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A 3-D boundary element model for the dynamic analysis of arch dams with porous sediments

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Abstract

A three-dimensional boundary element technique for dynamic analysis of arch dams including dynamic interaction and sediments on the bottom of the reservoir is presented. The dam and the foundation rock are assumed to be viscoelastic domains with linear behaviour. The water is assumed to be compressible and the sediment is considered as a two-phase poroelastic material according to Biot´s theory. The four domains (dam, foundation rock, water and bottom sediments) are discretized and the interaction between them is rigorously represented. The effects of sediments on the dynamic response of arch dams are evaluated for rigid and compliant foundation. Upstream, vertical and cross-stream excitation are considered. The influence of the degree of saturation of the sediment is analysed. Other modelling of the sediment as a single-phase scalar medium are considered in order to reduce the degrees of freedom of the system.

1 Introduction

The knowledge of the dynamic response of arch dams has experienced a great progress in the last decade. In spite of it, there are some important effects that may influence the dynamic behaviour of the dam and are not well evaluated yet. The existing numerical models for earthquake analysis of this kind of dams include important simplifications that may lead to non-realistic results.

One of the important matters that required some additional research efforts is the effects of bottom sediments on the seismic response. It has been shown that the sediment deposited at the bottom of the reservoir can have an important effect on the response of dams especially when these are partially saturated (Cheng [1]).

Fenves and Chopra [2] were the first to present a model that included reservoir bottom absorption for seismic analysis of gravity dams.

More recently, Domínguez et al. [3] presented a two-dimensional Boundary Element model with poroelastic sediments for the analysis of gravity dams. In this model the interaction effects among different mediums (dam-water-foundation-sediment) are taking into account rigorously.

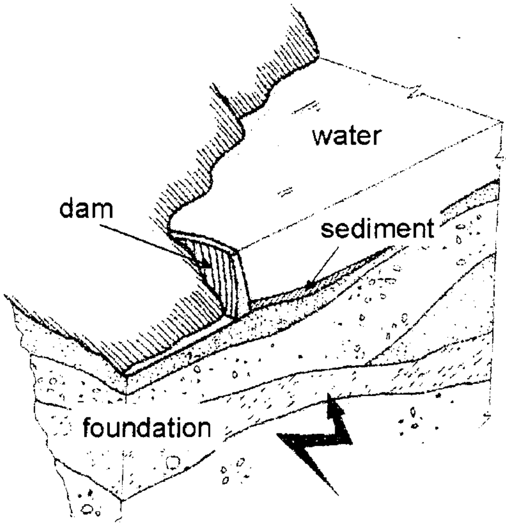

Figure 1: Dam-water-sediment-foundation rock system.

In present paper a three-dimensional Boundary Element (BE) model for dynamic analysis of arch dams that include the bottom sediments effects is presented. Like in [3], the sediment is into account using a rigorous representation of it as a fluid-filled poroelastic medium whose behaviour is governed by Biot's equations [4]. The subsequent boundary integral formulation of the problem (Domínguez [5]) includes all the materials parameters as added density and the dissipation coefficient. The dynamic behaviour of the water, the dam and the foundation are also represented using the Boundary Element Method (Maeso and Domínguez [6] and Domínguez and Maeso [7]). Recently, the authors of this paper presented preliminary results for dams on rigid foundations with this model [8].

2 Boundary element model

A representation of the dam-water-foundation-sediment system is shown in Fig.1. This system includes several domains with different properties and behaves in different way. An integral equation formulation and boundary element discretization is done for dam, water, foundation rock and bottom sediments. The dam and foundation rock are considered viscoelastic domains with linear behaviour. The water is assumed to be an inviscid fluid subject to small-motion pressure waves, thus the hydrodynamic pressure is governed by scalar wave equation. The sediment is assumed a poroelastic material whose behaviour is governed by Biot's equations. The interaction effects are rigorously take into account by satisfying equilibrium and compatibility over the interfaces.

The Morrow-Point arch dam (142m. high) was chosen for the numerical analysis of the influence on the response of the bottom poroelastic sediments. Geometry of the dam and the cannon, and material properties were taken from Hall & Chopra [9]. The concrete dam has the following properties: density $\rho=2481.5$ kg/m^3, Poisson's ratio $\nu=0.2$, shear modulus $\mu=11500$ Mpa , and internal damping factor $\beta=0.05$. The foundation rock has a density $\rho=2641.65$ kg/m^3 and Poisson's ratio, shear modulus and internal damping factor as for the dam concrete. The water has a pressure wave propagation velocity equal to 1438 m/s and density $\rho=1000$ kg/m^3.

