence over about half the territory of Romania, producing high intensity earthquakes. The upper limit of magnitudes for Vrancea earthquakes is considered to be $M_W \approx 8.0$. Taking into account all the aspects related to the seismicity of Romania, the general purpose of the above mentioned project was to develop and improve analytical and experimental procedures for risk reduction associated to large concrete dams, when subjected to severe dynamic motions.

2. DAMS SELECTED FOR THE RESEARCH PROJECT

The dams that were subject of the research project were three large concrete dams. The dams considered were the “Paltinu” dam, the “Poiana Uzului” dam and the “Gura Râului” dam. *The first selected dam* was the “Paltinu” dam, one of the most important of the 18 arch dams in operation in Romania. The arch dam heights range from 24 to 64 m, three of them exceeding 100m. From this type of dams, the “Paltinu” dam was selected, having in mind the following reasons: its age (period of construction between 1960 and 1971), its seismic location (incidence of the most seismic zone in Romania, Vrancea region, together with the seismic zone Câmpulung-Făgăraş), its maximum height above foundation – 108m and an abnormal behavior of the dam in 1974 (displacements larger than predicted, movements at the foundation level, joint openings, crack at the rock surface and significant increase of seepage, from 10l/s to 150l/s). *The second selected dam* was the “Poiana Uzului” buttress dam. Four solid head buttress dams with maximum heights ranging from 41 to 82 m, built during the seventh and the eight decade are under operation in Romania. The main reason for selecting this buttress dam is its height of 82 m, the highest buttress dam in Romania. The second reason was its abnormal behavior in time, especially in the period of April 16 – May 15, 1984. The increase of the collected flows was significantly higher; previously inactive drillings came into operation, water jets occurred directly from the rock in the drainage galleries along the contraction joints. Simultaneously with these seepage flow increase there were also recorded abnormal displacements higher than the previous ones and especially the sudden change of the displacement pattern. Upward movements of the blocks near the right abutment were also recorded (Stematiu, 2000). *The third dam selected* was the “Gura Râului” buttress dam, considering the favorable geological conditions of founding. For this dam, both movements and seepages were lower than for other existing buttress dams under operation.

3. MAIN ACTIVITIES OF THE PROJECT

During the development of the project, the following directions were kept in mind:

1) field measurements to obtain dynamic characteristics for the three large test dams;
2) computation of the vibration mode shapes, natural frequencies, and their correlation with the measured results;
3) theoretical analytical studies;
4) implementation of a surveillance concept for each dam, together with the seismic instrumentation of one of the three large dams;
5) a better control of the structural safety of dams and risk reduction represented by these engineering structures.

4. AMBIENT VIBRATION MEASUREMENTS

It is well known that the evaluation of vulnerability (especially the seismic one) of existing structures and the adoption of solutions of intervention, when needed, represent a highest technical challenge for the earthquake engineering activities. There are two main reasons for this situation:

- the fact that the physical state of an existing structure often can hardly be identified (from the viewpoints of material characteristics, of structural characteristics, of apparent and especially of hidden damage);
- the fact that the ability of engineers to model in a satisfactory way the various characteristics and aspects related to structural performance during earthquake loading are yet so limited at present.

This situation makes it necessary to simultaneously use alternative approaches and tools, including as far as possible analytical evaluation in correlation with experimental approaches. Ambient vibration experiments have always been a fast and efficient way of determining dynamic properties of dams in their linear range. Dynamic characteristics of a dam, including natural frequencies of vibration, mode shapes and damping ratio, play an important role in determining its response to any type of dynamic excitation, including base excitation resulting from a strong ground motion. Although theoretical structural models of calculus for evaluating these parameters have been developed in recent years, they usually introduce some approximations due to simplified assumptions. Carrying out dynamic tests on real dams is the most reliable method in determining these parameters.

