IN SITU TESTS FOR THE DETERMINATION OF THE DYNAMIC CHARACTERISTICS OF SOME ITALIAN DAMS

by

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SYNOPSIS

The purpose of one of the research programmes sponsored by the "D. S. R. - Direzione Studi e Ricerche" of the ENEL (the Italian National Board for Electric Power) has the aim to determine the dynamic behaviour of the most important italian dams, in order to be able to control the consequences on these structures of extraordinary occurrences, such as earthquakes. Therefore, it has been considered advisable to carry out a series of experimental studies on a number of dams. This paper illustrates the testing techniques and the results obtained from the tests carried out up to now, by ISMES of Bergamo, Italy.

1. INTRODUCTION

According to the criteria of modern seismic engineering, present-day codes suggest that when a dam is to be built in a seismic area, it should be checked by calculating actual dynamic response to the "design earthquake", rather than using the equivalent static horizontal force. Calculation of this response, of course, involves determining the characteristics of the first vibration modes (natural frequency, damping and shape) under the structures' actual operating conditions, thus taking into account both interaction between the dam and its foundations, and the influence of water in the reservoir. Calculation or experimental procedures by means of physical models make such a complex analysis possible only in part; as a matter of fact, various aspects of the problem, especially the exchange of energy between foundations and dam or hydrodynamic overpressure, are still little understood. With a view to clarifying the actual dynamic behaviour of a dam, and to be able to set up a sufficiently reliable seismic analysis, ENEL have undertaken, in cooperation with ISMES, a series of field tests on a number of dams; the purpose of this investigation, which is still in course, is to identify the natural frequencies, damping and mode shapes associated therewith, of some of Italy's main dams.

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2. TEST PROCEDURES AND DATA PROCESSING CRITERIA

The motion of a structure, that may be schematized as a concentrated mass system, is described - assuming damping forces of a viscous nature - by the following system of second-order differential equations:

$$(1) \qquad [M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{f(t)\}$$

$[M]$, $[C]$, $[K]$, represent mass, damping and rigidity matrices, respectively. By performing the Laplace transform, one obtains:

$$(2) \qquad (s^2[M] + s[C] + [K]) \cdot [X(s)] = [B(s)] \cdot [X(s)] = [F(s)]$$

whence:

$$(3) \qquad [X(s)] = [B(s)]^{-1} \cdot [F(s)] = [H(s)] \cdot [F(s)]$$

$[H(s)]$ is know as "transfer matrix" of the system and may be expressed in function of the mode characteristics by the relation:

$$(4) \qquad [H(s)] = \sum_{k=1}^{N} \frac{\{\phi_K\} \cdot \{\phi_K\}^T}{s - p_K} + \frac{\{\phi_K^*\} \cdot \{\phi_K^*\}^T}{s - p_K^*}$$

where:

$p_k, p_k^* = -\sigma_K \pm j\omega_K$	complex eigenvalue (complex root of the equation $\det[B(s)] = 0$)
σ_K	damping (rad/sec)
$\omega_K = 2\pi f_K$	f_k: natural frequency
$\xi = \sigma_K / \sqrt{\sigma_K^2 + \omega_K^2}$	damping %
$\{\phi_K\}, \{\phi_K^*\}$	complex eigenvectors (conjugate pairs)

(4) appears of special interest in selecting testing and data processing procedures.

The tests are performed by applying exciting force $F_q(s)$ in a present position q of the structure, and recording response^q $R_j(s)$ (with j = 1, N) in all measuring positions. In this way a column of $^j[H(s)]$ can be obtained:

$$h_{jq}(s) = \frac{R_j(s)}{F_q(s)} \qquad \text{with } j = 1, N$$

which, as desumed an examining (4), contains all information related to the structure's vibration modes. Excitation position q is obviously chosen so as not to coincide with, or approach, a node for any of the modes involved; in order to avoid this sort of shortcoming, two or more series of tests with different excitation positions are performed.

Data processing, which is carried out almost automatically by means of a computer, is made up of the following phases:

a) from tape recordings performed during testing, the electric transducer signals are collected and transfer functions built up in h_{iq} (s) digital form in the computer's memory;

b) modes present are identified and for each an estimate of parameters σ_k, ω_k and Φ_k are performed;

c) parameters determined in the earlier phase are replaced in (4) and transfer functions h_{iq} (s) are calculated;

d) a new and more accurate estimation of mode parameters is determined by means of a formula that minimizes the mean square error between transfer functions obtained experimentally and those calculated;

e) operations c) and d) are repeated until the error is reduced to values acceptable to the operator. Final data are then printed out and plotted.

