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DYNAMIC BEHAVIOUR OF AN ARCH DAM-FOUNDATION-RESERVOIR SYSTEM NUMERICAL MODELLING AND CALIBRATION WITH A FORCED VIBRATION TEST

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ABSTRACT

In this paper a comparison of different mathematical models for the study of the dynamic behaviour of an arch dam-foundation-reservoir system is performed. These models are calibrated with a forced vibration test of an arch dam by comparison of experimental and numerical transfer functions. The parameters obtained from the calibration of the different mathematical models are analyzed. The different mathematical models are used in order to compute the response to an earthquake of the dam-foundation-reservoir system.

KEYWORDS

Dam-foundation-reservoir system; Experimental transfer functions; Foundation with mass.

INTRODUCTION

The dynamic behaviour of the foundation can be usually neglected for the study of the seismic response of arch dams so, in many cases, massless foundation can be assumed in the mathematical models. However there are some cases where the dynamic behaviour of the foundation can not be neglected, for instance when the topology of the canyon magnifies the seismic waves. In such cases we could use mathematical models that assume foundation with mass and the radiation of the pressure and shear waves at the boundary of the rock-foundation block.

In this paper comparison of some results obtained with a mathematical model of massless foundation and a mathematical model of foundation with mass for the study of the seismic behaviour of coupled systems arch dam-foundation-reservoir is presented.

The reliability of the models are checked against the experimental data obtained in a forced vibration test of a portuguese arch dam (Alto Lindoso dam, 110 m high, Fig. 1). The tests were performed with full reservoir and Summer conditions about one year after the first filling (Câmara et al., 1993,1994).

ALTO LINDOSO DAM

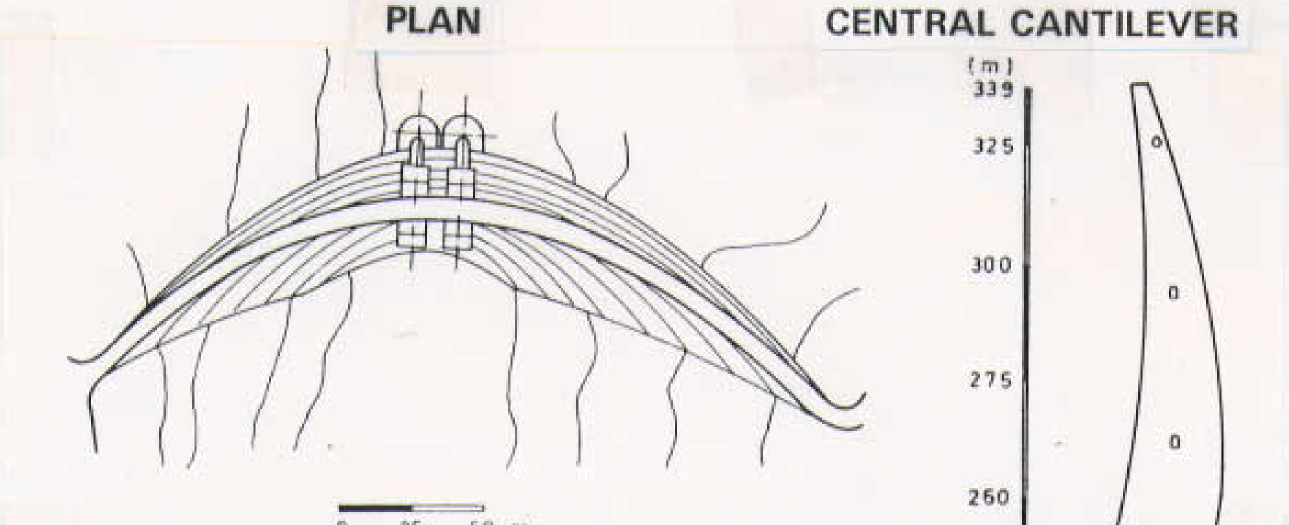


Fig. 1. Alto Lindoso dam. General view, plan and cross section at central cantilever.

