Transactions on the Built Environment vol 20, © 1996 WIT Press, www.witpress.com, ISSN 1743-3509

Structural response of a dam-foundation rock-impounded water model under seismic and thermal loading

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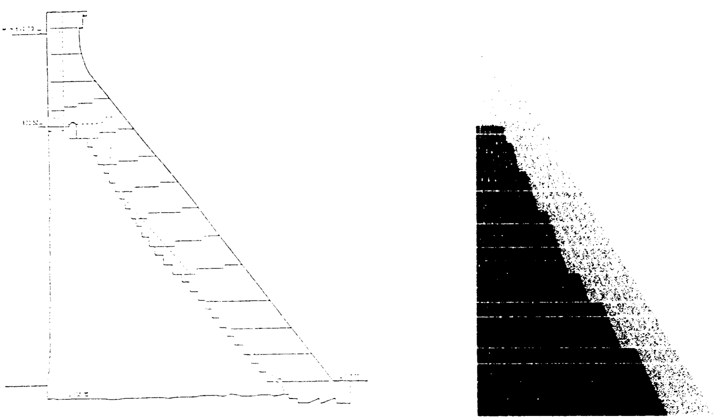
ABSTRACT

In this paper a comprehensive study of the existing spanish dam of Bolarque is presented. The dam was composed of two different classes of concrete and also two choices of material characteristic of the rock foundation were considered. The seismic analysis was carried out taking in account the dam-foundation rock-impounded water interaction. Additionally, thermal loadings were included by using an equivalent structural model. Overall 128 structural analyses were carried out to complete consider the necessary combinations of materials, seismic and thermal loadings. Numerical results are presented showing the behaviour of the dam under the worst situations for empty and full reservoir.

1. A BRIEF HISTORY OF BOLARQUE DAM

The Bolarque dam was built in 1910 and works to increase its height and therefore to improve the volume of impounded water were carried out in 1954-1955. Figure 1a shows the cross-section of the dam and Figure 1b the structural model which acommodate quite properly the actual geometry.



a) Actual cross-section *b) Structural model of the dam*

Figure 1. Geometry of Bolarque dam

The existing data of elastic modulus E of the dam materials from 1910 and 1954 belonged to a study made in 1987. It showed a great dispersion of values of compression strength and, therefore, elastic modulus of both types of concrete. Differences in data were so great that it was even nuclear what concrete was more strength, as sometimes the better numerical results belonged to specimen from 1911 concrete and sometimes to the concrete from 1954. Because of that two values were considered in the study, namely: $E_h = 20 \cdot 10^6$ KN/m^2, $E_h = 26 \cdot 10^6$ KN/m^2, for concrete material and $E_f = 26 \cdot 10^6$ KN/m^2 and $E_f = 13 \cdot 10^6$ KN/m^2, for the foundation. Therefore if we define

E_{h1}: elasticity modulus of initial concrete (1911),
E_{h2}: elasticity modulus of new concrete (1954),
E_f: elasticity modulus of foundation rock,

the complete set of cases considered in the analysis were the included in Table 1.

Table 1. Elastic modulus for concrete and foundation rock

Name	E_{h1}	E_{h2}	E_f
bol 1	$20 \cdot 10^6$	$20 \cdot 10^6$	$13 \cdot 10^6$
bol 2	$20 \cdot 10^6$	$20 \cdot 10^6$	$26 \cdot 10^6$
bol 3	$26 \cdot 10^6$	$20 \cdot 10^6$	$13 \cdot 10^6$
bol 4	$26 \cdot 10^6$	$20 \cdot 10^6$	$26 \cdot 10^6$
bol 5	$20 \cdot 10^6$	$26 \cdot 10^6$	$13 \cdot 10^6$
bol 6	$20 \cdot 10^6$	$26 \cdot 10^6$	$26 \cdot 10^6$
bol 7	$26 \cdot 10^6$	$26 \cdot 10^6$	$13 \cdot 10^6$
bol 8	$26 \cdot 10^6$	$26 \cdot 10^6$	$26 \cdot 10^6$

The dam is a part of the facilities linked to the nuclear power plant of Zorita (Spain) and because of that the Spanish Nuclear Security Board ordered a study to find out the safety coefficient of the system composed by dam-rock foundation-impounded water under the point actuation of the three following loads:

a) Static loads: Hydrostatic pressure and self-weight.

b) Thermal loads as indicated in paragraph 3.

c) Seismic loads as specified by the ground acceleration of NUREG/CR-0098 earthquake with a duration of 20 sec. divided in intervals of 0.005 sec., a maximum vertical acceleration of 0.047 g, and two horizontal accelerations (H_1 and H_2) with maximum values of 0.07 g.

