Contribution of the surveillance to the evaluation of the seismic efficiency of dams: example of the Ambiesta dam

CONTRIBUTION OF THE SURVEILLANCE TO THE EVALUATION OF THE SEISMIC EFFICIENCY OF DAMS. EXAMPLE OF THE AMBIESTA DAM

Dr. Aldo Castoldi - Director, Dynamic Department ISMES, Bergamo, Italy

SUMMARY

Present lack of information on site seismicity and approximation in usual design criteria require further research to be done in both theoretical and experimental directions to improve the knowledge on the seismic behaviour and, consequently, on the safety coefficient of large dams.

To this aim, an integrated research program, which includes in situ testing, mathematical models and seismic surveillance is proposed, and the technique adopted, as well as the results of a preliminary application of this program to the Ambiesta dam (Udine) during the aftershoçks of the Friuli earthquake of 1976 are presented.

1. INTRODUCTION

Present criteria for the seismic risk analysis of a structure require on the one hand, the knowledge of the local seismicity, and on the other, the schematization by means of reliable mathematical models of the structural behaviour under seismic effects. These criteria have been satisfactory applied for the nuclear plants and a well known procedure and regulation is now available in this field.

As far as the large dams are concerned, the problem of the seismic safety has been faced in these terms only in the last few years. Although the introduction of new methods has helped improve the computational techniques, theoretical difficulties still exist, particularly as regards the interaction between the dam and its foundation.

In order to achieve a correct set-up of the problem of the seismic risk evaluation for a dam, the checking of the reliability of available theories and procedures is required. In our view, this may be achieved through an approach which together with analytical computations and improved criteria for seismic surveillance, includes as well - at least in the most important cases - dynamic tests as a routine step of a research program for the long-term control and the safety-checking of a dam.

The following chapters illustrate a proposal for such a program, and describe the technique and the results of a preliminary application made on the Ambiesta dam for the recording of the Friuli earthquake aftershocks in October 1976.

2. PROPOSAL OF AN INTEGRATED PROGRAM FOR THE ANALYSIS OF THE SEISMIC EFFICIENCY OF A DAM

The analysis of the seismic risk of a dam and the evaluation of the effects of an earthquake have to be carried out by means of a series of operations which, notwithstanding their considerable validity even when taken singly, assume a most important significance if inter-related within the frame of an integrated program. The fundamental phases of this program should be the following:

a) In situ testing to determine the dynamic characteristics of the dam.

b) Setting up of a mathematical model for the calculation of the seismic response.

c) Carrying out of the seismic surveillance, to collect data on site seismicity as well as on the response of the dam.

d) Check up of the structure (both by the mathematical model or by testing) after a strong earthquake.

The close links among these phases are illustrated in fig. 1.

Phase a) has the aim of obtaining a sort of "identity card" of the structure, in which are listed the characteristics of its dynamic behaviour (possibly for different external conditions, such as the various levels of the impounded water).

These data can be obtained by different methods, such as forced or ambient vibrations, blast excitation, etc. The presently available recording and processing equipment assure highly precise results, as required for subsequent processing.

As regards phase b), although a mathematical model is usually developed in the design stage (this is not true, however, for dams designed several years ago), the above-mentioned theoretical complexity of the problem, together with the uncertainties of the design data (as to the geological and geophysical characteristics, and site seismicity) require that the model itself be carefully checked, and, if necessary, modified. To this aim, the experimental data obtained from phases a) and c) should be used as a reference stand, and the means to validate or to improve the reliability of the analytical schematization. It has to be underlined, however, that present experience on this subject is poor, and further investigations are necessary to fully exploit the experimental data for the above purposes.

