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Model for the seismic analysis of arch dams including interaction effects

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ABSTRACT: A three-dimensional boundary element model for the seismic analysis of arch dams is presented. The soil and the dam are assumed to be viscoelastic domains the former being boundless. The water is assume to be compressible subject to small amplitude motions. The three domains are discretized into B.E. in a single model which includes a rigurous representation of the dam-foundation rock interaction, the water-foundation rock interaction and the traveling wave effects. The response of an arch dam (The Morrow Point dam) to harmonic waves propagating vertically is studied. The important influence of the abovementioned interaction and traveling wave effects is clearly shown by computed results. These results are in contrast with some obtained by other authors using a F.E. model.

1 INTRODUCTION

The analysis of the seismic response of dam-reservoir systems is an important problem within the field of earthquake engineering. The seismic response can not be studied considering the structure as an isolated body under the influence of a uniform base motion. There are important effects due to the space distribution of the excitation, the dam-water, dam-foundation and water-foundation interaction, that make necessary the use of models including the three media and the interaction between them. A great effort has been dedicated to this subject in the last two decades. The studies of Hall and Chopra (1983) and Fok and Chopra (1986) who analysed the significance of a number of factors contributing to the responsee shold be mentioned. Those studies have been done using the Finite Element Method.

The model of Fok and Chopra (1986) led to an extraordinary advance in the earthquake analysis of arch dams. However it still contains important simplifications which may give rise to unrealistic results. It's main simplifying assumptions and limitations are:

a) The model includes a massless foundations which is only justified by the necessity of representing a boundless compliant foundation using a finite model. The soil-structure interaction is not properly represented and the traveling wave effects can not be taken into account. Very recently Zhang and Chopra (1991) have started to analyse an alternative to this model of the foundation using a two-dimensional boundary integral formulation combined with a Fourier expansion.

b) A bottom absorption coefficient is used to represent the water-foundation interaction. It is based on the one dimensional representation of the wave reflection between the water and a uniform half-space.

c) The model does not take into account the joint water-foundation-dam interaction. The model of the foundation rock used for the interaction with the dam is independent of that used for the water-foundation rock interaction.

d) The assumption of an uniform cross section extending from the vicinity of the dam to infinity may

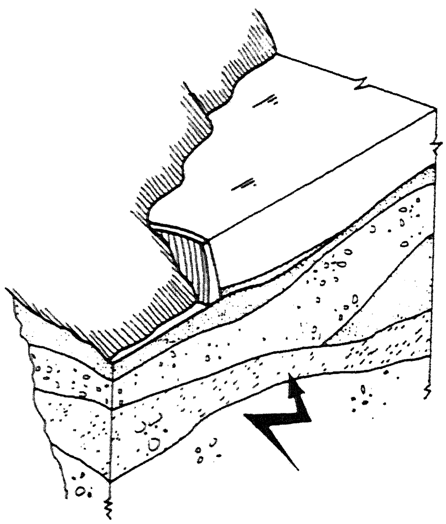

Fig.1. Arch dam-water-foundation system.

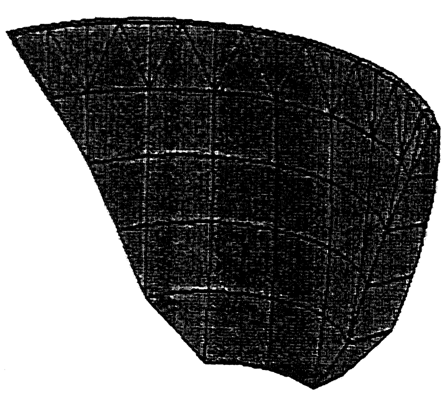

Fig.2. Boundary elements model of the arch dam substructure.

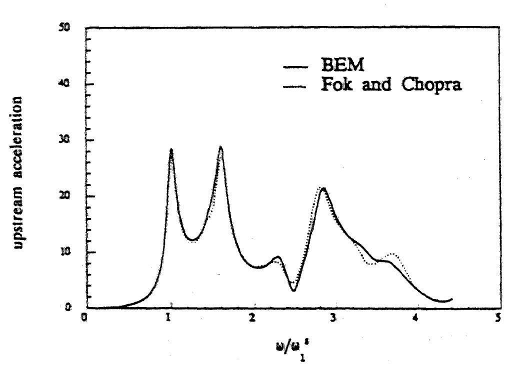

Fig.3. Upstream amplification. Rigid foudation, empty reservoir.

be far from the actual geometry of the reservoir and may lead to unrealistic results.