An important problem that has emerged from combined analytical/experimental investigations is the task of identifying the differences between results predicted by F.E. analysis and results obtained from experiment. Although both F.E. and experimental methods can be accurate from a theoretical viewpoint, inaccuracies do exist in their applications to real structural problems. In the case of F.E. modelling there is considerable uncertainty in the modelling of items such as boundary conditions, joint flexibilities and damping. Because of this, the F.E. results are not exact, since the input data itself is approximated. It is not possible to completely eliminate experimental errors. F.E. analysts take the responsibility for producing theoretically correct computer codes, but sometimes do not place enough emphasis on predicting the behaviour of real world dam structures. The experimentalist, by means of testing, often show the limitation of the F.E. analysis, but do not always present clear cut procedures for quantifying the differences in a useful manner (Lawrence, 1986).

The acquisition of the experimental data was achieved with highly sensitive modern Kinemetrics equipment. Consequently, several schemes for positioning the transducers on the dams were adopted. There were used SS-1 RANGER seismometers in simultaneous configurations, in order to record the response of the three test dams. The layouts of the sensors were performed in order to point out the maximum displacements at the crest level, the characteristics of the fundamental eigenmode of vibration of the dams, together with the frequency content of the recorded signals.

5. "PALTINU" DAM INVESTIGATIONS

The Paltinu dam structure consists of a 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. The cross-section of the dam sector presents a large morphological asymmetry determined by the presence of a wide terrace on the left slope located at one third of the dam height and under the crest level. This solution with perimetric joint was agreed in order to provide a symmetric geometry of the central dam, the reduction of the geological condition asymmetry of both slopes, the reduction of the traction stress on the dam contour, close to the foundation, as well as in order to provide a pulvino to take over the local, morphological and geological irregularities.

In the period 2006-2008, there were performed several instrumental measurements with different configurations for the mounting of the pick-ups. Sensors were simultaneously positioned at the crest level, on a horizontal radial direction, on a horizontal tangential direction and on a vertical direction. As it has already been mentioned, the records have been carried out taking into account the ambient vibration source, together with vibrations produced by hydromechanic equipment operating in the body of the dam. The following typical types of analysis have been carried out:

- numerical integration in time domain, obtaining in this manner from the basic signal (velocities) the vibration displacements;
- Fast Fourier Transform (FFT) of the real signal, both for velocities and displacements (Fourier Amplitude Spectra);
- auto-correlation functions, by means of which it is possible to detect an inherent periodicity in the signal itself and to determine the damping ratio.

The Fourier Amplitude Spectra and the auto-correlation functions emphasized the frequency content of the recorded motions, as well as the increase of the dominant compounds. In Table 1 and in Figure 1 the eigenfrequencies (radial direction) and the fundamental eigenshape obtained both instrumentally and by FE analysis are presented.

Table 1. "Paltinu" dam. Natural frequencies/periods of vibration

Recording direction	NATURAL FREQUENCIES/PERIODS											
	f_1 (Hz)	T_1 (sec)	f_2 (Hz)	T_2 (sec)	f_3 (Hz)	T_3 (sec)	f_4 (Hz)	T_4 (sec)	f_5 (Hz)	T_5 (sec)	f_6 (Hz)	T_6 (sec)
Horizontal radial	2.26	0.44	2.87	0.35	3.78	0.26	4.33	0.23	5.5	0.18	6.23	0.16

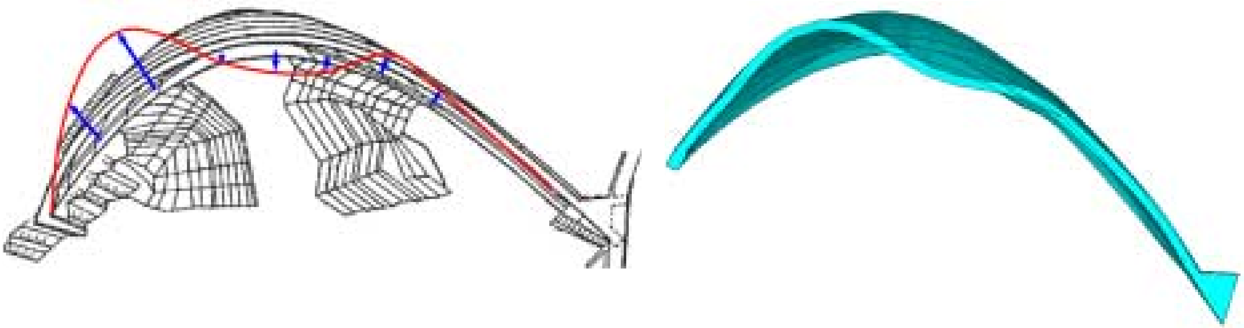

Figure 1. Fundamental eigenshape of vibration in case of "Paltinu" dam.

