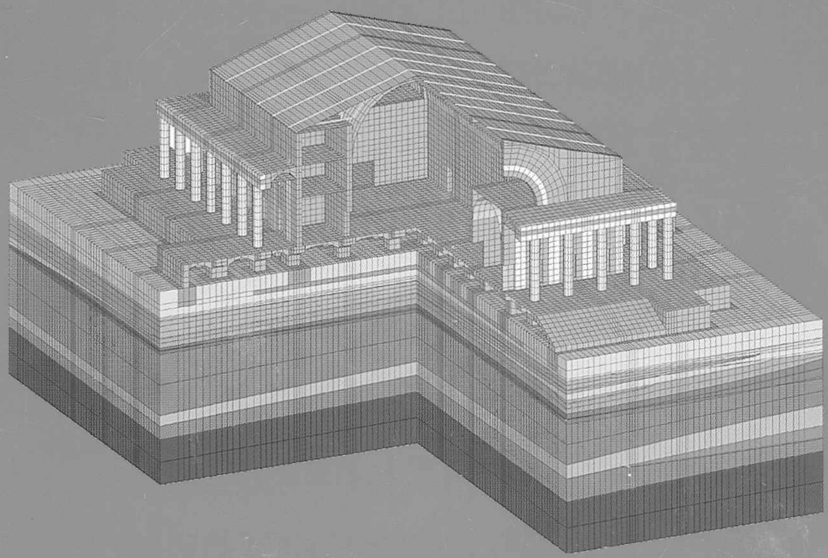

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# SOIL-STRUCTURE INTERACTION: CALCULATION METHODS AND ENGINEERING PRACTICE

## Volume 1

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# SOIL-STRUCTURE INTERACTION: CALCULATION METHODS AND ENGINEERING PRACTICE

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## Section 2. Soil-structure interaction under dynamic loads

# Analysis of the seismic response of arch dams. An application of Boundary Element Method.

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ABSTRACT: The effects of ground motion spatial variation, the canyon geometry and the bottom sediments on the seismic response of arch dams is studied in this paper. To do so, a three-dimensional boundary element model which allows for the rigorous representation of the dynamic interaction between de dam, the foundation rock, the water and the bottom sediment is used. The dam and the unbounded foundation rock is modeled as a viscoelastic solids, the water reservoir as a compressible fluid and the bottom sediment as a two-phase poroelastic domain. The analysis is carried out in the frequency domain considering time harmonic excitation due to longitudinal, shear and Rayleigh waves impinging the dam site from different directions.

## 1. INTRODUCTION

The seismic response of arch dams is conditioned by a series of characteristic of the foundation-dam-reservoir system in addition to the dam geometry and its material properties. Three kinds of factors can be mentioned:

1.- Factors related to the location, geological and geotechnical characteristic of the site and local topography.

2.- Factors having a direct influence on the hydrodynamic pressure, e.g., reservoir geometry and bottom sediments.

3.- The space distribution of the excitation. This effect depends of the size of the dam and the type, frequency and direction of the waves.

An analysis of the influence of these factors was done by the Authors using a three-dimensional boundary element model in the frequency domain. See e.g., Maeso & Domínguez (1993), Domínguez & Maeso (1993), Maeso et al. (2002), Maeso et al. (2004) and Aznárez et al. (2005).

In this paper, this boundary element model for the seismic analysis of arch dams is shown. The model is fully three-dimensional and is able to represent properly the dam-water-foundation interaction, the effects related to the location, reservoir geometry, bottom sediments and space distribution of the excitation.

## 2. BOUNDARY ELEMENT MODEL

A dam – reservoir – sediment - foundation rock system with realistic geometry is studied. The Morrow Point Dam has been selected following the previous work of Hall & Chopra (1983) and Fok & Chopra (1987). This dam is a quasi-symmetric 142 m high arch dam that is assumed symmetric for the present study. The canyon and surface topography are also symmetric.

The dam concrete is assumed to be a linear isotropic viscoelastic material with the following properties: density $\rho_d$ = 2481.5 kg/m$^3$, Poisson's ratio $\nu_d$ = 0.2, shear modulus $G_d$ = 11500 MPa and internal damping ratio $\xi_d$ = 0.05. The foundation rock is also assumed to be linear viscoelastic with the same shear modulus, Poisson's ratio and damping ratio as the dam concrete and density $\rho_f$ = 2641.65 kg/m$^3$. Water is assumed to be an inviscid compressible fluid under small amplitude motion with density $\rho_w$ = 1000 kg/m$^3$ and pressure wave velocity $c_w$ = 1438 m/s.