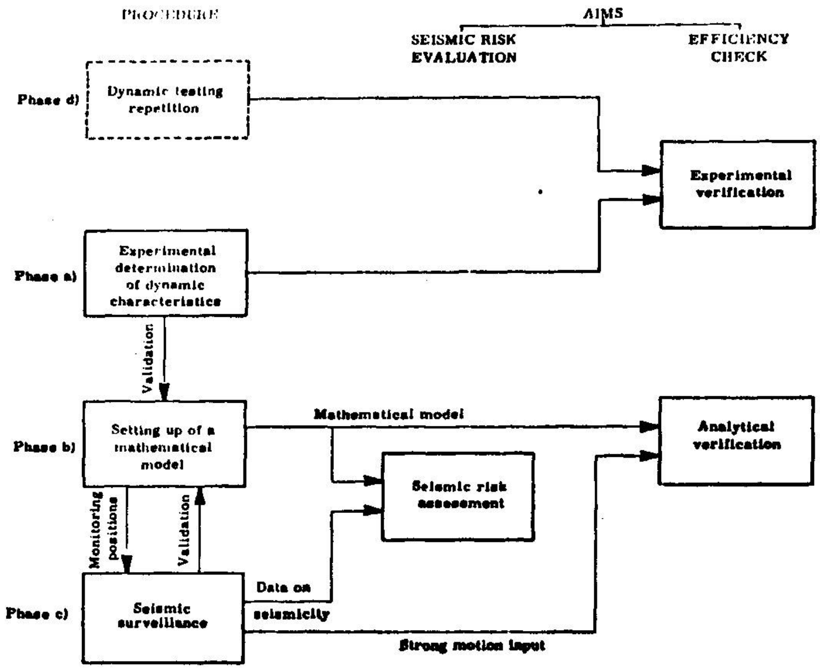


Fig. 1: Integrated program for the evaluation of the seismic efficiency of a dam.

The seismic surveillance of the dam (phase c)), is mainly intended to collect information on the seismicity of the site. Though a long term step, it is a necessary one, however, for the currently available data are usually unsatisfactory, and, especially for large reservoirs, local seismicity may be affected by the reservoir itself. Together with this aim, it should also allow the recording of shocks of medium or strong intensity and the determining of the structural response to these shocks. It is thus advisable to choose the recording points on the basis of the data supplied by the mathematical model, not only in order to simplify the interpretation of the results, but also in view of a possible further validation of the model itself.

The availability of a reliable mathematical model, as well as of significant data on the site seismicity, allow one both to meet and resolve in real terms the problem of the seismic risk analysis. Moreover, should a strong earthquake occur, as a consequence of which the structural integrity might be compromised, the problem arises of an immediate assessment of the structural safety. In this case the mathematical model, using as input the recorded seismic motion, can supply meaningful information on the state of stress induced by the earthquake in the structure; on the basis of this information it may be advisable to carry out a new phase of the program (phase d)), in which, through the repetition of the dynamic tests, the "identity card" of the structure is checked.

Finally, another important outcome, which ought not to be disregarded, is that the data collected on the particular dam under control, may have a more general significance and may be profitably used both for theoretical analyses and for design or regulation purposes.

3. VIBRATION TESTS AND RECORDING OF AFTERSHOCKS ON THE AMBIESTA DAM

3.1. After the second main shock of the Friuli earthquake on September 15, 1976, ENEL entrusted ISMES with a program for the installation on the Ambiesta dam of an automatic system for the recording of the aftershocks, and for their processing. The Ambiesta dam is a small double-curvature arch dam, located near the epicentral area (fig. 2); the crest length is about 145 m, the maximum height is 60 m. Within framework of a research program supported by ENEL for the determination of the dynamic behaviour of the most important Italian dams, ISMES carried out forced vibration tests on the Ambiesta dam in 1975.