6. "POIANA UZULUI" DAM INVESTIGATIONS

The "Poiana Uzului" dam is a concrete buttress structure with a maximum height above foundation of 82 m, a crest length of 500 m and a total reservoir capacity of 90,000,000 m^3. The dam was designed and constructed between 1965 and 1972. The dam structure consists of 33 blocks, out of which 3 blocks have a massive structure, other 3 ones are outflow blocks, and 27 ones have polygonal head buttress. For each block, the buttress is supported at the base by a 15 m foundation pad, equal to the head width. The buttress itself is divided into 13.2 m wide columns by means of the contraction joints that are parallel to the downstream slope (Stemetic, 2000). It should be pointed out that during the 1977 earthquake the dam survived without significant consequences on the structure.

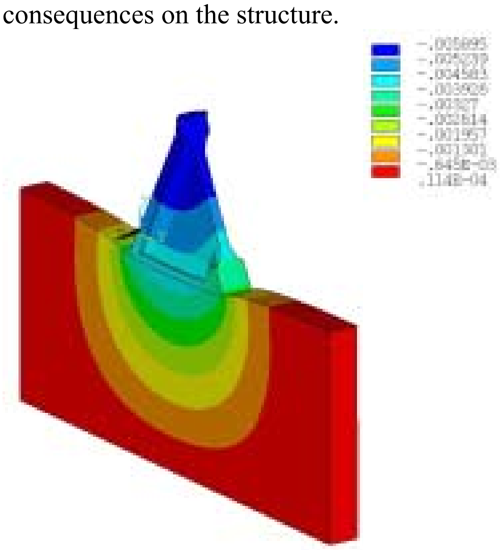

Figure 2. Displacements distribution.

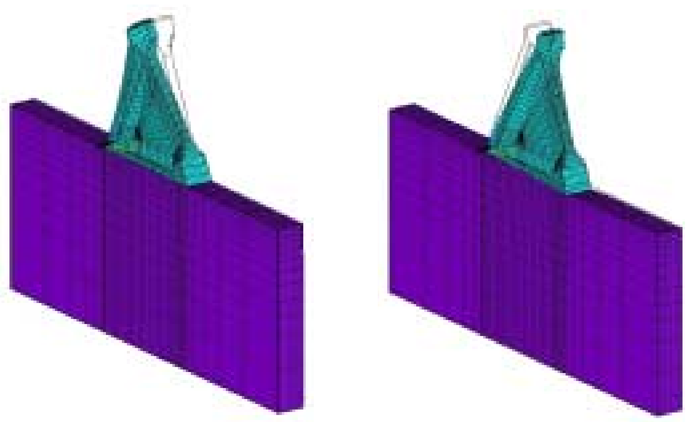

Figure 3. The first two eigenshapes of vibration

The instrumental investigation of "Poiana Uzului" dam helped to establish different structural models of analysis. For the central buttress, the vertical displacement distribution is given in Figure 2. By analytical methods, for the same central buttress, the first two eigenshapes of vibration were obtained and are shown in Figure 3. The corresponding eigenperiods of the above eigenshapes were T_1= 0.25s and T_2 = 0.15s, respectively.

7. "GURA RÂULUI" DAM INVESTIGATIONS

The "Gura Râului" dam is of polygonal head buttress type, with crest length of 330 m, and including 22 blocks of 15 m wide. The thickness of buttresses is variable between 4.5–8.0m, the slope of upstream face is 1:0.57, while the slope of downstream face is 1:0.28. Dimensioning of block type was made starting from the principle of optimal distribution of concrete volume, namely the distribution was done considering a gradual thickening of the buttress on normal direction to solid head (Prişcu – Popovici mathematical optimization of structural model of calculus). Thus it has been possible to lower the block gravity center and to increase the fly wheel moment of the foundation section and, implicitly, to reduce the volume of the concrete (Stematiu, 2000). The maximum height of the "Gura Râului" dam above foundations is 73.50 m and the reservoir capacity is 15,000,000 m^3. The construction period was in between 1973–1980. The dam is located within a macroseismic area of intensity I = 7_1 (MSK).