MODELS AND METHODS

The equilibrium conditions of the system dam-foundation-reservoir, expressed in terms of dynamic displacements, velocities, accelerations and water pressures, may be discretized by the finite element method yielding the following equations (Pedro and Câmara, 1986; Câmara, 1992; Galindo et al., 1992; Faria, 1994)

$$\begin{bmatrix} \overline{M} & \rho G^T \\ 0 & M \end{bmatrix} \begin{Bmatrix} \ddot{P} \\ \ddot{U} \end{Bmatrix} + \begin{bmatrix} \overline{C} & 0 \\ 0 & C \end{bmatrix} \begin{Bmatrix} \dot{P} \\ \dot{U} \end{Bmatrix} + \begin{bmatrix} \overline{K} & 0 \\ -G & K \end{bmatrix} \begin{Bmatrix} P \\ U \end{Bmatrix} = \begin{Bmatrix} \overline{F} \\ F \end{Bmatrix}$$

MASSLESS FOUNDATION	FOUNDATION WITH MASS
$C = C'$	$C = C' + C_r$
$\overline{F} = -\rho G^T \ddot{U}_0$	$\overline{F} = 0$
$F = -M\ddot{U}_0$	$F = 2C_r\dot{U}_r$
U Relative displacement	U Total displacement

C' Structural damping

C_r Radiation damping

$\ddot{U}_0$ Uniform accelerations prescribed at the boundary

$\dot{U}_r$ Velocity of incident wave prescribed at the boundary

In the above equations: M, C and K are the mass, the damping and the stiffness matrices of the dam-foundation whole, and $\overline{M}$, $\overline{C}$ and $\overline{K}$ are the corresponding matrices of the reservoir; $\ddot{U}$, $\dot{U}$ and U represent accelerations, velocities and displacements at nodal points and P, $\dot{P}$ and $\ddot{P}$ represent water pressures and their time derivatives at nodal points; G is an interaction matrix, relating water pressures and forces on the solid-water interface; ρ is the unit specific mass of water; F and $\overline{F}$ are applied loads. In the case of forces applied on the structure $\overline{F}$=0.

U and P are considered as superpositions of the vibration modes of the dam-foundation and of the vibration modes of the reservoir.

The damping matrix of the reservoir depends on the radiation of pressure waves at the water-water boundary where the gradient of the pressure is proportional to the first time derivative of the pressure, the proportionality constant being the inverse of the pressure wave velocity.

In the hypothesis of foundation with mass the damping matrix of the structure (C) depends on the viscous modal damping of the structure (C') and on the damping (C_r) created by the radiation of pressure and shear waves at the boundary surfaces of the rock foundation block where the normal and shear stresses are proportional to the normal and tangential velocities, the proportionality constants being respectively the product of the specific mass of rock by the normal and shear wave velocities.

Since the structure has no fixed boundaries the modes of vibration are computed by adding the stiffness to the mass matrix of the structure. This gives the same vibration modes and a shift of a unit of the square of the angular frequencies.

In the hypothesis of massless foundation the damping matrix of the structure (C) depends only on the viscous modal damping of the structure (C').

In Fig. 2 are presented schematically the different hypotheses of the two models.