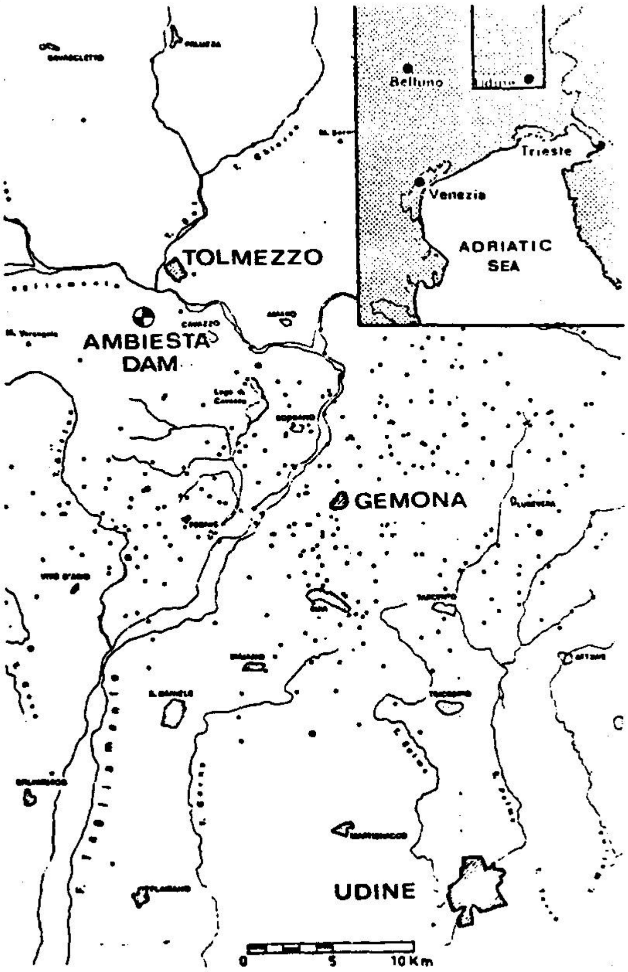


Fig. 2: Location of the Ambiesta dam (• : epicenters of shocks from 6.5.1976 to 16.6.1976).

3.2. For the excitation of the dam, a mechanical vibration generator, delivering a sinusoidal force of up to 10 tons within the frequency range from 2 to 20 cps was used. This was placed in different positions on the crest arch, to allow a correct excitation of symmetric and antisymmetric modes. The response of the dam was recorded by means of 47 seismometers; the processing of the data carried out digitally by means of a Fourier analyzer, allowed the determination of the first resonance frequencies, modal shapes and damping coefficients. At the same time, a preliminary finite element mathematical model of the dam has been set up by ENEL. Since the dam is symmetrical, this model takes into account only half the structure; the foundation rock is considered of infinite stiffness. The main results of the vibrations tests as well as of the mathematical model are listed in table 1.

3.3. As to the practical application of the research program, examples of seismic surveillance, as previously discussed, or reference literature could not be found. In effect, as far as is known, usually a single position on or near the dam is monitored by a single or three direction seismograph; obviously, this is not sufficient to carry out a seismic surveillance according to the criteria illustrated above.

In this preliminary phase of setting up of the criteria as well as of the most suitable procedure, the practical problems met with were as follows:

Mode no.	Type	Frequency (cps) Test	Model	Damping (%)
1	Antisymmetric	4.1	4.5	-
2	Symmetric	4.7	5.1	1.8
3	Symmetric	7.1	7.7	3.3
4	Antisymmetric	8.5	9.0	-
5	Symmetric	9.3	9.4	2.8
6	Antisymmetric	-	10.5	-

Table 1: Dynamic characteristics of the Ambiesta dam.

- to choose and set up a reliable and easy-to-handle digital equipment, for a continuous long term monitoring;

- to select the positioning of the recording instruments, and to establish the criteria of the data processing, in order to obtain the features of the earthquake excitation in several points along the foundation, as well as the characteristics of the response of the dam, to be compared with the results of the vibration tests.

In the particular case of the Ambiesta dam, 30 seismometers were used, 10 of which were placed along the foundation (two horizontal seismometers in each measuring position, oriented orthogonally to each other) and 20 on the downstream face in radial direction (fig. 3). This number is rather generous, and can be reduced for routine applications. However, it was justified by the lack of previous experience and by the need to avoid missing potentially useful information.