In the case of the "Gura Râului" dam, alternative settings of the pick-ups were performed, one of the several mountings being shown in Figure 4. The sensors have been positioned on the horizontal direction (longitudinal and transversal).

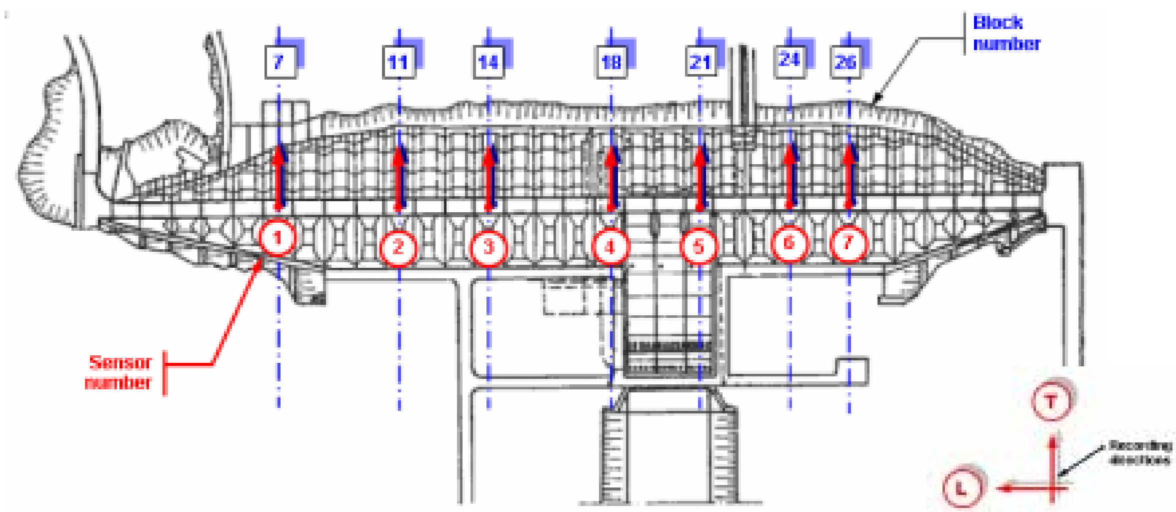

Figure 4. "Gura Râului" dam. Location of sensors at the crest level.

Figure 5 shows the first two modeshapes of vibration that have resulted by analytical methods (for the central buttress).

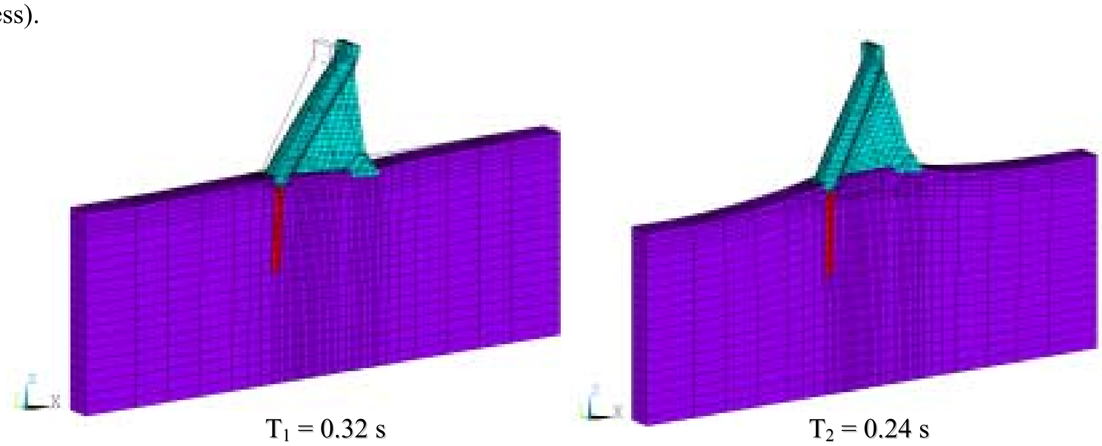

Figure 5. The first two modeshapes of vibration.