The sediment is a poroelastic material with porosity $\phi=0.6$, shear modulus of the solid skeleton $\mu=7.7037\times10^6$ N/m^2, Poisson's ratio $\nu=0.35$, internal damping factor in skeleton $\beta=0.05$, density of the solid grains of skeleton $\rho_s=2640$ Kg/m^3, density of the pore fluid (water) $\rho_w=1000$ Kg/m^3 , and Biot's constants $b=3.5316\times10^6$ Ns/m^4 (dissipation constant corresponding to a permeability equal to 10^{-3} m/s), $Q=8.2944\times10^8$ N/m^2 , and $R=1.24416\times10^9$ N/m^2 (both corresponding to a fully saturated sediment).

For partially saturated sediment, the effective bulk modulus of the pore fluid changes (Verruijt [10]). In this case and assuming a degree of saturation of 99.5%, $Q= 8.9328\times10^7$ N/m^2 and $R= 1.3399\times10^8$ N/m^2.

The BE discretization used for the analysis is shown in figure 2 where due geometrical symmetry, only one half of the model is presented. Two types of elements are used: nine nodes quadrilateral elements and six nodes triangular elements, both of them having quadratic variation of geometry and boundary variables. The foundation rock free surface is discretized up to a distance approximately equal to 2.5 times the dam height. Other studies of this geometry ([6],[7]) show that more extensive boundary discretizations leads to very similar results. The effects of the downstream cannon geometry at that distance from the dam are also negligible.

The fluid domain is discretized into boundary elements on the water-dam, water-foundation and water-bottom sediments interfaces only. On the other hand, an infinite channel with uniform cross section is used to represent the far field wave radiation effects in the reservoir.

The maximum size of the elements on the boundaries is determined by the wavelength of the waves in each medium. In this case, the properties of the sediment force to use an element size smaller than in soil or water boundaries.

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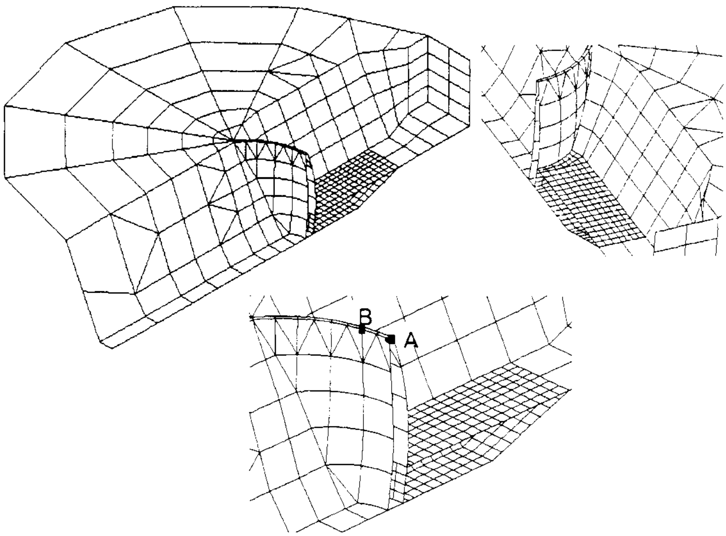

Figure 2: BE discretization including bottom sediments.

An incident field of time-harmonic waves coming from infinity is assumed. The problem is solved in terms of scattered field, so the radiation conditions are satisfied. For the sake of simplicity only P- or S- waves propagating vertically are considered (other kinds of excitations can be easily considered). These waves produce vertical, up-steam, or cross-stream surface motion. The response of the dam is determined in terms of amplitude of upstream acceleration, frequency-response functions, of two points at the dam crest, relative to the free field surface ground motion. The upstream acceleration of the point located on the plane of symmetry (point A in figure 2) is shown for the vertical and up-stream excitations, and the point at an angle of 13.25° from that plane (point B) for the cross-stream excitation. The amplitude of acceleration is plotted versus the excitation frequency normalized by the fundamental frequency of the dam with empty reservoir on rigid foundation, taking the first symmetric mode for the vertical and upstream excitations, and first skewsymmetric mode for the cross-stream excitation.

Two foundation conditions under the dam-reservoir system are considered: rigid foundation and uniform viscoelastic half-space with the given properties.

3 Dam on rigid foundation

In this case, neither dam-foundation rock interaction nor water- foundation rock interaction exist. Thus the effects of bottom sediments are particularly clear.