The bottom sediment is considered as a two-phase porous material whose behavior is represented by Biot´s theory (Biot, 1956). The properties of this region will be presented in another section

All domains (dam, reservoir, foundation and sediments) are discretized using boundary elements. Two types of elements are used in this model: nine node quadrilateral elements and six node triangular elements. Both of them have quadratic variation of geometry and boundary variables. No free surface elements are required for the water since the fundamental solution satisfying the zero pressure condition on the surface has been used.

Boundary equations are written for the four different regions and coupling conditions (equilibrium of traction and pressure and displacement compatibility) are imposed at the interfaces.

## 3. SEISMIC EXCITATION AND RESPONSE QUATITIES REPRESENTED

The different excitation cases analyzed are summarized in Figure 1. The coordinate origin is located at the midpoint of the dam crest with the $x$ axis along the canyon axis and the $y$-$z$ plane tangent to the dam midsurface. Plane harmonic waves impinging the dam site from infinity with directions contained in the vertical $y$-$z$ plane and forming an angle $\theta$ with the horizontal directions are considered. Three types of these waves are considered: SH waves, SV waves and P waves. The effect of the spatial distribution of Raleigh surface waves is also studied. Waves propagating upstream and downstream forming different angles with the canyon axis are considered.

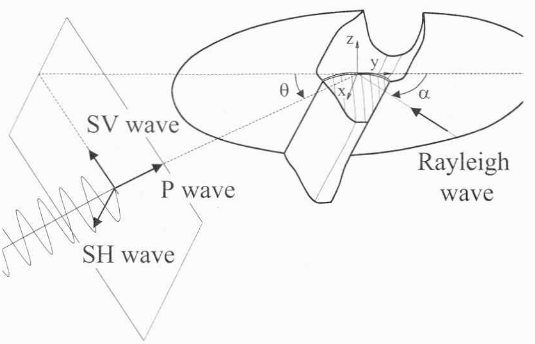


Figure 1. Description of the problem. Plane waves impinging the dam site.

The amplitudes of the complex-value frequency-response functions are represented. They are acceleration components of points located at the dam crest on the upstream face of the dam due to harmonic waves that would produce unit ground acceleration at the coordinate's origin of the foundation rock were a uniform halfspace. The upstream acceleration ($x$ axis) of the dam crest point located at the plane of symmetry ($x = y = z = 0$) is shown for SH, P and Rayleigh waves. For SV-waves excitation, the upstream acceleration of the dam crest point located at an angle of $13.25^{\circ}$ from the plane of symmetry is shown.

In each case the amplitude of the acceleration in plotted versus dimensionless frequency for a significant range. The dimensionless frequency for SH, P and Rayleigh wave excitation is defined as $\omega/\omega_{1S}$, where $\omega$ is the excitation frequency and $\omega_{1S}$ the fundamental resonant frequency of the dam on rigid foundation and empty reservoir conditions for a symmetric mode. For SV wave excitation, the dimensionless frequency is $\omega/\omega_{1A}$, where $\omega_{1A}$ is the fundamental resonant frequency of the dam on rigid foundation and empty reservoir conditions for antisymmetric mode.

## 4. EFFECTS OF CANYON SHAPE ON DAM RESPONSE.

The analysis of influence of the canyon geometry is done using the boundary element discretization shown in Figure 2. Three canyon shapes are considered. The first is a 142 m deep canyon (*Canyon 1*), the second a 284 m deep canyon, double of the first, (*Canyon 2*) and a third one where the canyon width gradually increases upstream of the dam (*Canyon 3*). Two different situations are considered: empty reservoir and full reservoir. In both cases, reservoirs without sediments are considered in this section.

For a full reservoir conditions, in the three canyon shapes, the reservoir is assumed to extend from the end of the BE models to infinity as a water channel with uniform cross-section. This assumption is obviously geometrically unrealistic, however, in the present model, it is only used at a rather distance of the dam and the only purpose is to represent the water wave radiation out of the region close to the dam. To represent this condition, an absorbing boundary in the water channel is used (Domínguez, 1993) as shown in the BE mesh of Fig.2.