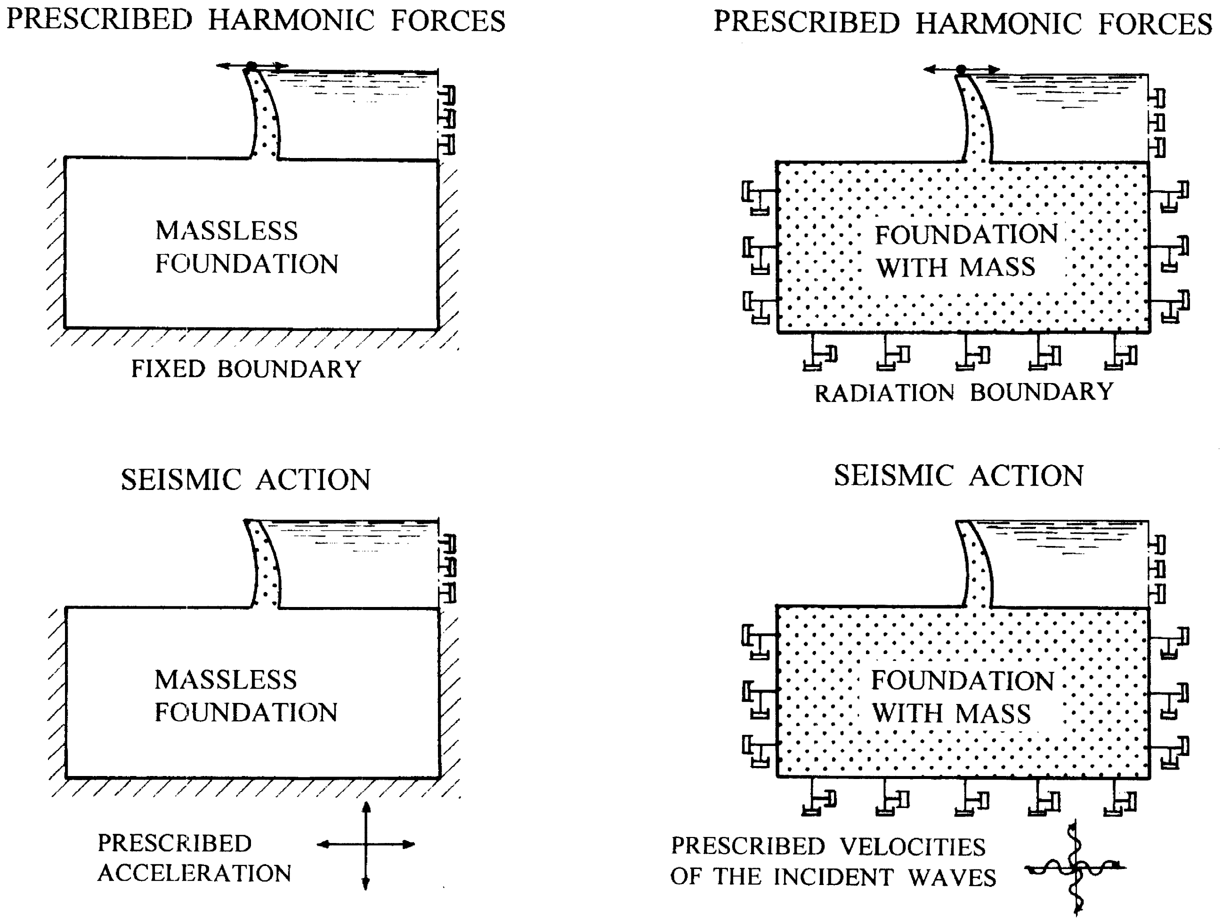
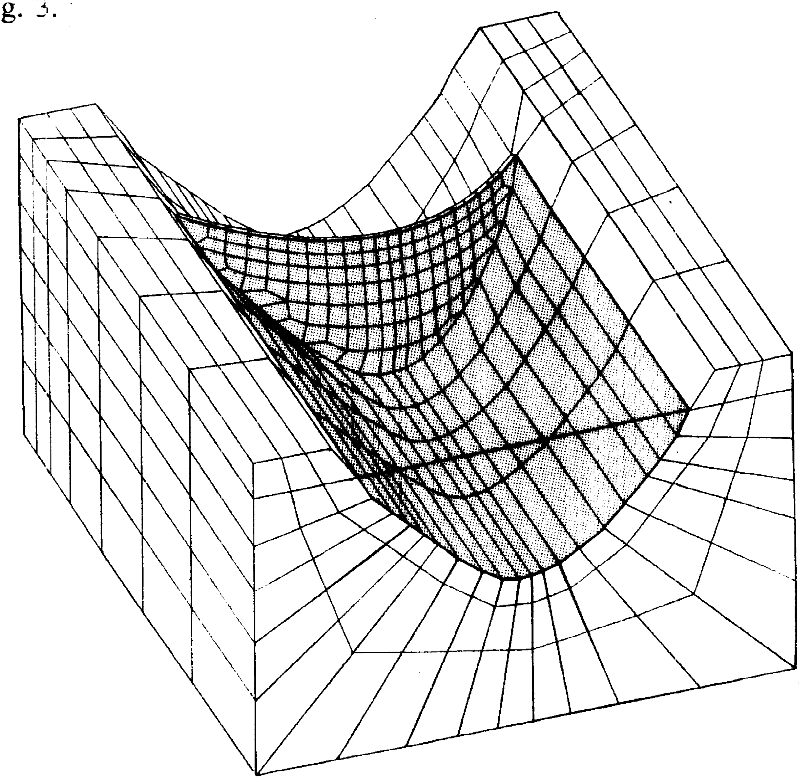