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2. SEISMIC ANALYSIS

Seismic analysis of the Bolarque dam was carried out considering both static loads (hydrostatic pressure and self-weight) and ground acceleration of the aforementioned earthquake. The structural model considered was composed by an infinite viscoelastic domain, representing the foundation rock and an elastic domain, with two different materials and hysteretic damping representing the dam.

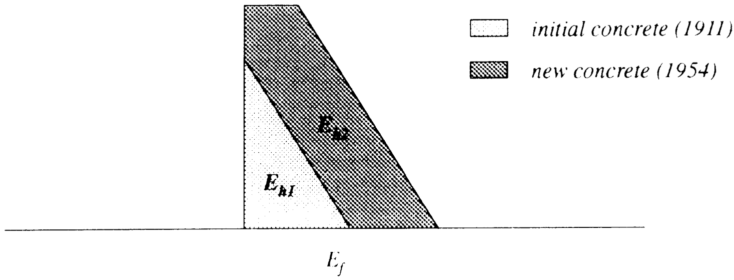

Figure 2. Structural model for seismic analysis

The computer code was EAGD-84, developed by Chopra and coworkers [1-6].

2.1. Dynamic parameters of the structural model

A hysteretic damping of value η_s = 0.1 was chosen. That means a viscous damping of value $\varepsilon = \eta_s / 2 = 0.05$. Ten vibration frecuencies were calculated for each structural model (*bol 1* to *bol 8*). The numerical results are presented in Table 2.

Table 2. Vibration frecuencies (Hrz)

	bol 1	bol 2	bol 3	bol 4	bol 5	bol 6	bol 7	bol 8
1	6.54	7.66	6.74	7.98	6.73	7.96	6.92	8.29
2	13.10	16.94	13.31	17.42	13.23	17.15	13.43	17.62
3	15.62	17.38	16.21	18.09	16.29	18.31	16.94	19.10
4	25.16	28.67	25.72	29.54	26.60	30.27	27.25	31.20
5	40.55	44.15	41.75	45.41	43.50	47.00	45.02	48.65
6	45.48	47.21	49.00	50.56	47.83	49.70	51.34	52.96
7	58.94	62.59	61.66	65.28	62.70	66.38	65.96	69.63
8	66.89	69.62	73.27	75.68	68.37	71.51	75.12	78.15
9	73.71	76.06	79.11	82.24	76.68	78.89	82.80	85.78
10	79.11	83.37	84.09	87.90	82.36	87.60	88.54	93.27

2.2. Selection of seismic response parameters

a) For a specified maximum excitation frecuency F, the computation of the frecuency response functions and earthquake response, via the *FFT* algorithm, depends on two parameters: *NEXP*, which is related to the number of excitation frecuencies and time intervals; and the time interval *DT*, in seconds. *NEXP* is related to the number of time intervals N. Namely $N = 2^{NEXP}$. As *NEXP* must be an integer number the actual number of time intervals $N = 4000$ was incremented to $N = 4096$, adding 96 seconds with zero vertical and horizontal accelerations and the end of the NUREG earthquake data. Therefore the duration of the earthquake increased to $T = 4096 \times 0.025$ sec = 20.48 sec. And $NEXP = 12$.

b) The frecuency increment Δf is obtained as $\Delta f = 1/2T$, therefore $\Delta f = 0.0244$ Hrz and it must be small enough to represent the frecuency response functions for the generalizaded coordinates, especially near the fundament resonant marks. It is recommended that $\Delta f \leq 0.02 f_1$, being f_1 the smallest frecuency. The lowest value of f_1 in Table 2 is $f_1 = 6.54$ Hrz. Therefore $0.02 f_1 = 0.131$ Hrz and the constraint is accomplished.

c) The maximum frecuency represented F comes from the expresion $F = N\,\Delta f$. Therefore $F = 100$ Hrz. Obviously this value needs to be greater than every value of Table 2 to represent adecuately the vibrations, what is, in fact, also accomplished. The value of F has another constraint

$$F \leq w_{max} = \frac{5}{2\pi b}\sqrt{\frac{E_f}{2(1+\nu)\rho_f}}$$

where
E_f elastic modulus of foundation rock,
ν Poisson modulus of foundation rock,
b length between nodes on line connecting the dam and the foundation rock,
ρ_f density of foundation rock.