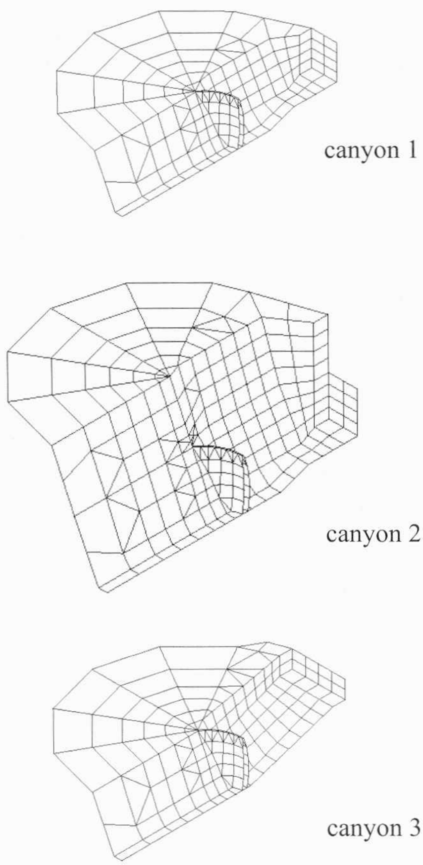


Figure 2. Boundary element model for arch dam on compliant foundation rock. Effects of the canyon shape.

Figs. 3 and 4 show the dam crest amplification for the three canyon geometries in empty and full reservoir conditions, respectively, and vertical SH wave coming vertically ($\theta$=90°).

The influence of the canyon shape is relevant when the reservoir is full as can be seen from the figures. It should be noticed that the reservoir geometry is the same for *Canyon 1* and *Canyon 2* and the differences in the dam response are mainly due, also in this case, to the traveling wave and free-field amplification effects. However, the reservoir geometry is different in the case of *Canyon 3*. The main difference is on the depth of the reservoir at certain distance from the dam. This fact produces a certain increase in the first natural frequency of the system.

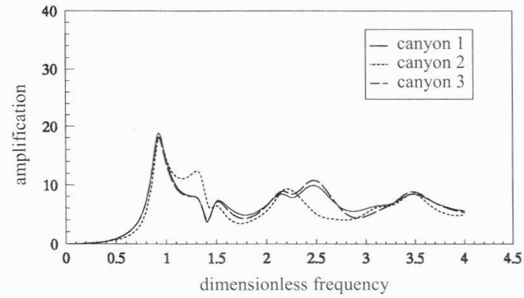


Figure 3. Response at dam crest to SH-wave excitation for different canyon geometries. Empty reservoir. Incident angle: $\theta = 90°$.

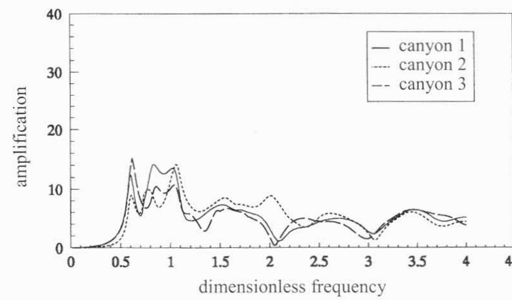


Figure 4. Response at dam crest to SH-wave excitation for different canyon geometries. Full reservoir. Incident angle: $\theta = 90°$.

## 5. EFFECTS OF SPACE DISTRIBUTION OF EXCITATION.

When seismic waves impinge on a large dam, the excitation of the dam-foundation rock interface is not uniform. Different points along this interface are under the effect of different foundation acceleration values at the same time. In other words, the seismic waves travel along the dam-foundation rock interface. The importance of this effect depends of the dam size, the length of the seismic waves and its direction of propagation. How it will see, the assumption of an uniform excitation along the dam-foundation rock interface may lead to erroneous consequences.

In this section, some numerical examples are presented to show the influence of the angle of incidence of the waves on the seismic response of the dam. Results of amplification at the dam crest to SH, SV waves propagating in the *y-z* plane and arriving to the dam site with different angles θ, are shown in Figures 5, 6 respectively. Result of amplification for Rayleigh wave with incident angle α are shown in Figure 7. In all this examples, the canyon shape corresponds to *Canyon* 1 and the reservoir is full of water. The response of rigid foundation conditions is also included in figures for SH and SV excitations.

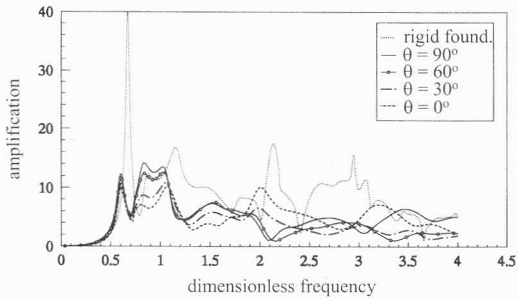


Figure 5. Travel wave effect. Response at dam crest to SH-wave excitation. Full reservoir.