A team of engineers, supervised by prof. Dan Stematiu, performed the F.E. models of analysis for the test-dams.

8. THEORETICAL ANALYTICAL STUDIES

A first, main, direction of these developments was concerned with the analysis of oscillations of dams. After some references to the formulation of the system of mathematical relations and problem, more detailed references were made to some aspects that raise at present several difficulties while to be considered in engineering activities. The topics referred to were the dam-rock dynamic interaction, the non-synchronous nature of seismic action along the dam - rock interface and the theoretical need to consider non-classical eigenvalue problems while analyzing natural modes in order to derive solutions of the oscillation problem. Stochastic models were referred to in connection with non-synchronous actions. The eigenvalue problem was dealt with in the space of Laplace-Carson images of the functions of time occurring in the analysis of oscillations. A simple illustrative example put to evidence the features of the solutions (eigenvalues and eigenvevctors depending on the oscillation frequencies, transfer functions derived on this basis). Another direction was concerned with the analysis of seismic hazard affecting dam sites. New expressions were derived for the recurrence functions of magnitudes, for the three most important seismogenic zones of Romania. On the basis of corresponding probabilistic convolutions, recurrence functions of intensities were derived in a parametric way for some dam sites of Romania. A review of some main problems of monitoring of dams, mainly in relation to the seismic risk, was developed (contribution of dr. H. Sandi, CEEX project, 2006-2008).

9. OBTAINED RESULTS

An analysis of the seismic effects on dam response is a complex task. It requires the availability of not only realistic mathematical models, but also of mathematical theory and algorithms to translate the information contained in the experimental data into practical information.

As it has been already mentioned, a series of ambient vibration tests was initiated in 2006. The eigenfrequencies, eigenshapes and damping ratios that have been identified were used for the development of mathematical models for assessing the structural evolution of the selected test-dams, together with the application of powerful calibration techniques for the mathematical models used for the assessment of their structural evolution, based on the information provided by the instrumental measurements. During the research program, several sets of measurements were performed for both cold and warm seasons, taking into account the water level for each dam reservoir.

By extracting the modal parameters as well as vibration intensities from the measuring results, and comparing those with the computer models of structural analysis, statements on the actual load – bearing behaviour, the maintenance condition and forecasts for the future development of the structure were possible. For this purpose, several steps have been carried out:

- establishment of an F.E. model of structural analysis based on the existing plans for each test dam structure selected;
- determination of the eigenfrequencies and mode shapes for each dam structure by applying a dynamic analysis; the eigenfrequencies are an essential parameter for the description of the vibration behaviour of a dam in the linear elastic field;
- determination of the testing points for ambient vibration measurements based on the results of analytical tests;
- measurements concerning the vibration performance by means of highly sensitive velocity sensors installed at established characteristics points under ambient excitation for each dam;
- representation of the measuring results, assessment of the quality of the individual measurements and the FFT for the determination of the Fourier amplitude spectra for every check point;
- comparison of the eigenfrequencies identified from the spectra with the values calculated by the FE model of structural analysis, accurate calibration of the models after each set of measurements and interpretation of the differences;
- calculation of the structural damping parameters from ambient vibration measurements by means of the random decrement technique; assessment of the results based on tests already carried out and also on

damping parameters known from literature; the damping properties are a significant value for system identification, in particular an indicator of the current degree of exploitation of the load-bearing of a dam; therefore, during a dynamic test of a dam, the determination of the damping properties is necessary, in order to obtain a complete picture on the load-bearing behaviour.

10. CODE FOR THE SEISMIC INSTRUMENTATION OF DAMS

This code is in force starting with 2004 (MTCT code, NP 090-03). The main topics included in this code are briefly presented as follows.