In the finite element mesh of Bolarque dam $b = 1.683$ m. Also $\nu = 0.33$, $\rho_f = 2.6$ t/m^3

For material with $E_f = 26 \cdot 10^6$ KN/m^2

$$F = 100 \text{ Hrz} < w_{max} = 917.82 \text{ Hrz}$$

For material with $E_f = 13 \cdot 10^6$ KN/m^2

$$F = 100 \text{ Hrz} < w_{max} = 649 \text{ Hrz}$$

d) To reduce the aliasing error it is recommended for the duration of the earthquake T that:

$$T > \frac{1.5}{\eta f_1}$$

being η the histeretic damping $\eta = 0.1$ and f_1 the smallest value in Table 2. In this case

$$T = 20.48 > 2.294$$

therefore the constraint is not violated.

e) The absorptiveness of the reservoir botton materials is characterized by the wave reflection coefficient α, which is defined as the ratio of the amplitude of the reflected hydrodynamic pressure wave to the amplitude of a vertically propagating pressure wave incident on the reservoir bottom. The materials at the bottom of the reservoir determine the value of the wave reflection coefficient α according to the following equation

$$\alpha = \frac{1-K}{1+K} \qquad K = \frac{\rho C}{\sqrt{E_f \rho_r}}$$

where ρ water density

C velocity of pressure waves in the water (C = 1438.6 m/sec)

ρ_r bottom materials density (ρ_r = 2.6 t/m^3)

E_f elastic modulus of bottom materials

For foundation rock with $E_f = 26 \cdot 10^6$ KN/m^2

$$k = 0.175 \qquad \alpha = 0.7$$

For foundation rock with $E_f = 13 \cdot 10^6$ KN/m^2

$$k = 0.247 \qquad \alpha = 0.6$$

2.3. Load combinations

We consider the load combinations included in Table 3.

Table 3. Load combinations

Full reservoir	Empty reservoir	Full reservoir	Empty reservoir
Self weight	Self weight	Self weight	Self weight
Hydrostatic pressure	—	Hydrostatic pressure	—
Vertical acc. V	Vertical acc. V	Vertical acc. V	Vertical acc. V
Horizontal acc. H_1	Horizontal acc. H_1	Horizontal acc. H_2	Horizontal acc. H_2

These four combinations were applied to eight structural models (*bol 1* to *bol 8*).

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2.4. Graphical interfaces

A software application was worked out to allow a CAD presentation of the structural models to be processed in EAGD-84 and a graphical visualization of the structural responses of the models.

The visualizer module of the COSMOS/M software [7], called GEOSTAR, was used both as CAD utility and structural responses visualizer. The flowchart of modules as appears in the Figure 3.

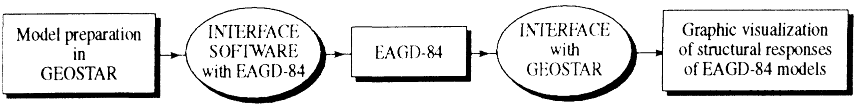


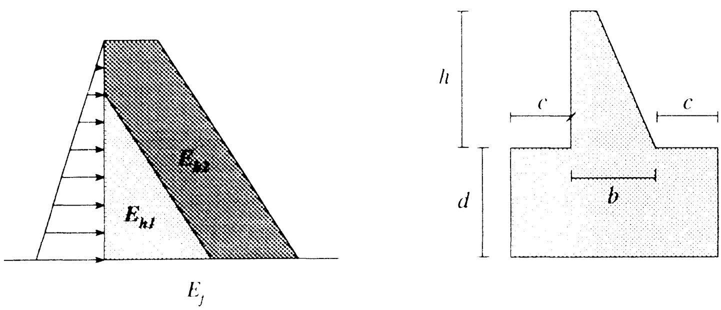
Figure 3. Graphical interfaces between GEOSTAR and EAGD-84

3. THERMOELASTIC ANALYSIS OF BOLARQUE DAM

3.1. Equivalent structural model for thermal loadings

The analysis of Bolarque dam included temperature loadings. As EAGD-84 does not consider such effects, the following procedure was stablished.

a) Structural models from Table 1 were analyzed using EAGD-84 software under a set of loading composed by the self-weight and hydrostatic pressures.



a) Structural model of EAGD-84 *b) Equivalent model for COSMOS/M*

Figure 4. Structural models of Bolarque dam

b) Several structural models composed of the Bolarque dam geometry and a part of the foundation rock were created as indicated in Figure 4b. The elastic modulus of materials were those considered in *bol 6* model. Many models with different values of *c* and *d* parameters were processed in order to mach the structural responses in the COSMOS/M software with those obtained with EAGD-84.