The technique presented in this paper uses a Boundary Element representation of the dam, the water and the foundation, which allows to avoid or reduce most of the abovementioned limitations. All the dynamic interaction and traveling wave effects are rigurously represented. The actual geometry of the reservoir can be discretized up to a significant distance from the dam.

2 MODEL FOR THE SOLID DOMAINS. EMPTY RESERVOIR ANALYSIS

The system to be studied includes several domains. A model of the whole system is required.

In the present paper the Morrow Point dam-foundation rock-reservoir system previously studied using F.E. by Fok and Chopra (1986) is considered. Because of the lack of space only a few cases of excitatin and reservoir conditions are presented. A more complete analysis can be seen in the two papers by Maeso and Dominguez (1993) and Dominguez and Maeso (1993). Time harmonic waves propagating vertically from the soil which produce a unit free field horizontal motion along the upstream direction are assumed. The dam is modeled as a viscoelastic domain using nine node quadrilateral and six node triangular elements with quadratic shapee functions in two directions both for the field variables and the geometry. Figure 2 shows the B.E. model for the dam. The properties of the concrete are: density = 2481.55 Kg/m^3; Poisson's ratio= 0.2; shear modulus= 11500 MPa and damping ratio = 0.05. Figure 3 shows the amplifications of the upstream motion at the dam crest versus frequency when the foundatin rock is assumed to be rigid and the reservoir empty. The results show a very good agreement with the F.E. ones obtained using shell elements (Fok and Chopra, 1986). The frequency is normalyzed by the first natural frequency of the dam and the dam crest acceleration by the horizontal acceleration produced by the incident waves at the soil free surface far from the dam.

The effect of the soil-dam interaction is analysed by doing cupled models including the dam and the soil. The soil is modeled as a linear viscoelastic solid with the following properties: density = 2641.65 Kg/m^3; Poisson's ratio = 0.2; shear modulus = 11500 MPa and damping ratio = 0.05. The soil is discretized using the same kind of elements as for the dam. The discretization is left open at a certain distance from the dam. Figure 4.a shows the dam-foundation rock model for the Morrow Point reservoir in which the water basin is consider to extend uniformly to infinity. In Figure 4.b the model for an assumption of a finite geometry of the reservoir is shown. The Figure shows one half of the symmetric models. The analysis of the dam response for both geometries when the reservoir is empty produces almost identical results. This shows that the soil topography far from the dam does not have influence on the dam response for empty reservoir conditions.

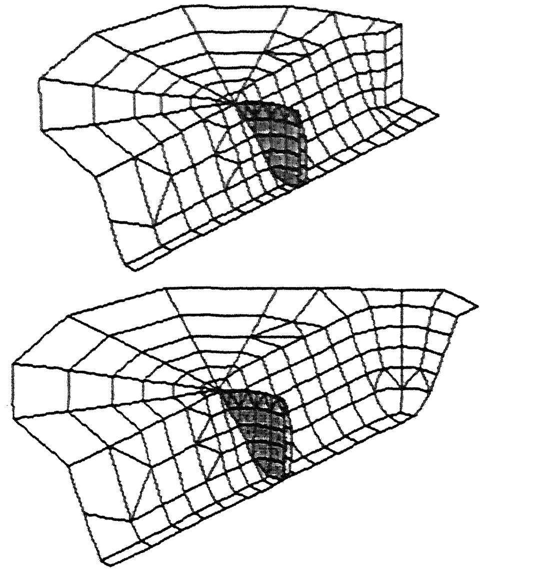

Fig.4. Geometry and boundary elements discretization of the coupled system. (a) infinite reservoir; (b) finite reservoir.

Figure 5 shows the upstream amplification at the dam crest for the dam-foundation rock system. The results obtained show important differences with those obtained by Fok and Chopra (1986) using finite elements. It can be shown that the differences are due to the fact that the F.E. model includes a massless soil assumption and hence do not represent properly the dam-foundation rock interaction and can not take into account the spacial distribution of the excitation. If the B.E. code is run assuming a density of the foundation rock one thousand times smaller than that used before and a zero damping ratio, the obtained results are very close to the F.E. results as shown in Figure 5.