3. EQUIPMENT USED

Dam excitation was obtained through a variable-frequency sinusoidal force acting horizontally in a radial direction, applied at crest arch. This force, whose frequency was continuously varied within a range between 2 and 15 cps, and whose maximum intensity was 10 tons, was generated by a mechanical vibration generator. Velocity transducers "Geotech-Teledyne" type S 13 and "Kinemetrics" type SS-1 were used to measure dam response. Signals coming from the seismometers were relayed to variable-gain differential amplifiers and thence to two 14-track tape-recorders FR 1300. Also signals for measuring excitation frequency and phase difference between dam force and responses were relayed to the recorders.

4. RESULTS ACHIEVED

Tests carried out so far (others are still in course) concerned 11 dams; for some of these, main characteristics (dam type, size and shape, rock features) are summarized in the table A. Also data relating to the first 4 modes, obtained according to the technique described earlier, are listed on this table. As regards the Fiastra dam, data concern two different sets of tests performed with two different reservoir levels.

The following remarks apply to results obtained:

A) Natural frequency and mode shapes

Frequencies up to 15 cps were investigated an all dams and 4 or more vibration modes were ascertained. The order in which symmetrical and asymmetrical type modes follow each other is reversed when passing from arch dams to gravity dams. 50 to 70 measuring points were considered, with instruments placed radially (on arch dams too, the tangential motion component was omitted) and by this means a proper definition of mode shapes at lower frequencies was obtained. For the latter modes it is also stressed that the imaginary component of mode shapes was often negligible, enabling to apply the concept of "normal" modes rather than the more general motion of "complex" modes. This simplification appears no longer acceptable with higher modes; also mode shape is usually far less clearly defined, not only owing to the limited number of measuring points, but mainly owing to the dam's tendency to behave no longer as a monolithic body but as though made up of blocks.

B) Damping

Data obtained so far make it possible to establish that damping generally shows different values with arch dams as compared with gravity dams; in the former case, damping values range from 1% to 3% in the latter, from 4% to 8%. Values encountered, of course, arise with extremely modest vibration amplitudes, around $1 \div 10 \cdot 10^{-3}$ mm; it was not possible to find a reliable damping variation law with the order or type of modes.

C) Behaviour of the reservoir

The influence of the reservoir on the Fiastra dam was studied. The table C shows a comparison between results achieved in both reservoir conditions. Frequency variation is of the order of 10% in relation to first symmetrical modes and 8% for first asymmetrical modes. Damping variation is negligible.

D) Comparison with calculation

The table B lists early results achieved with a calculation program based on finite elements applied to the Alpe Gera gravity dam. The example was chosen in view of the lack of water in the reservoir during testing. The calculation was performed under two different conditions: in the first case, only the dam was considered; in the second, the presence of a restricted extension of foundation rock was taken into account. Characteristics of the concrete and of the rock are shown on the table. B.

5. CONCLUSIONS

The article makes mention of some of the results achieved by forced vibration tests on italian dams. Studies are presently taking place to clarify the influence of the presence of water, in the reservoir, on the dam's response to earthquakes.

The finite element programme for calculating a dam's dynamic re sponse is moreover being set up with the execution of comparison between experimental and analytical data.

TABLE B: ALPE GERA DAM

Experimental frequency f (cps)	Computed frequency	
	Without rock foundation f (cps)	With rock foundation f (cps)
3.47	4.21	3.66
4.72	5.59	5.02
6.16	6.91	6.32
7.43	8.25	7.34
8.58	9.74	8.08
9.21	-	-

Specific gravity for concrete and rock: 2.5 ton/m^3

Young's modulus for concrete: $3.3 \cdot 10^5$ Kg/cm^2

Young's modulus for rock foundation: $2.0 \cdot 10^5$ Kg/cm^2

TABLE C: FIASTRA DAM

FREQUENCIES AND DAMPING FOR DIFFERENT RESERVOIR CONDITIONS					
Low level (619.25 m)		High level (632.10 m)		f_0/f_1	Mode shape
f_0 (cps)	ξ %	f_1 (cps)	ξ %		
4.72	3.27	4.29	3.30	1.10	symmetric
5.97	2.46	5.[illegible]3	2.56	1.08	asymmetric
7.87	2.38	7.34	2.80	1.07	symmetric
9.72	2.50	9.16	2.49	1.05	asymmetric
11.62	2.59	11.05	2.47	1.05	symmetric