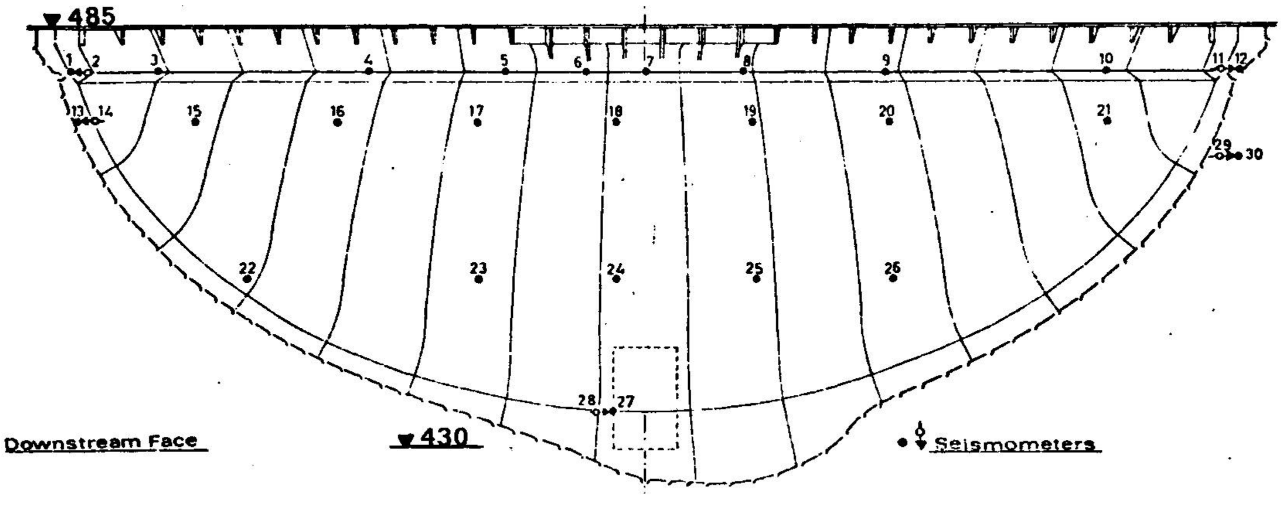


Fig. 3: Layout of the measuring points on the Ambiesta dam.

After digitization by an analog to digital converter, the signals coming continuously from the seismometers were sent to a minicomputer which stored on a magnetic tape only the seismic events exceeding a prefixed intensity threshold.

The intensity was checked out on the signal coming from the seismometer placed at the base of the central cantilever, in radial direction (position 27). In this way, electrical noise and other minor disturbances were disregarded, since only significant seismic events were recorded. Moreover, a single operator was required from time to time to replace the magnetic tapes.

3.4. The system was operative during the period from 8 to 27 October 1976, and 118 seismic aftershocks were recorded. Their intensity is very small since the maximum velocities recorded at point 27 ranged from $5\cdot 10^{-4}$ cm/sec to $4\cdot 10^{-2}$ cm/sec. Therefore, the processing was carried out on 35 records, showing maximum velocities larger than $2\cdot 10^{-3}$ cm/sec; the records of lower intensity were disregarded.

4. PROCESSING AND ANALYSIS OF THE RECORDS

4.1. The analysis of the recorded data was intended to supply information able to enlight the phenomena connected with the energy exchange between the foundation and the dam, and to check the accuracy - and, consequently, the reliability - of the hypotheses currently adopted for the computing methods. As is well known, these methods, even the most sophisticated ones, take into account a three-dimensional continuum made up of the dam and a part of its foundation, and apply to its boundary an uniform excitation, equal to that of the "bedrock".

Under these hypotheses, and making use of the modal analysis techniques, it is easy to obtain the relationships between the response $\{q\}$ of the dam and the input excitation. In particular, the expression of the transfer functions related to the upstream-downstream (x) and longitudinal (y) directions are:

$$\{Q(\omega)\}/A_g^{(x)}(\omega) = \{h^{(x)}(\omega)\} = \sum_{k=1}^{\infty} c_x^k \cdot \{\phi^{(k)}\} \cdot B^{(k)}(\omega)$$