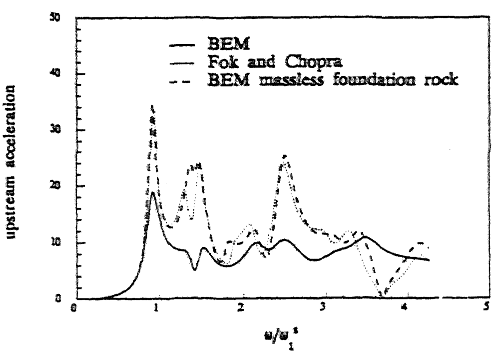

Fig.5. Upstream amplification. Compliant foundation, empty reservoir.

3 MODEL FOR THE FLUID DOMAIN. DAM-WATER-FOUNDATION ROCK INTERACTION

The water is modeled as an inviscid compressible fluid under small amplitude harmonic motion. It's behaviour is governed by the Helmholz equation. The B.E. for the fluid are quadratic nine or six node elements as in the solid case. The interaction conditions between the water and the solid regions (dam and soil) are: equal normal pressure and displacement on the solid and fluid boundaries in contact, and zero shear traction on the solid elements of the contact surfaces. Two geometries for the reservoir are considered as shown in Figure 4. One includes an infinite uniform rectangular cross section channel to represent the reservoir extending towards a very long distance; the other is finite consisting of an uniform region closed by a spherical surface.

The main advantages of the Boundary Element Method for the kind of problem at hand lies in the fact that only the boundary of the domains have to be discretized. Because of that, the actual geometry of the reservoir can be included in the model up to a distance from the dam several times the dam height.

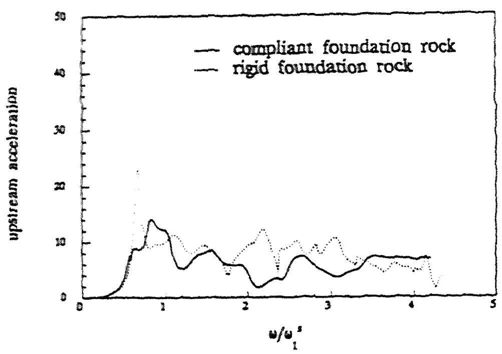

Fig.6. Upstream amplifications. Infinite reservoir full of water.

The geometry of a reservoir may be such that the whole fluid domain can be included in the model. However, in other cases the reservoir may extend to very large distances and only part of it can be discretized into elements. Then an infinite channel model may be used in combination with a realistic Boundary Element representation of a significant part of the reservoir close to the dam. The water-foudation rock interaction effects and the near field wave reflectin in the reservoir topography are taken into account by the Boundary Element discretization which includes the stiffness and mass properties of the foundation rock. An infinite channel with uniform cross section is used to represent the far field wave radiation effects in order to avoid spurious wave reflections. The assumption of uniform cross section is obviously geometrically unrealistic for most reservoirs; however, in the present model, this assumption is only done at a rather large distance from the dam. The significant water-foundation rock interaction and water wave reflection effects are well represented by the B.E. discretization of an extensive part of the reservoir. Taking into acount that the shape of the cross section of this channel would be in any case unrealistic, that the channel is placed far from the dam and the fact that it is only intended to represent the radiation effect, a very simple geometry (rectangular) is assumed for the cross section. By doing so the wave propagation modes along the channel are known and no eigenvalue problem has to be solved numerically. If the channel were located very close to the dam, as done in the F.E. models, it would make sense to have a more complicated cross section to have a better representation of the near field in spite of the fact that the actual shape of the reservoir would hardly remain uniform after some distance.

An artificial absorbing boundary is located closing the zone of the reservoir which has been discretized into B.E. This boundary represents the uniform cross section channel extending from that point up to infinity. The boundary conditions for that boundary are given by the matrix relation between the pressure and the flux obtained from the rectangular channel analytical solution. The half-space fundamental solution is used for the fluid domain B.E. equations to avoid the need of discretizing the free surface.

The following effects are rigurously taken into account by the proposed approach: the dam-foundation interaction, the water pressure waves absortion at the reservoir boundary and the space distribution of the excitation. The coupled indirect interaction effects are also represented by the model.

Figure 6 shows the upstream acceleration frequency response functions for upstream. The results are compared with the corresponding ones for rigid foundation rock. The traveling wave effects, dam-foundation rock interaction and the water-foundation rock interaction produce substantial changes in the dam response. The first peak moves to higher frequencies being smaller the maximum value. Important differences exist in the rest of the frequency range analysed.

