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SEISMIC MONITORING OF DAMS A NEW ACTIVE SURVEILLANCE SYSTEM: BASIC CRITERIA, OPERATING METHODS AND RESULTS OBTAINED

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SUMMARY

The paper resumes basic criteria and operating characteristics, and illustrates some significant results of an active monitoring system operating since September 1986 on the Talvacchia arch dam in Central Italy. The system gathers information on the dam dynamic behaviour - carrying out twice a day forced vibration tests and recording earthquakes - as well as on static (plumb line, joint opening) and environmental conditions (water level, temperatures). Influence of these quantities on dynamic and static response, and mutual correlations are presented. Some interesting features of these correlations could be of help in detecting or forecasting possible degrading and structural damage.

INTRODUCTION

In recent years, the development of instrumentation (both transducers and computerized acquisition and processing systems) allowing a large amount of data to be rapidly and reliably interpreted, has led to a new concept as to the monitoring process. This has no more the only aim of signalling and characterizing the earthquake, but also of recording the structural response to it (accelerations, strains etc.), which is important for a direct knowledge of the dam behaviour, and for the comparison with the results of the analytical models as well as for their validation.

A further extension in the objectives of the monitoring is that of the identification of possible damages, through the determination of structural parameters the values of which may change owing to structural damages or degrading. Among these parameters, the dynamic characteristics (natural frequencies, modal shapes and dampings) are of great importance, and can be obtained by processing the response to natural excitation (microseisms) or, for a greater accuracy, to an artificial one (forced vibrations tests). Should these dynamic data be completed with static and environmental ones, a comprehensive picture of the dam behaviour can be obtained, which is also of great help for the setting up and check of reliable numerical models, thus enabling a proper surveillance process. Infact, possible uncorrelations of the incoming data w.r.t. those already collected or the computed ones, could be a symptom of a damage occurred or of a degrading process.

Finally, it has to be pointed out that among the aims of the surveillance, is that of obtaining data on the structural behaviour under high loading conditions. In fact, only through these data can be gained an understanding of the complex phenomena set up during a quake, such as non linear effects in materials and joints, ground-water-structure interactions, etc. Thus, the surveillance system becomes a very useful tool for basic research.

THE SURVEILLANCE SYSTEM OF THE TALVACCHIA DAM

According to the criteria illustrated above, the surveillance system installed on the Talvacchia Dam (77 m high, crest length 226 m) performs the following tasks:

- records seismic events in 9 points of the dam, including base and abutments;
- carries out twice a day forced vibration tests (frequency range 3 to 11 Hz) recording the response in the 9 points mentioned above;
- records the values of static and environmental quantities (plumb line, 5 joint openings, water level, 35 air and concrete temperatures).

Without going into details as to the hardware (Refs. 1, 2) suffice it to recall that the mechanical vibrator delivers a rotating vector force of 35 kN max; clockwise and counterclockwise rotation allows the dam response to both radial and tangential excitation to be worked out.

The surveillance system for the Talvacchia dam is integrated with a f.e.m. mathematical model (Ref. 3), which includes dam body, foundation rock and reservoir. The model has been calibrated through the comparison with the static data (crest arch displacement versus temperatures and water levels) used for the control of the dam. The model is based on the hypothesis of elastic linear behaviour: this allows the splitting of the total displacements into water thrust and thermal effects. The hydrostatic component is the sum of the three different contributions due to deformations of the dam body, foundation and reservoir; the thermal one is the sum of three periodical "loads": yearly, half-yearly and daily temperatures, which depend on position and time with sinusoidal variations $T = T_o \sin(\omega t + \psi)$ through the relationship:

$$T(x,y,z,t) = \Sigma_j f_j(x,y,z)\ T_j(t) + \Sigma_j \Phi(x,y,z)\ \dot{T}_j(t)$$

The thermal analysis is carried out through a f.e.m. model of the central cantilever, using the 21 thermometers installed on it. The thermal distribution is then extended to the entire dam body and constitutes the input for the structural model.