The structural responses considered were:

—Horizontal displacement at the top.

—Vertical stresses in dam material.

The aim of the procedure was to identify a structural model in COSMOS/M producing the same results for static loading than the EAGD-84 model. After having found out that, a complete seismic study of Bolarque dam was carried out by adding the following analyses:

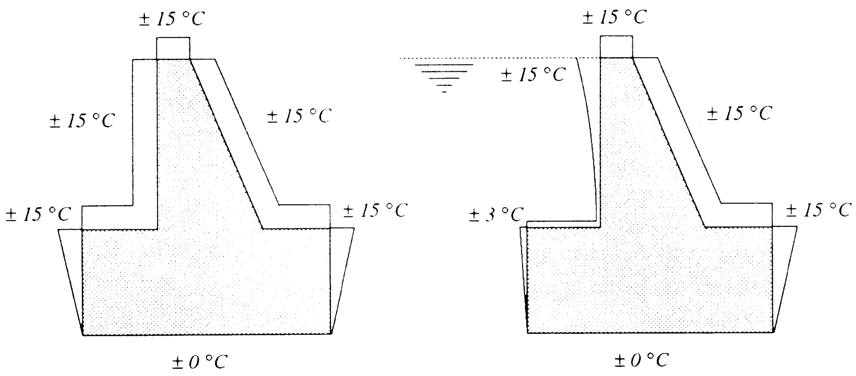
a) Structural results in EAGD-84 for static and seismic loading.

b) Structural results in COSMOS/M for thermal loading.

After a quite extensive checking a final candidate was selected having $c = 0.1b$ and $d = 0.65b$.

3.2. Thermal loadings considered

Loading conditions were variations of ± 15 °C with respect to a reference temperature. Depending of the existence or not of impounded water, the temperature variations considered in the analysis along the boundaries of the model are presented in Figure 5. The second order line on the reservoir side of the dam in Figure 5b was selected according with water temperature data from existing dams.



a) Empty reservoir *b) Full reservoir*

Figure 5. Variation of temperatures on boundaries

A line for the variation of temperatures at the central points of the dam was also defined. It was assumed that the temperature at the center of the bottom of the dam had no variation from the temperature of reference (this hypothesis was

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justified by experimental data from other spanish dams), and it was also assumed a linear variation at that central line from bottom to top as presented in Figure 6.

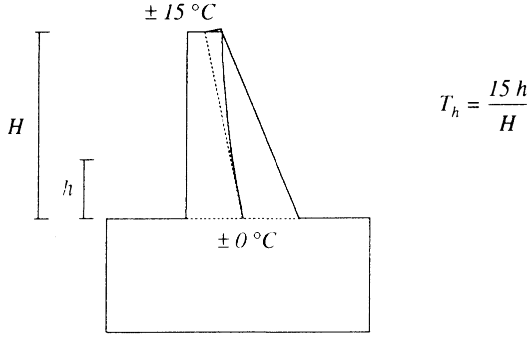

Figure 6. Variation of temperatures at central points of the dam

The temperature distribution in the domain of the dam was defined by accepting a linear variation from the boundaries. Experimental data showed gradients from 1 °C/m to 2 °C/m. Therefore both values were considered in the models as indicated in Table 4.

Table 4. Values of ΔT and g_T

Reservoir	ΔT	g_T (°C/m)
Full	± 15°	1
		2
Empty	± 15°	1
		2

The linear variation of temperatures from the boundaries to the interior of the dam would produced two different situations at a point of the domain, as presented in Figure 7. Let define