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Figures 3, 4 and 5 show the dam crest amplification for full reservoir under upstream, vertical, and cross-stream excitation, respectively. Three different situations are represented: no sediment, fully saturated sediment and partially saturated sediment. The sediment depth is equal to 0.2 the dam height (Figure 2). It can be seen from the figures that the existence of a saturated sediment does not change substantially the response; however, the partially saturated sediment modifies the response by shifting the resonance peaks and changing the amplitude of many of them. It can be concluded that the degree of saturation of the sediment should be carefully evaluated.

Two simplified mono-phase scalar models for the sediment are tested. Both have the same density as the poroelastic material. The first model (Model 1) has a pressure wave velocity at each frequency equal to the fastest wave velocity of the poroelastic material. The second scalar model (Model 2) has a pressure wave velocity with the same real part as that of model 1 and an imaginary part that would correspond to the internal damping of the solid skeleton (5%).

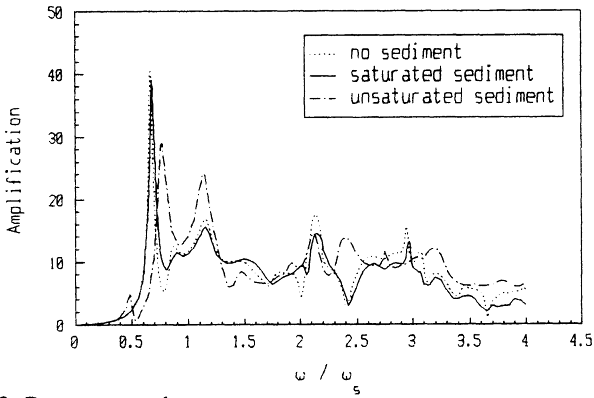

Figure 3: Response at dam crest to upstream excitation, rigid foundation.

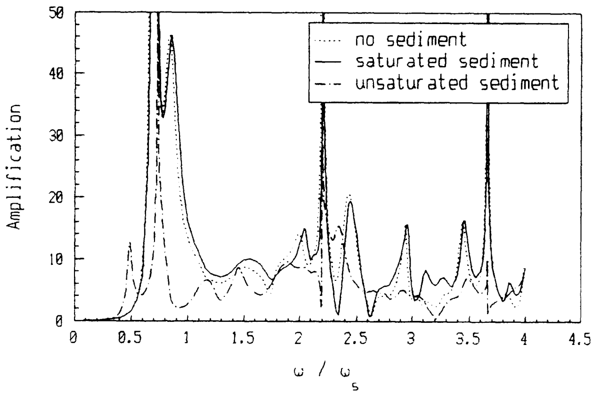

Figure 4: Response at dam crest to vertical excitation, rigid foundation.

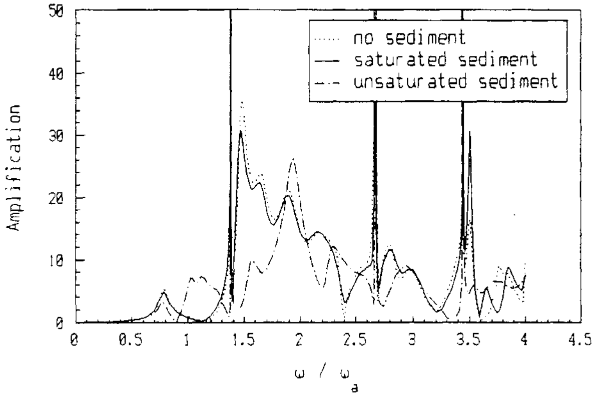

Figure 5: Response at dam crest to cross-stream excitation, rigid foundation.

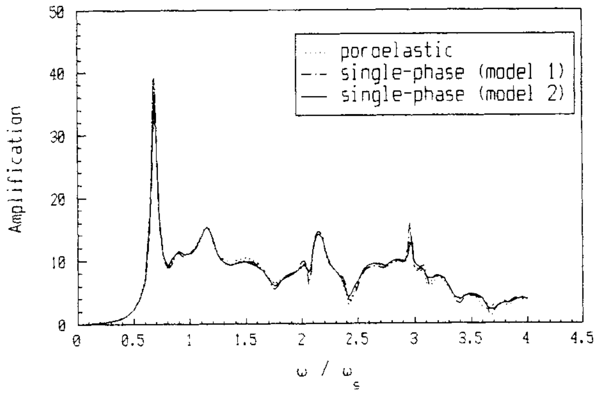

Figure 6: Upstream excitation, rigid foundation, fully saturated sediment.