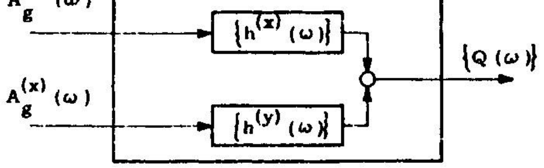
$$\{Q(\omega)\}/A_g^{(y)}(\omega) = \{h^{(y)}(\omega)\} = \sum_{k=1}^{\infty} c_y^k \cdot \{\phi^{(k)}\} \cdot B^{(k)}(\omega)$$

where: $c_{x,y}^k$ are the participation coefficients for the k-th mode in direction x and y respectively

$\{\phi^{(k)}\}$ is the modal shape of the k-th mode

$$B^{(k)}(\omega) = 1/\left[\omega_k^2\left(1-\frac{\omega^2}{\omega_k^2}\right)+2j\zeta\frac{\omega}{\omega_k}\right]$$

According to this procedure, the time histories $\{q(t)\}$ recorded on the dam may be interpretated as being generated by two different inputs (the two components of the seismic excitation) as illustrated in the sketch. An estimation of the function $\{h^{(x)}(\omega)\}$ and $\{h^{(y)}(\omega)\}$ obtained through the theory of the linear systems and of the random processes, allows one to make an assessment of



the reliability of the assumptions by comparing these functions with those obtained employing the mathematical model.

In the present case, as a first approach to the problem, it was thought sufficient to proceed according to a simpler scheme, and to leave to future processing a further investigation, in case of interesting results being obtained from this approach. Such simplifications are justified by the following observations:

- The input motion, that is the components of the earthquake at the "bedrock", is obviously unknown; the time histories recorded at the bottom of the dam only as a first approximation may be considered as the inputs of the system.
- The contribution of the two components of the input motion to the response at a point of a dam has different weight depending on the frequency range considered, as it is determined by the transfer functions $\{h^{(x)}(\omega)\}$ and $\{h^{(y)}(\omega)\}$ which in turn depend on the participation coefficients c_x^k and c_y^k. As is known, these are rather different for the two components depending on the modal shape. According to this, for example as far as the first mode is concerned, when $\omega \simeq \omega_1$ the following is obtained:

  $$Q_i(\omega) = h_i^{(x)}(\omega) \cdot A_g^{(x)}(\omega) + h_i^{(y)}(\omega) \cdot A_g^{(y)}(\omega) \simeq h_i^{(x)}(\omega) \cdot A_g^{(x)}(\omega) = H(\omega) \cdot A_g^{(x)}(\omega)$$

  It follows that the relationships between the response and the input motion can be replaced, at least in certain frequency intervals, by that relative to a single input linear system.

Therefore, the transfer function has been calculated by using the following relationship:

$$H(\omega) = G_{ab}(\omega) / G_{aa}(\omega)$$

where $G_{ab}(\omega)$ is the cross-spectral density function between the input signal a (t) and the output signal b (t); $G_{aa}(\omega)$ is the power spectral density of a (t).

The coherence function $\gamma(\omega)$ defined as:

$$\gamma^2(\omega) = |G_{ab}(\omega)|^2 / (G_{aa}(\omega) \cdot G_{bb}(\omega))$$

($G_{bb}(\omega)$ being the power spectral density of b (t)) is an indication of the correlation between the input and output signals. Low values of $\gamma(\omega)$ indicate poor correlation, which may be due to different reasons, such as presence of noise or external disturbance in the signals, physical lack of correlation between the signals, inadequate description of the phenomenon through the assumed hypotheses.

Together with the calculation of $H(\omega)$ it was thought that also the determining of the amplifications at several points of the foundation and the dam body (as ratios between the maximum values of the time histories recorded at these points and at the bottom of the dam) could supply an indication, even though rather approximated, of the reliability of the assumptions.