Fig. 2. Schematic representation of the different hypotheses for both mathematical models used.

The discretization of the dam-foundation-reservoir system and the main parameters of the F.E. model are presented in Fig. 3.



$E_c = 37\ GPa$

$E_r = 2\ E_c$

$\gamma_c = 24\ kNm^{-3}$

$\tau = 5\%$ (*seismic action*)

Fig. 3. Three-dimensional F.E. model of the system dam-foundation-reservoir.

The dam and the rock foundation block were discretized with cubic 3D subparametric F.E. of 8 nodes (3 displacements D.O.F.per node). The reservoir was discretized with cubic F.E. of 8 nodes (1 pressure D.O.F. per node).

The concrete was assumed elastic with a Young's modulus E of 37 GPa (approximately the static modulus) and the rock foundation was also assumed elastic with a Young's modulus twice the one of the concrete. Both were assumed with a Poisson's ratio $\nu=0.2$. The concrete was assumed with a dead weight γ of 24 kN/m^3 and in what concerns the foundation rock two hypotheses were assumed: i) massless foundation and; ii) foundation with mass with a dead weight equal to the one of the concrete.

The viscous modal damping of the structure was assumed equal to 5% for both hypotheses of massless foundation and foundation with mass when analyzing the response to an earthquake, for all the computed structural vibration modes. The viscous modal damping of the structure chosen to fit the transfer functions obtained in the forced vibration tests were 0.8% for all the computed vibration modes in the case of foundation with mass and 1% for the 1st vibration mode and 2% for the 2nd and other computed vibration modes in the case of massless foundation. In the computations 100 reservoir vibration modes and 50 structural vibration modes were used in the case of massless foundation, and 250 structural vibration modes in the case of foundation with mass.

COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS. FORCED VIBRATION TEST.

The reliability of the mathematical model was checked against the experimental data obtained in a forced vibration test of Alto Lindoso arch dam. In this paper the results for full reservoir conditions are presented.

The forced vibration tests consist of loading the dam with harmonic horizontal forces at several frequencies. This forces were generated by an eccentric mass shaker with a single harm which produces a maximum force of about 50 kN in a frequency range between 1 and 7 Hz. Velocity transducers were used at 7 points as shown in Fig. 4.