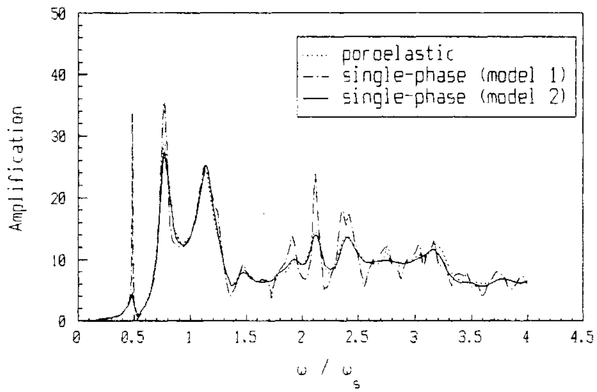

Figure 7: Upstream excitation, rigid foundation, partially saturated sediment.

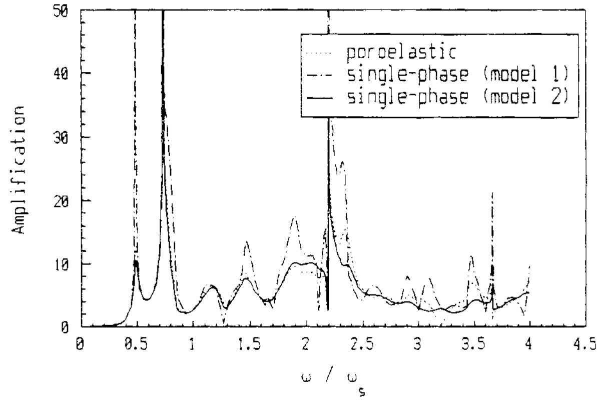

Figure 8: Vertical excitation, rigid foundation, partially saturated sediment.

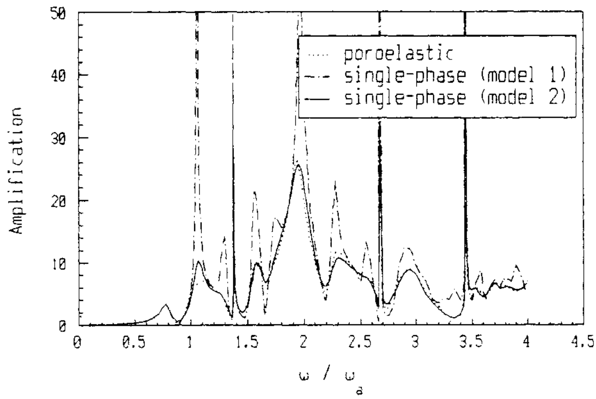

Figure 9: Cross-stream excitation, rigid foundation, partially saturated sediment.

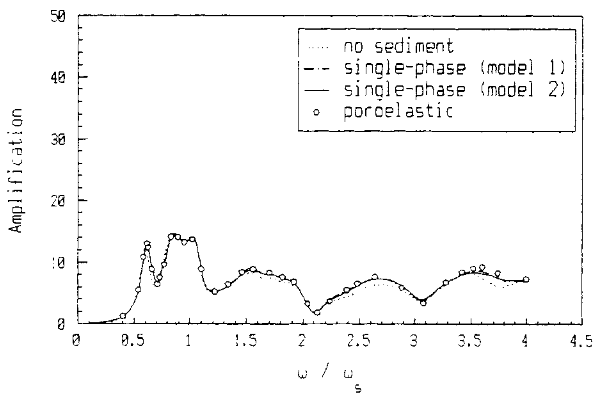

Figure 10: Upstream excitation, compliant foundation, fully saturated sediment.

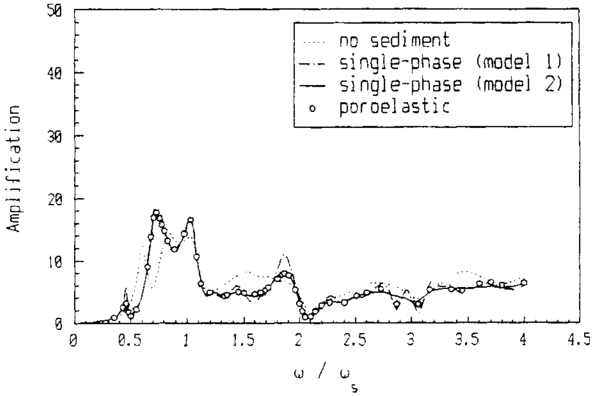

Figure 11: Upstream excitation, compliant foundation, partially sat. sediment.