4.2. Some observations on the results of this preliminary processing are as follows:

a) <u>Motion at foundation</u>

The records obtained at positions 1, 12 and 27 (transverse direction) and at positions 2, 11 and 28 (longitudinal direction) have been examined. Table 2 lists the average values of the maximum amplifications recorded at these points, from which the following consideration may be drawn:

	Reference	Average of maxima	Standard deviation
Foundation	Pos. 1/Pos. 27	3.11	0.77
	Pos. 12/Pos. 27	2.75	0.71
	Pos. 2/Pos. 28	1.92	0.38
	Pos. 11/Pos. 28	1.88	0.42
	Pos. 27/Pos. 28	0.98	0.26
Crest arch	Pos. 7/Pos. 27	5.84	1.93
	Pos. 8/Pos. 27	7.93	2.44
	Pos. 9/Pos. 27	10.59	3.75
	Pos. 10/Pos. 27	6.88	1.84

Table 2: Average values of the ratios between the maximum velocities recorded.

- The two components of the motion at the bottom are, on the average, of the same intensity. Their values are, however, rather scattered, as it is obvious, owing to the large differences in the patterns of the records. This is clearly illustrated in fig. 4, which shows the Fourier transforms of some earthquakes recorded at position 27. As may be noted, the energy distribution over the frequency range differs greatly from earthquake to earthquake. This may be justified by the different hypocentral locations and by the varied paths of the travelling waves.

- The amplifications of the abutments are rather large (as shown in fig. 5, in which the time histories are given, and in fig. 6, which gives the response spectra at the same points), being respectively about 3 times and 2 times the motion in transverse and longitudinal direction. The attempt to calculate the transfer functions H (ω) did not prove satisfactory, as may be seen from the fact that their patterns are dispersed, and the coherence very low (fig. 7). This could de

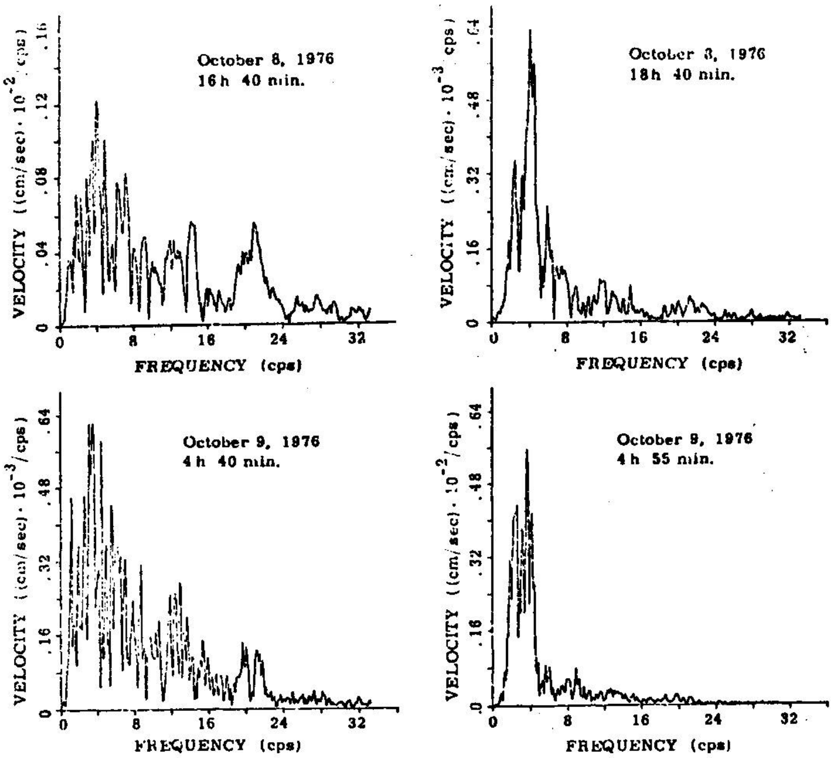


Fig. 4: Fourier transforms of different aftershocks at the bottom of the dam.