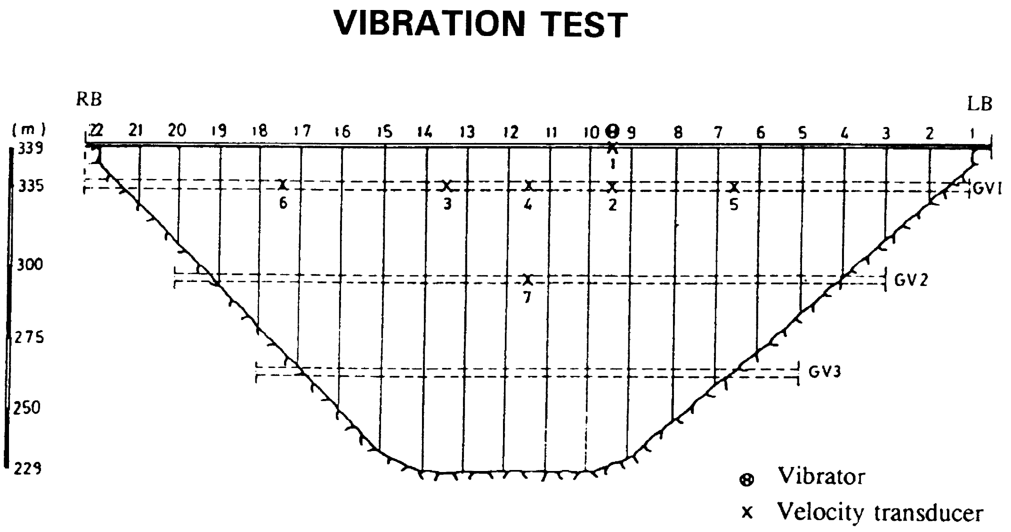


Fig. 4. Position of the eccentric mass shaker and velocity transducers.

The time series obtained in the forced vibration tests were treated by means of a computer code in order to obtain the transfer functions. The two hypotheses of massless foundation and foundation with mass were used in the numerical computations. In Fig. 5 the numerical and experimental results were compared in terms of the transfer function of force applied by shaker to the radial displacement of a point near the shaker position. The measured frequencies of the 1st and 2nd resonances are approximately equal to the computed ones, as well as the height of the correspondent peaks.