ΔT_{ar} Temperature on the upstream face of the dam

$\Delta T_{ar} = \pm 15°$ for empty reservoir

$3° \leq \Delta T_{ar} \leq 15°$ for full reservoir

$-3° \geq \Delta T_{ar} \geq -15°$ for full reservoir

$\Delta T_{ab} = \pm 15°$ Temperature on the downstream face of the dam

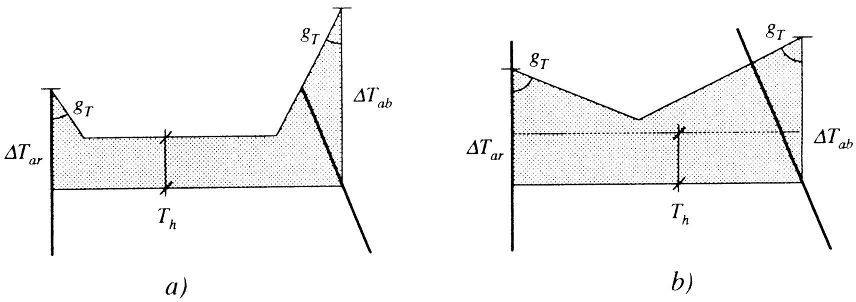

Figure 7. Variation of temperatures inside the dam

If the crossing point between the lines representing the linear variation from the boundaries stood at a temperature lower than T_h, a situation as presented in Figure 7a appeared. In the opposite case the distribution of temperatures was as indicated in Figure 7b.

4. NUMERICAL RESULTS

Let remember that the total number of seismic analysis was 8 x 4 = 32 (eight structural models by four load combinations). The envelope of stresses of the complete set was also combinated with the thermal loadings of Table 4. That means a number of 32 x 4 = 128 combinations. The numerical results obtained were the following.

4.1. Worst situation with full reservoir

That situation arised for the following case:

- Structural model: *bol 8*
- Seismic loading: $V + H_2$
- Thermal loading:
  For tensile stresses (P_1) the worst case contained the thermal loading $\Delta T = -15$ °C, $g_T = 1$. For compressive stresses (P_3) the worst case contained the thermal loading $\Delta T = 15$ °C, $g_T = 2$.

Figure 8 shows values of P_1 (separated into components) and Figure 9 presents values of P_3.

4.2. Worst situation with empty reservoir

This situation corresponded to:

- Geometric model: *bol 8*
- Seismic loading: $V + H_2$

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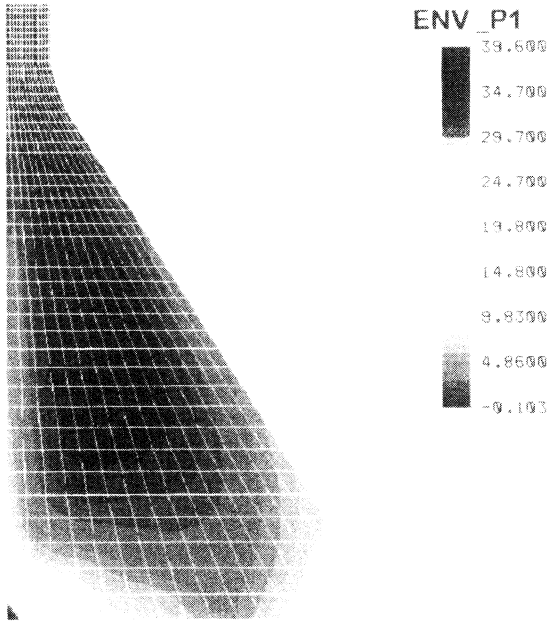

Figure 8. Values of P_1 (kg/cm^2) for the worst loading combination with full reservoir.

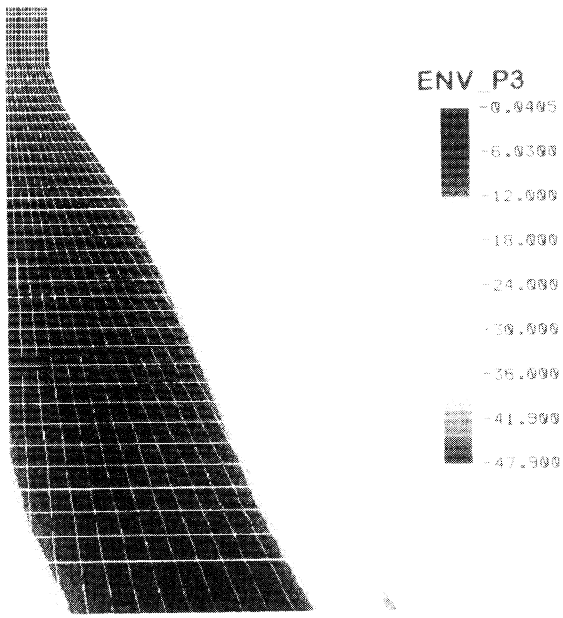

Figure 9. Values of P_3 (kg/cm^2) for the worst loading combination with full reservoir.