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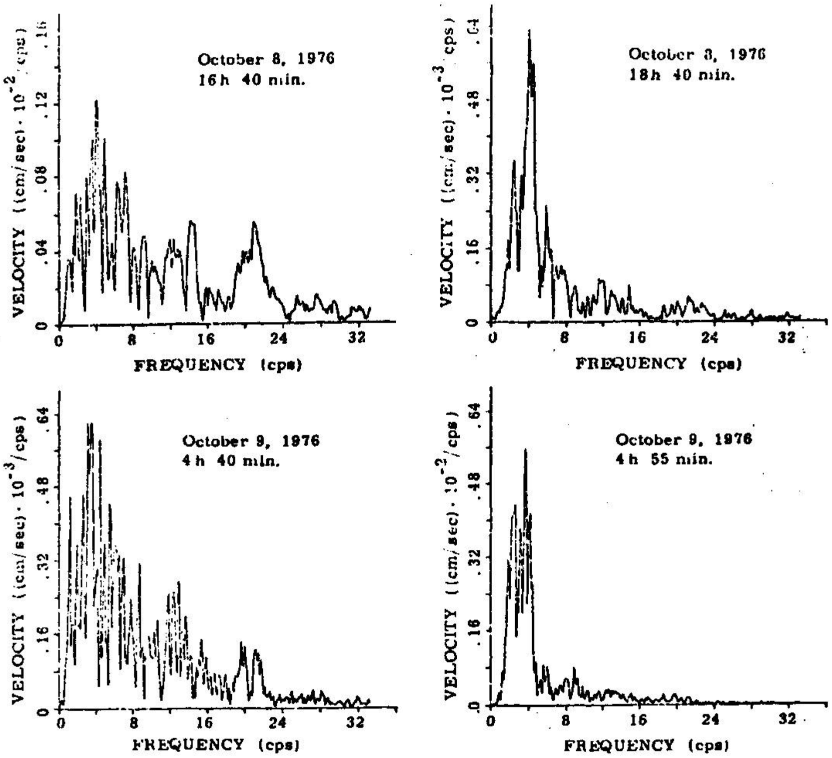

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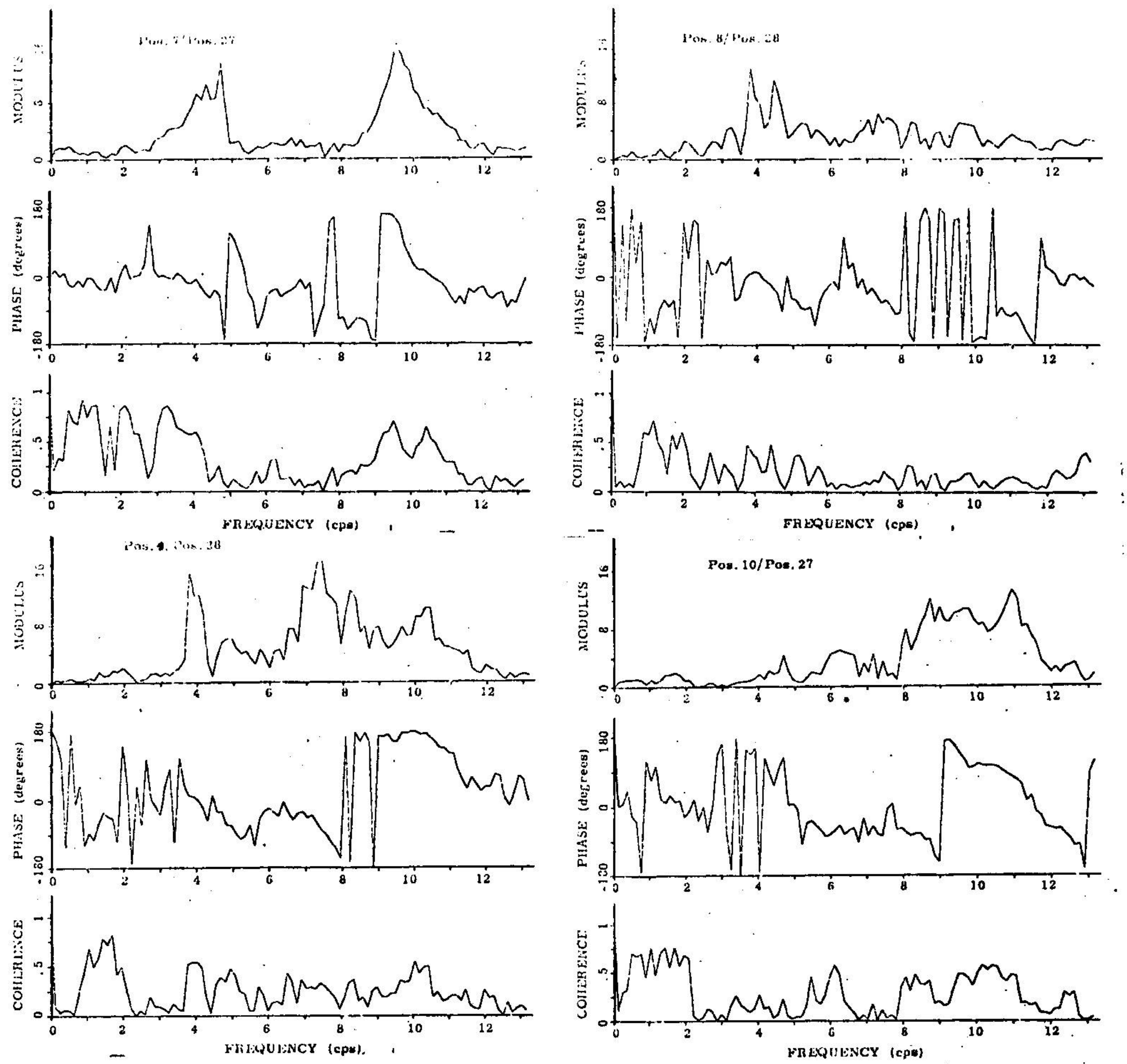