The code also allows the calculation of dynamic parameters taking into account foundation and reservoir interaction.

Comparison of these results with the experimental ones (for the same water level) is shown in columns 3 and 4 of table 1, whereas fig. 1 shows experimental and computed displacements, these with their thermal and hydrostatic components.

ANALYSIS OF THE RESULTS

Dynamic data The transfer functions (fig. 2) clearly show the presence of six vibration modes, whose characteristics vary depending on the different dam conditions, as shown in table 1.

Table 1: Dynamic characteristics of Talvacchia Dam

Mode no.	Frequency (Hz) measured	comp.(*)	meas.(*)	Type	Damping (%)
1	3,5- 4,0	4,19	3,96	1st antisymm.	1,5 - 2,5
2	3,6- 4,6	4,40	4,45	1st symm.	2,0 - 3,0
3	5,1- 5,7	5,58	5,56	2nd symm.	1,7 - 2,7
4	6,2- 6,8	6,62	6,75	2nd antisymm.	1,5 - 2,0
5	7,8- 8,7	-	-	3rd symm.	1,8 - 2,8
6	9,4-10,4	-	-	3rd antisymm.	1,7 - 2,3

(*) at the same water level.

The natural frequencies assume different values for the same water level (especially when the latter is low); moreover, for higher modes they increase when water level increases. This unespected behaviour makes it likely that other quantities have some bearing on the dynamic response: among these, temperatures and their distributions and derivatives, and joint conditions. Changes in modal damping are small, and their correlation with other quantities is not evident so far, while response amplitudes are remarkably related to water level.

Seismic data Since September 1986 only three small and distant earthquakes have been recorded, although the trigger threshold (dam base) is 150 μm/sec. One of the quakes (M = 5,5) had its epicenter in Yugoslavia (250 km), the others (M = 4,5 - 4,9) in Italy (45 km). From the frequency analysis of the recorded responses (not shown here owing to lack of space) the first three resonances of the dam can be detected: however, it should be noted that the seisms were almost devoided of energy at higher frequencies. Dam amplifications are around 5 to 6.

Correlations The dynamic, static and environmental quantities have been correlated each other: the most interesting are the correlations of frequencies, displacements and joint opening with both water level and temperatures (two reference temperatures have been chosen, both inside the dam body, high and low elevation). It should be noted first that - in similar conditions - second cycle data (1987/88) correspond almost completely to 1st cycle data (1986/87). As already said, the dependence of frequencies on water level is not simple: only when water level is higher than approx. 75% of dam height the correlation is clear, but it is linear only for the first symmetric mode (fig. 3). At lower water level, natural frequency clearly does not depend on it. In fact, for the first two modes, frequency seems to be depending on temperature conditions and trends, and tends to separate in two "layers", the higher corresponding to high temperatures, the lower to decreasing or low temperatures (fig. 4). For higher modes, points scatter so that a correlation does no more exist. It is evident the already mentioned fact that the lowest frequencies correspond to the lowest levels (fig. 5).

Some correlations of static quantities with environmental conditions are shown in figs. 6 and 7. Joint opening is practically linearly correlated with surface temperature in the vicinity, whereas phase lag is evident with internal thermometer (the extent of opening within the dam body is being measured by some dilatometers placed in the dam ducts).

Plumb line and water level show a complex correlation: to better understand it, the data have been grouped in 4 different thermal periods and 3 different joint conditions as shown below (see also fig. 8):

	Temperatures High thermom.	Low thermom.	Joints	
Group A	decreasing	increasing	Group E	opening
Group B	decreasing	decreasing	Group F	closing
Group C	stationary	decreasing	Group G	closed
Group D	increasing	increasing		

As can be seen in fig. 7, the thermal periods do not seem to have much influence, whereas the joint conditions seem to be the commanding phenomenon. Approximately, three types of behaviour can be seen: strong, fair and zero dependence of the plumb line displacement on water level. Strong dependence is shown when joints are closed, fair when they are closing, irrespective of temperature behaviour and increase or decrease of water; the same fair dependence is shown when joints are opening but only when level increases whereas a level decrease does not affect the displacements (so far, the condition of water increase with closed joints has not been obtained).