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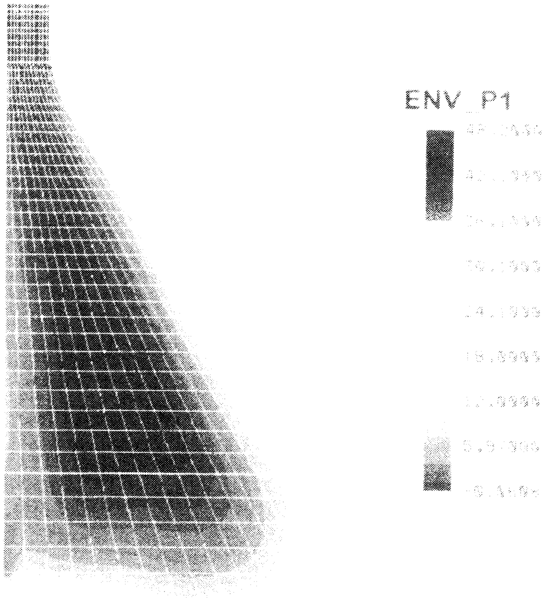

Figure 10. Values of P_1 (kg/cm^2) for the worst loading combination with empty reservoir.

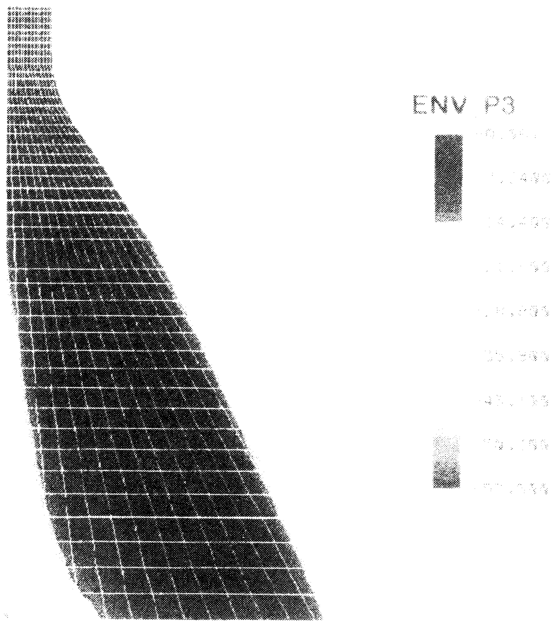

Figure 11. Values of P_3 (kg/cm^2) for the worst loading combination with empty reservoir.

- Thermal loading:
  For tensile stresses (P_1) the worst case contained the thermal loading $\Delta T = -15\ ^{\circ}C,\ g_T = 1$. For compressive stresses (P_3) the worst case contained the thermal loading $\Delta T = 15\ ^{\circ}C,\ g_T = 2$.

Total values of principal stresses P_1 and P_3 are showed in Figures 10 and 11, respectively.

5. REFERENCES

1. CHOPRA, A.K.; CHAKRABARTI, P. and GUPTA, S.: *Earthquake Response of Concrete Gravity Dams Including Hydrodynamic and Foundation Interaction Effects.* Report Nº UCB/EERC-80/01, Earthquake Engineering Research Center, University of California, Berkeley, California, Jan. 1980.
2. DASGUPTA, G. and CHOPRA, A.K.: *Dynamic Stiffness Matrices for Viscoelastic Half Planes.* "Journal of the Engineering Mechanics Division", ASCE, Vol. 105, Nº EM5, Oct. 1979, pp. 729-745.
3. FENVES, G. and CHOPRA, A.K.: *Eartquake Analysis of Concrete Gravity Dams Including Reservoir Bottom Absorption and Dam-Water-Foundation Rock Interaction,* "Earthquake Engineering and Structural Dynamics", Vol. 12, pp. 663-680 (1984).
4. HALL, J.F.: *An FFT Algorithm for Structural Dynamics,* "Earthquake Engineering and Structural Dynamics", Vol. 10, Nº 6, Nov.-Dec. 1982, pp. 797-811.
5. FENVES, G.; CHOPRA, A.K.: *Effects of Reservoir Bottom Absortion and Dam-Water-Foundation Rock Interaction on Frecuency Response Functions for Concrete Gravity Dams,* "Earthquake Engineering and Structural Dynamics", Vol. 13, pp. 13-31 (1985).
6. FENVES, G.; CHOPRA, A.K.: *EAGD-84. A Computer Program for Earthquake Analysis of Concrete Gravity Dams.* Report Nº UCB/EERC-84/11. Earthquake Engineering Research Center, University of California, Berkeley, California, August 1984.
7. COSMOS/M 1.71 version. User's Manual, SARC. Santa Monica, California, 1994.