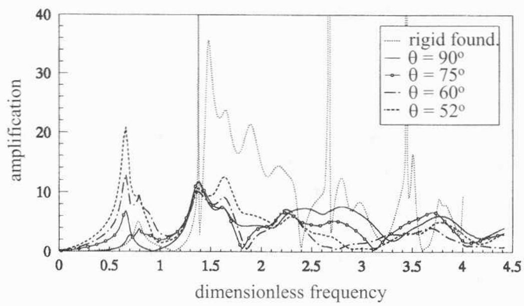


Figure 6. Travel wave effect. Response at dam crest to SV-wave excitation. Full reservoir.

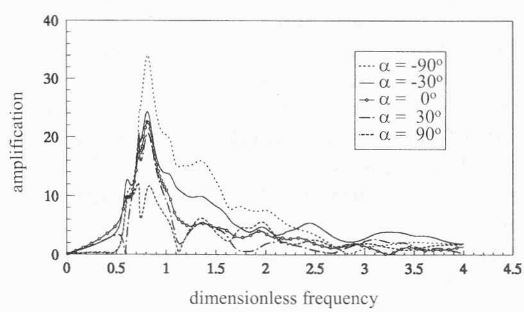


Figure 7. Travel wave effect. Response at dam crest to Rayleigh wave excitation. Full reservoir.

It is clear from Fig. 5 (SH-wave) that foundation rock flexibility reduces the amplitude of the resonance peaks and the first natural frequency. In addition to that, the traveling wave effect and the angle of incidence of the wave modify the response in all the frequency range represented. For SV-waves (Fig. 6) (critical angle = 52°) and Rayleigh waves (Fig. 7) the effect of the angle of incidence is more important. For SV-waves a very important increase of the response at the fundamental frequency takes place as the angle of incidence decreases. For Rayleigh waves the amplitude of the dam motion increases substantially as α tends to -90° for an important part of the frequency range. In particular, for frequencies close to the dam fundamental frequency. The effect of the angle of incidence is smaller and it is reduced to a smaller frequency range for upstream propagating waves than for downstream propagating waves. Notice that the scattering effect of the reservoir and the phase difference between displacement components are different in these two cases.

Similar conclusions can be drawn for the response in the case of reservoir empty of water, not shown for sake of brevity.

## 6. EFFECTS OF RESERVOIR BOTTOM SEDIMENTS.

In this section, a porous sediment bottom layer with a depth equal to 20% of the maximum dam height, and extending in the upstream direction up to a distance of 172 m from the dam will be assumed. This bottom sediment is a two-phase poroelastic domain whose dynamic behavior is represented according Biot´s theory, with the following properties (taken from Bougacha & Tassoulas, 1991): porosity $\phi = 0.6$, shear modulus of the solid skeleton $G_s = 7.7037 \text{x}10^6$ N/m$^2$, Poisson's ratio $\nu_s = 0.35$, internal damping ratio of the solid skeleton $\xi_s = 0.05$, solid material density $\rho_s = 2640$ kg/m$^3$, pore water density $\rho_w = 1000$ kg/m$^3$, added density $\rho_a = 0$, and dissipation constant $b = 3.5316\text{x}10^6$ Ns/m$^4$ (corresponding to a permeability $k = 10^{-3}$ m/s). Two different saturation conditions are assumed: one is fully saturated sediment (Biot's constants $Q = 8.2944\text{x}10^8$ N/m$^2$ and $R = 1.24416\text{x}10^9$ N/m$^2$); the other, is partially saturated sediment with a saturation degree 99.5%, and Biot's constants $Q = 8.9328\text{x}10^7$ N/m$^2$ and $R = 1.3399\text{x}10^8$ N/m$^2$.

The boundary element discretization of the dam-water-sediment-foundation system is shown in Figure 8. In this model, the canyon shape corresponds to *Canyon 1* in Fig.2.

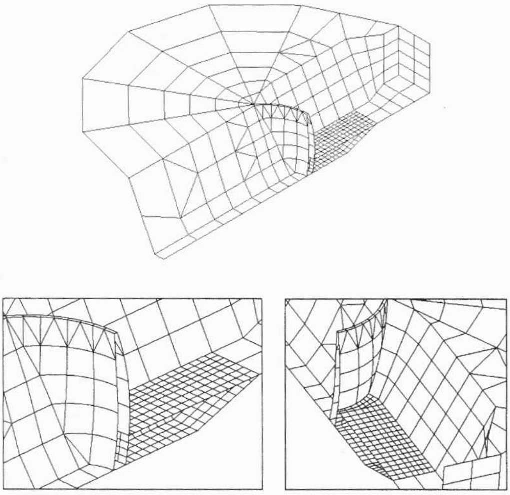

Figure 8. Boundary element model for coupled dam-water-sediment-foundation rock system.