Chapter 1. Object of the code. This chapter contains an introduction, presents the categories of importance of the dams, the connection with the existing national dam legislation, together with its harmonization with the new European one (Eurocodes).

Chapter 2. General specifications regarding the seismic monitoring of dams. The first two subchapters present the objectives of the seismic monitoring of dams and the general requirements of a dam seismic instrumentation system. The next three subchapters are devoted to the monitoring of the input seismic action, of the structural response of the dams to seismic actions and of the monitoring of the reservoir.

Chapter 3. Seismic instrumentation of dam layouts. This chapter deals with the requirements of the monitoring of the seismic action. There are also presented configurations of seismic instrumentation systems together with the main features of their components, like sensors, data acquisition systems etc. It is specified that large dams operators must establish a seismic system on their dams. The seismic system should include:

- installation of strong motion accelerographs on the dams, in order to study their dynamic behavior during strong earthquakes;
- installation of free-field strong motion accelerographs next to the dams, in order to acquire seismic input to the dams;
- installation of weak motion seismic stations (seismographs) in order to monitor potential induced seismicity in the vicinity of the dams.

Chapter 4. Concepts and methodology of dam instrumentation. An instrumentation project entails a preliminary phase of specifications, an intermediate phase of evaluation and a final phase of implementation. In what concerns the selection of representative dams with regard to type, geometry and foundation, this must be carried out in order to ensure that the findings could be applied to a large number of dams. The code specifies the typological groups of dams that are fit for seismic instrumentation. The content of the seismic instrumentation project is also given. Other subchapters are devoted to the instrumental investigations carried out in order to establish the location of the seismic instruments, to the decision of the central recording site, and to the measures taken into account in order to assure the integrity and the functioning of the installed equipment. Finally, the code contains directions for a strategy of seismic instrumentation of dams at national level.

11. FINAL REMARKS

a) The procedures for predicting the earthquake response of concrete dams are important, not only for the obvious function of designing new structures to be built in seismic regions; at present time, more important is the evaluation of the safety of many such structures already standing in areas of important earthquake activity. Most of these dams were designed using oversimplified concepts with respect both to the structural model of calculus and to the dynamic response mechanism.

b) An important limitation of the analytical methods that were used extensively is that they assume the structure to be linearly elastic. In general, it seems reasonable to require a concrete dam to resist the maximum expected earthquake without exceeding the strength of the materials, and for such designs a linear analysis would generally be appropriate. However, this requirement may not ensure that the systems will behave linearly; for example, opening of the joints between monoliths of an arch dam would introduce a nonlinear mechanism. Current analysis capabilities make possible a much more reliable estimate of their expected earthquake behavior.

c) The analysis of the behavior of dams subjected to the Romania earthquakes of 1977, 1986 and 1990, clearly showed that these engineering structures have a high proper capability to resist the seismic forces, provided they are well designed and built. However, the worldwide experience of strong earthquakes that have produced remarkable damage to some dams implies that the actual seismic behavior of these structures is not yet fully understood. These considerations support and justify the intention of the Romanian Authorities to study the actual behavior of large dams subjected to dynamic actions, in order to take the most efficient measures in case of damage.

d) In order to be successful and to reach the above mentioned targets, the first proposed activities in the research program were to obtain a reliable "*diagnostics*", by means of which a deep knowledge of the actual conditions of the three test dams be accomplished. To this end, such an activity required a suitable program of *in situ* ambient vibration tests. Parallel to this program, a mathematical modeling for a correct and comprehensive analysis of the gathered data, together with the existing margin of safety, was performed.

e) Another target of the research program was to provide the owner of a dam and its engineers with the criteria to be adopted for a proper design of a complete surveillance system. As already pointed out, the two main targets of the research program are to gather data for a safe operation of the dam and to improve the knowledge of the seismic actions affecting the dam, its foundations and the reservoir.

f) Once the code for the seismic instrumentation of dams was enforced, it gave the legal possibility to the owners of large dams in Romania to initiate programs for developing strategies in order to fulfill the requirements of the official regulation. Consequently, a decision for the seismic instrumentation of the "Paltinu" arch dam was taken; monitoring Kinemetrics equipment was chosen and will soon be installed.

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