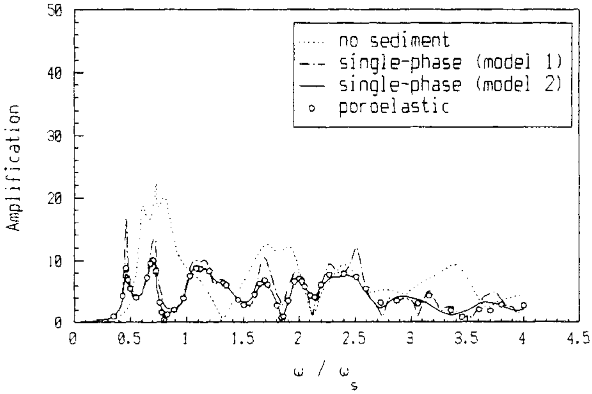

Figure 12: Vertical excitation, compliant foundation, partially sat. sediment.

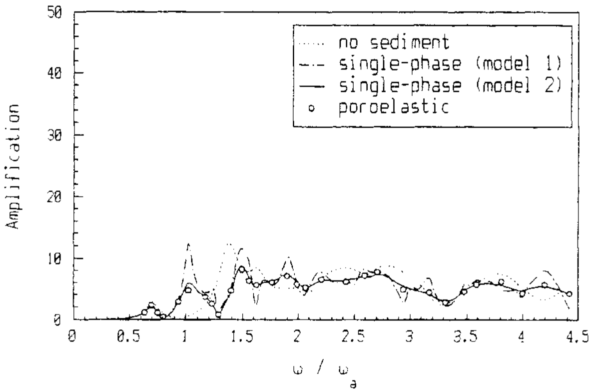

Figure 13: Cross-stream excitation, compliant foundation, partially sat. sediment.

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Figure 6 shows a comparison of the three models for upstream excitation when the sediment is saturated. The response is very similar for the porous material model and the two simplified models. The same behavior is observed for other excitations. The behavior of the two simplified models is not so similar when the sediment is only partially saturated as shown in Figures 7,8 and 9 for full reservoir under upstream, vertical, and cross-stream excitation, respectively. In such cases, Model 2 reproduces rather accurately the actual behavior of the porous material whereas Model 1 presents spurious oscillations and lower damping than the porous model.

4 Dam on compliant foundation

The effects of a saturated sediment on the response to upstream excitation are shown in Figure 10. The figure shows that the effects are very small in this case and consequently both simplified models produce correct results.

On the contrary, the effects of partially saturated sediments are significant as shown in Figures 11, 12 and 13, where the dam crest amplification for full reservoir under upstream, vertical, and cross-stream excitation, respectively, is represented. A partially saturated sediment modifies the resonance frequencies of the system and reduces the peak values. It is also appreciated in the figures that simplified scalar Model 1 yield an under-damped response whereas Model 2 yields accurate results as compared to the porous model.

5 Conclusions

A three-dimensional boundary element model for the dynamic analysis of continuous systems consisting of water, viscoelastic and poroelastic zones of arbitrary shape has been applied to a dam-reservoir-sediment-foundation system subject to ground motion. The model includes bottom sediments, which are considered as a two-phase fluid-filled poroelastic medium, the dam and the foundation, which are considered as viscoelastic solids, and the water, which is considered as a compressible fluid. This model is used to evaluate the effects of fully and partially saturated sediments on the seismic response of arch dams. The following conclusions can to be drawn.

The sediments properties, particularly its compressibility and its degree of saturation, have a great influence on the dynamic response of arch dams-reservoir systems. The effect of fully saturated sediment is of a little importance for the layer thickness studied (0.2 times the dam height), specially when foundation flexibility be taken into account.

Partially saturated sediments produce important changes in the system response. Decrease of the symmetric system fundamental frequency, increase the response to upstream and cross-stream excitation at second frequency, and shifting of the higher resonance peaks for all kinds of ground motion are consequences of the existence of partially saturated sediment.

Simplified single-phase models of the poroelastic sediment have been evaluated. They can be adequate, both for fully saturated and partially saturated

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sediments. For the properties of sediment studied in this paper, the pressure wave velocity of the single-phase model should have the same real part as the faster longitudinal wave of the poroelastic model. If the sediment is partially saturated, it is important that the imaginary and part of the pressure wave is set to be able to represent the internal damping of the porous two-phase material.

Acknowledgments

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