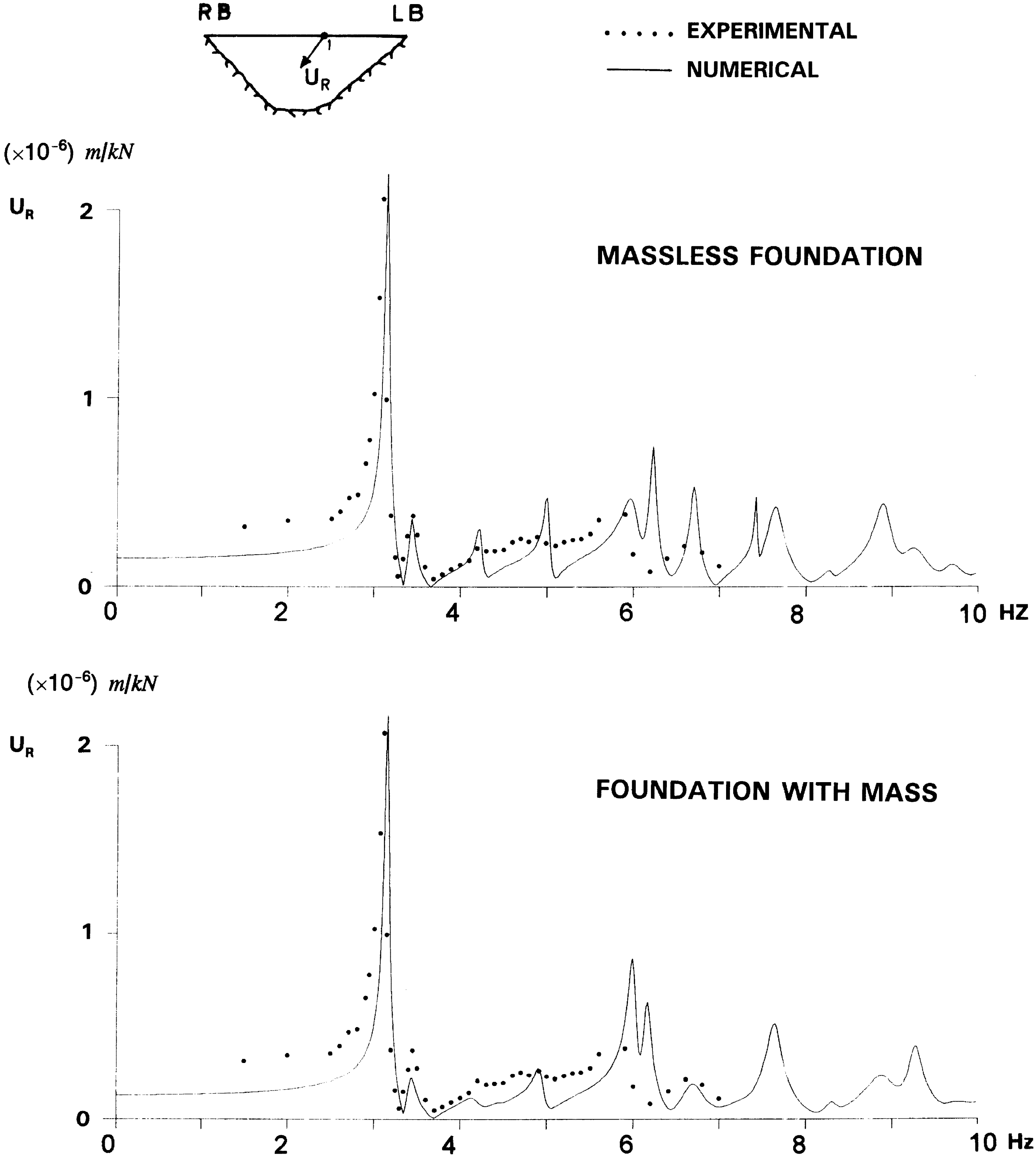


Fig. 5. Transfer function of force to radial displacement for point 1. Comparison of the experimental and numerical results.

SEISMIC RESPONSE. NUMERICAL RESULTS OBTAINED WITH THE HYPOTHESIS OF MASSLESS FOUNDATION AND FOUNDATION WITH MASS

It was computed the response of the arch dam to a seismic action given by the density power spectrum of accelerations showed in Fig. 6, cut at the frequency of 10 Hz. The input was assumed horizontal and independent at two orthogonal directions. The density power spectrum of velocities is obtained by multiplying the density power spectrum of accelerations by the inverse of the square of the angular frequency.

After computing the covariance matrix of the modal coordinates and of its time derivatives, the median of the peak of the stresses during the earthquake is computed by Cramer rule.

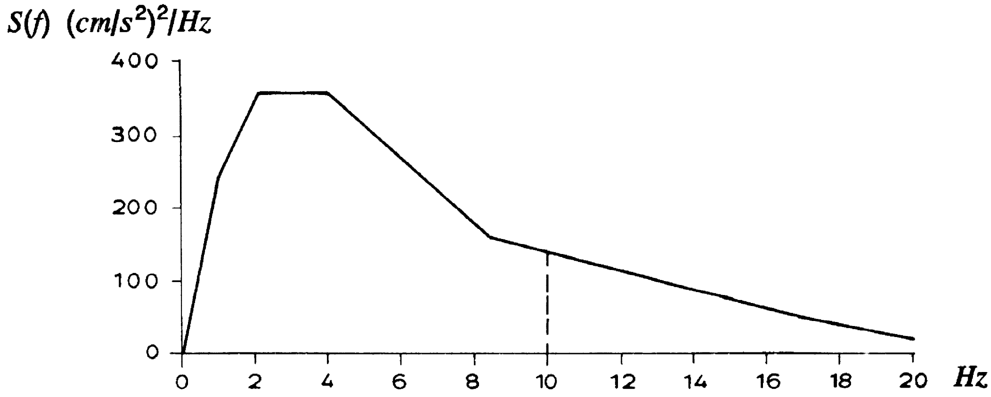


Fig. 6. Seismic action. Acceleration density power spectrum.

Fig.7 presents the peak of hoop stresses at the crest arch at the downstream face and at the upstream face, for both hypotheses of massless foundation and foundation with mass.
The peak stresses for the two models are a bit different in amplitude although they have approximately the same shape. This is owing to the differences of the two models namely the ones related with the input and the ones related with the boundary conditions. In the model with massless foundation the accelerations are prescribed at the boundary of the foundation block and in the model of foundation with mass it is the velocities of the incident waves that are prescribed at the foundation boundary. On the other hand, in the first model the foundation boundary is fixed and in the second one the foundation boundary is assumed transparent for the outgoing waves.