It has to be added that the "absolute" value of water level does not seem to have bearing in this case, whereas the value of approx. 75% of the max is a critical one w.r.t. first natural frequencies.

CONCLUSIONS

Although more data have to be collected, to cover all possible environmental conditions and a longer period of time (at least two complete yearly cycles), which will also allow a deeper analysis of the results to be made, it is possible to draw the following observations:

- the system is operating successfully and supplies a large amount of data on the static, dynamic and seismic behaviour of the dam, from which interesting and in some cases unespected features of the structure have been detected;

- the structural behaviour of the dam can be analyzed from a large number of different points of view;

- in most cases, although not clearly understood so far, the behaviour of the dam follows well defined patterns, which repeat themselves when the same conditions are present. Consequently, should these patterns undergo modifications after an exceptional event, or show unespected trends w.r.t. the experimental or computed data, this could be interpreted as a symptom of an occurred damage or of some degrading process being developing.

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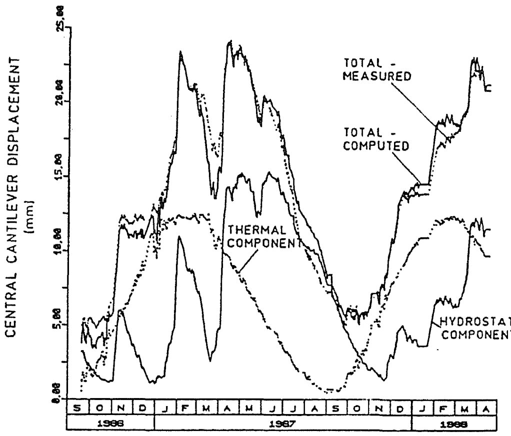

Fig. 1 Comparison between computed and measured total displacement.

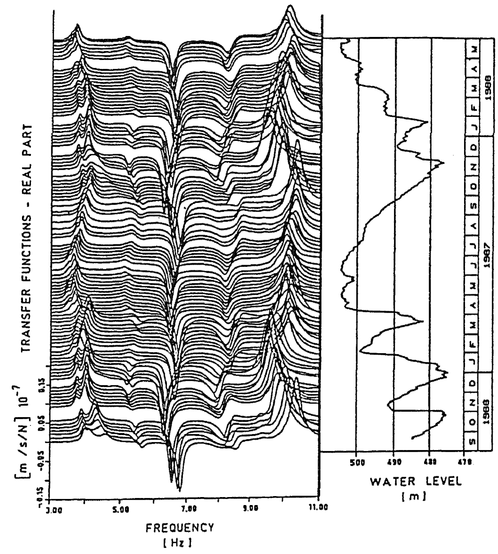

Fig. 2 Examples of transfer functions and water level variations.

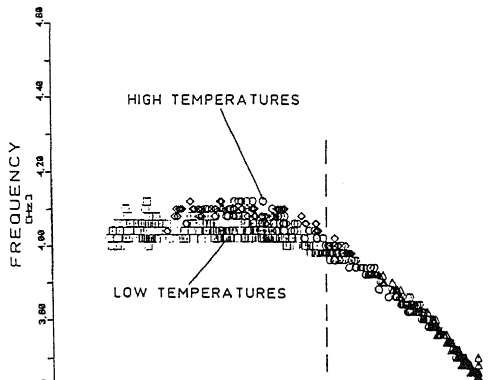

Fig. 3 Second mode frequencies versus water level.