Fig. 8: **Transfer functions H (ω) relative to crest arch points.**

Mode no.	Resonance frequencies (cps)		Amplifications recorded in position						
			7		8		9		10
	R	T	R	T	R	T	R	T	R
1	3.8 ÷ 4.4	4.1	10.5	-	12.8	-	13.3	-	-
2	4.5 ÷ 4.8	4.7	13.3	40.5	11.2	13.5	-	21.6	4.1
3	7.3 ÷ 7.8	7.7	-	52.4	-	17.5	22.0	30.1	-
4	8.7	8.5	-	-	-	-	-	12.5	12.1
5	9.5 ÷ 9.9	9.3	15.2	43.5	-	-	13.7	-	-

Table 3: Resonances and amplifications at the crest arch from records (R) and vibration tests (T).

5. CONCLUSIONS

Although still incomplete and with the processing of the data still at a preliminary stage, the experience gained from the program carried out in the particular case of the Ambiesta dam has nevertheless made it possible to draw up a series of useful clues concerning the validity of the proposed method.

As far as the single stages of the program are concerned, it may be concluded that both the determination of the modal characteristics of the structure as well as seismic surveillance are problems that by now have been solved - be it from the point of view of methodology or the instrumentation to be employed.

The cost as well may be considered altogether reasonable when compared with the financial commitment that the construction of a dam calls for.

The weightier problems present themselves in the stage involving the interpretation of the data in light of the behaviour models in use at present, which, in our view are not altogether adequate for the explanation of the phenomena as a whole and, therefore, are not able to duplicate analytically the experimental data.

In effect the lack of a direct correlation between the motion at the base of the dam and the response may be attributed only partly to the introduction of simplifications. It is probably explained, instead, by the fact that the behaviour model adopted assumes the existence of a physical link between the input and the output which in reality is absent. In other words, the motion at a point cannot be correlated with the hypothetical uniform motion of the bedrock, but it may be explained by taking into account rather more complex seismic wave propagation phenomena.

From this point of view, parameters such as the position of the hypocenter and the direction of wave propagation play an important role not only in that they determine the frequency contents of an earthquake but also because they are able to influence the manner with which the structure and its foundation exchange energy.

In conclusion, the extension of similar surveillance in future to other dams put up in seismic areas is to be recommended, not only for purposes of a better assessment of the seismic risk involved but also from the point of view of acquisition of data and information related to the characteristics of excitation and structural response.

The availability of further case histories can lead to a better understanding of the phenomena and thus make good the present deficiencies in the interpretation of the data.

6. ACKNOWLEDGMENTS

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