CONCLUSIONS

The computer transfer functions from forces applied by shaker to radial displacements fit well the experimental data, obtained during forced vibration tests, for the two models of massless foundation and foundation with mass.

The structural modal damping coefficients are different for each model because: i) the vibration modes of the massless foundation model cannot be compared with the vibration modes of the foundation with mass model; and ii) in the massless foundation model there is no radiation damping at the boundary of the rock foundation block and in opposition with what happens in the foundation with mass model;

The numerical seismic responses are computed in the assumption that the structural viscous damping is higher than the structural damping measured during the forced vibration test which seems reasonable taking into account that the seismic vibrations are much more intense than the vibrations induced by the shaker.

The seismic responses computed with each model are a bit different owing to the differences of the two models namely the ones related with the input and the ones related with boundary conditions. So experimental data from monitoring prototypes dynamic behaviour during earthquakes is needed in order to calibrate both models for seismic actions and to assess their reliability.

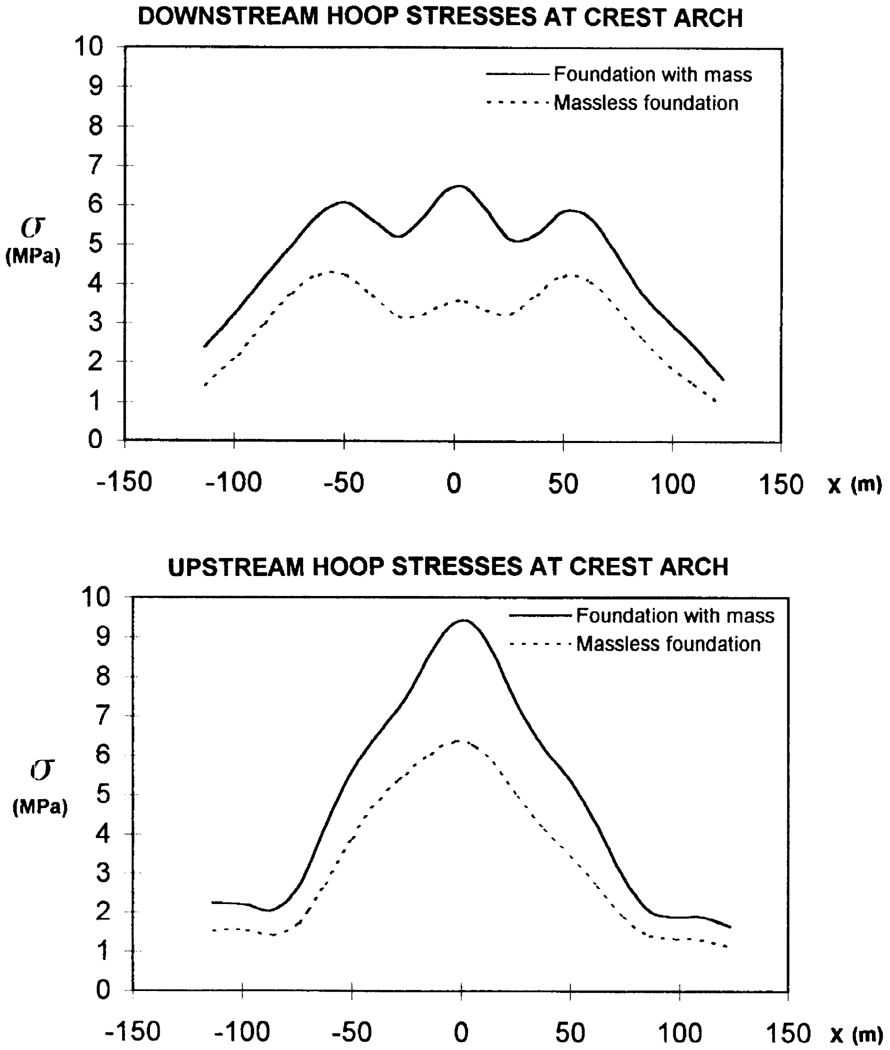


Fig. 7. Seismic action. Peak hoop stresses at crest arch.

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