ALPE GERA DAM

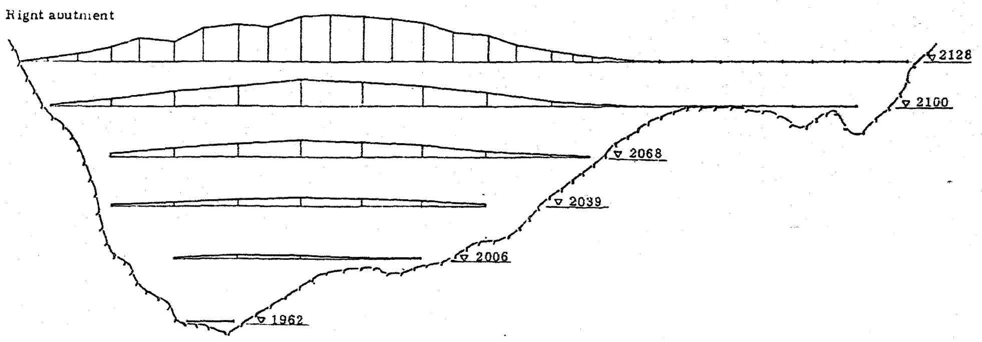

FIG. 1: FIRST VIBRATION MODE (f = 3.47 cps) DETERMINED BY FORCED VIBRATION TEST

TABLE A

VIBRATION TESTS ON ARCH AND ARCH-GRAVITY DAMS

Dam	Characteristics						Foundation	Shape of the valley	Vibration modes			
	h (m)	R (m)	α_c (°)	α_f (°)	l (m)	t (m)			Reservoir	f (cps)	ξ %	Type
Lumiei (double-curvature)	136	82	104	114	240	3.5 ÷ 15.6	Upper triassic dolomites and dolomitic limestones	U	near full	3.99 5.65 8.92 11.84	1.17 1.00 1.10 1.20	asymm. symm. asymm. symm.
Ambiesta (double-curvature)	59	74	112	84	145	2.1 ÷ 7.8	Upper triassic dolomite	Middle width V	near full	4.11 4.72 7.20 9.42	6.00 1.90 4.00 3.00	asymm. symm. asymm. symm.
Talvacchia (double-curvature)	78	119	104	28	216	4.7 ÷ 16.0	Sandstone containing partly calcareous and partly clayey binder alternating with micaceous and marly strata	Middle width V	near full	3.68 3.80 5.35 6.70 8.35	(*) 3 ÷ 5 3 ÷ 5 3 ÷ 5 3 ÷ 5 3 ÷ 5	asymm. symm. symm. asymm. symm.
Fiastra (arch-gravity)	87	157	95	23	254	3.4 ÷ 31.0	Limestone with clay parting. Eocene	Middle width V	low level	4.72 5.97 7.87 9.72 11.62	3.27 2.46 2.38 2.50 2.59	symm. asymm. symm. asymm. symm.

h = maximum height
R = upstream radius of crest
α_c = central angle at the crest
α_f = central angle at the base
l = crest length
t = thickness (central cantilever)

VIBRATION TESTS ON GRAVITY DAMS

Dam	Characteristics						Foundation	Shape of the valley	Vibration modes			
	h (m)	i_m	i_v	α_0 (°)	l (m)	t (m)			Reservoir	f (cps)	ξ %	Type
Suviana (surface curved on horizontal plane with radius of 550 m)	91	0.07	0.81	24	225	7.0 ÷ 80.0	Siliceous sandstone with argillaceous schist partings	Trapezoidal	low level	6.00 8.66 10.61 12.55	8.65 7.27 3.65 3.88	symm. asymm. symm. asymm.
Campo Moro (surface curved on horizontal plane with radius of 200 m)	97	0.03	0.70	57	198	5.0 ÷ 71.0	Greenschists (serpentine)	Triangular	low level	6.24 8.78 11.69 14.39	4.03 3.00 4.10 4.30	symm. asymm. symm. asymm.
Alpe Gera (straight-line plant)	174	0.03	0.70	-	528	5.0 ÷ 127.0	Greenschists (serpentine)	Irregular	near empty	3.47 4.72 6.18 7.43 8.58 9.21	4.41 4.54 4.50 3.43 2.70 2.71	- - - - - -

h = maximum height
i_m = upstream slope
i_v = downstream slope
α_0 = central angle at the crest
l = crest length
t = thickness

(*) Damping was not evaluated by the technique described in the paper, but using $\sqrt{2}$ method.