The short wavelength in porous sediments determines the size of the element used in the discretization of this region. The use of non-conforming elements simplifies the mesh definition.

The sediment effects on the response has been analyzed by others authors (see e.g.: Cheng, 1986 and Domínguez et al., 1997). Those authors concluded that bottom sediments can change the dynamic behavior of the system, in particular when they are partially saturated (presence of undissolvable gases in the sediment). The Figures 9 and 10 shows this effect for the response of arch dams. These figures show the dam crest amplification for vertical SH and P waves respectively. Three different situations are considered: full reservoir without sediments, full reservoir with a fully saturated bottom sediment layer, and full reservoir with a partially saturated bottom sediment layer (99.5%).

It can be seen from figures that the existence of a fully saturated sediment layer has a very small influence on the system response. On the contrary, the effect of a partially saturated sediment layer is important. It reduces the first symmetric natural frequency, reduces the peak amplitude at that frequency, changes the position of other natural frequencies and reduces the system amplification at higher resonant frequencies except for some parts of the upstream (SH-wave) excitation case.

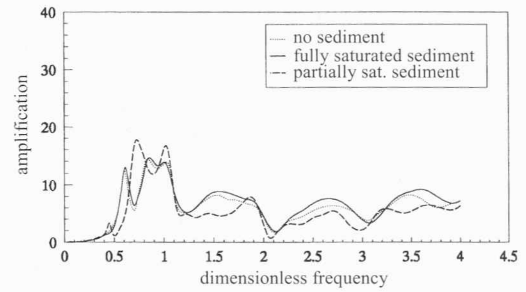


Figure 9. Influence of sediment saturation degree. Response at dam crest to SH-wave excitation. Incident angle: $\theta = 90^{o}$.

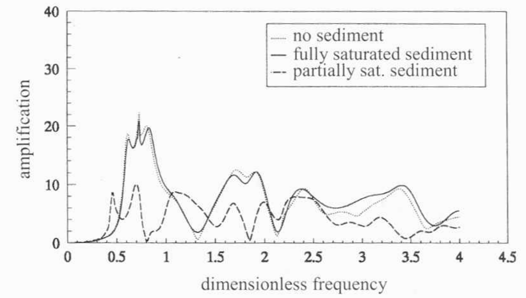


Figure 10. Influence of sediment saturation degree. Response at dam crest to P-wave excitation. Incident angle: $\theta = 90^{o}$.

## 7. SUMMARY AND CONCLUSIONS

A three-dimensional boundary element technique for the seismic analysis of arch dams including dam-reservoir-bottom sediment-foundation rock interaction has been presented in the present paper.

The model presented clearly exploits two of the advantages of Boundary Elements: one is that only the boundary has to be discretized; and the other, that the foundation rock boundary discretization can be left open with automatic satisfaction of the radiation conditions, and without spurious wave reflection. These two advantages make possible to accomplish a realistic representation of the actual geometry and the three-dimensional effects existing in this kind of problems.

The main factors affecting the seismic response of arch dams have been briefly studied: the canyon geometry, the spatial variation of the excitation and bottom sediments. In addition to other phenomena such water compressibility, foundation rock flexibility have a significant influence on the dam response. The boundary element model used in this paper allows for a realistic representation of all these phenomena.

The effect of the spatial variation of the excitation has been studied by considering different types of harmonic waves impinging the dam from different directions. P-waves, SV-waves, SH-waves and surface Rayleigh waves have been considered. The obtained results show that the direction of propagation of the exciting wave has an important influence on the seismic response of the dam in particular in cases where the reservoir is full. The amplification of the seismic motion is particularly sensitive to the angle of incidence of the waves in the vicinity of the system fundamental frequency, which in most cases is where the amplification of the seismic motion is higher.

The main factors affecting the hydrodynamic pressure on a dam has shown in the results presented. The canyon depth and the reservoir geometry have an important influence on the global dam response. The existence of a partially saturated sediment layer changes very significantly the hydrodynamic pressure on the dam and consequently its response. Therefore, the seismic analysis of a 3-D arch dam requires the identification of bottom sediments, the adequate evaluation of their properties (in particular saturation degree and consequently compressibility), and the use of a numerical model which includes proper representation of these bottom sediments.

## 8. ACKNOWLEDGEMENTS

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