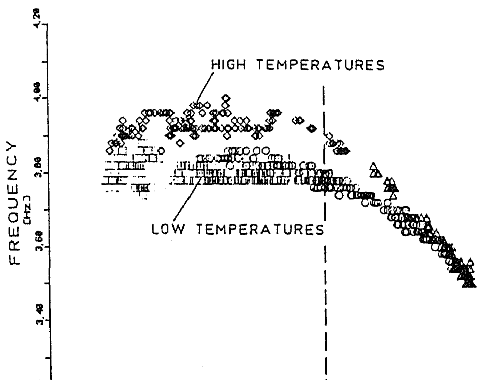

Fig. 4 First mode frequencies versus water level.

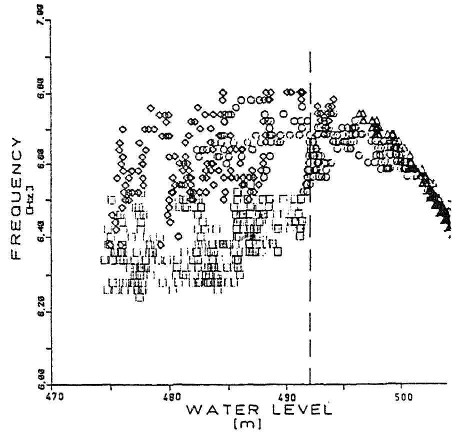

Fig. 5 Fourth mode frequencies versus water level.

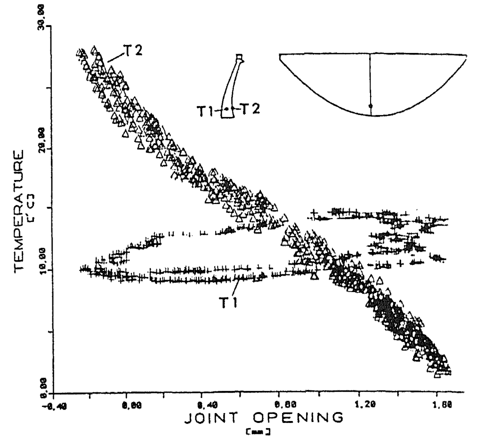

Fig. 6 Joint opening versus internal and external termometers.

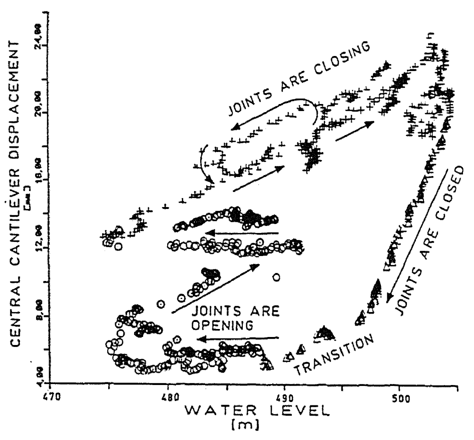

Fig. 7 Dam displacements versus water level at different joint conditions.

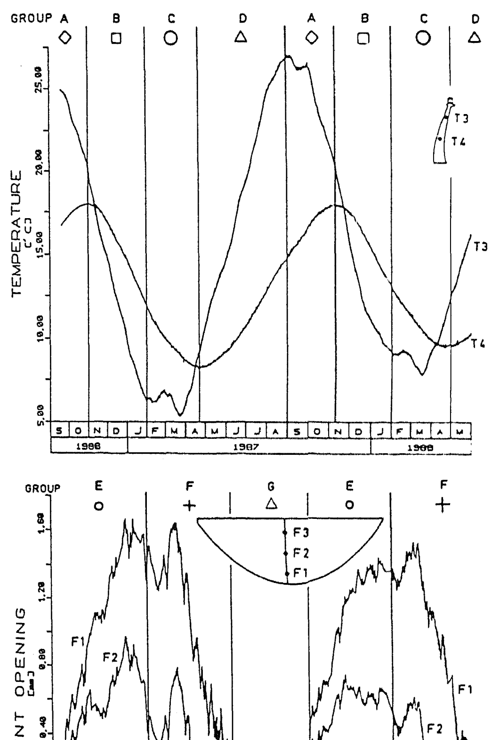

Fig. 8 Reference temperatures. Thermal periods and joint conditions.