The B.E. results for full reservoir and compliant foundation rock conditions are now compared with the F.E. results obtained by Fok and Chopra (1986) for the same dam. Figure 7 shows this comparison for upstream excitation. The F.E. results have been taken directly from the figures of the paper by Fok and Chopra (1986) and may have small discrepancies with the exact numerical values. They correspond to an absortion coeffitient $\alpha = 0.75$ which very close to that obtained for the assumed foundation rock properties.

Important differences between the B.E. and the F.E. results are shown by

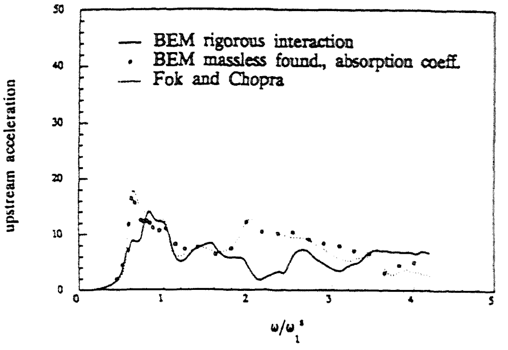

Fig.7. Upstream amplification. Compliant foundation rock. Infinite reservoir full of water.

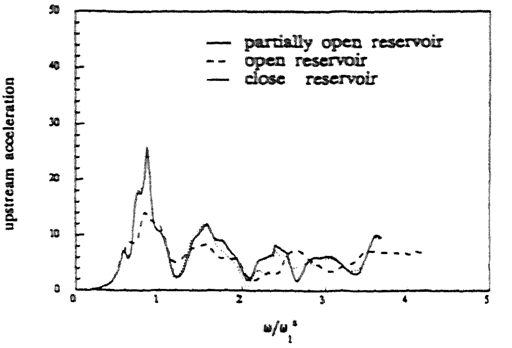

Fig.8. Upstream amplification. Compliant foundation rock. Reservoir full of water.

Fig.7. Those differences are due to the traveling wave effect which is not taken into account by the F.E. model and by the water-foundation rock interaction which is approximated by the one dimensional theory in that model. Both effects are rigurously considered in the proposed B.E. approach. To show the above statement, again a numerical experiment is done. The B.E. analysis is repeated assuming a density of the foundation rock one thousand times smaller than that used before and a zero damping factor. The shear modulus and the Poisson's ratio remain the same. The aproximate boundary conditions for the reservoir bottom and banks assumed in the F.E. model are also introduced in the B.E. model for the near and intermediate field. Traction free conditions are assumed for the foundation rock and

$$\frac{\partial p}{\partial n} = \rho_w \, \omega^2 \, u_n + i \, \omega \, q \, p \qquad (1)$$

for the fluid domain (Hall and Chopra, 1983). The results obtained are also shown in Fig.7. They show a remarkable agreement between the B.E. results obtained using massless foundation rock and absortion coefficient and the F.E. results.

The actual geometry of a reservoir is more complicated than a uniform channel extending to infinity. Some reservoirs can be almost close at a certain distance from the dam. In such cases, the B.E. approach permits a realistic representation of the fluid and the foundation rock domains. To show the effect of having a close fluid domain on compliant foundation rock, the symmetric close reservoir (shown in Fig.4b) is assumed now. The previously obtained results for the open reservoir are now compared with those obtained for the close fluid domain. The comparison is shown in Fig.8.

The differences between the dam response for open and close reservoir conditions are important. It is worth to analyse if those differences are exactly due to the close reservoir model does not allow any wave radiation in the fluid domain. In many cases the reservoir is connected to an upstream water zone with a cross section much smaller that the main reservoir zone. The question is whether in those cases the dam response will be of the same type of that corresponding to the open reservoir case, because there is wave radiation mechanism, or on the contrary the response will be of the same type of that obtained for the completely close reservoir. To answer this question the B.E. model of Fig.9 has been assumed for the dam-reservoir-foundation system. An infinite uniform channel with rectangular cross section is assumed at the end of the reservoir main zone which is discretized into boundary elements. In this case the channel has a cross section 57 m high and 60 wide, which is much smaller than that of the open reservoir case.

Fig.8 also shows the upstream frequency response function of the dam crest center point for this case. It can be seen in the figure that the dam response for the partially open reservoir case studied is almost the same as that for the close reservoir case in the frequency range up to the first cut-off frequency of the

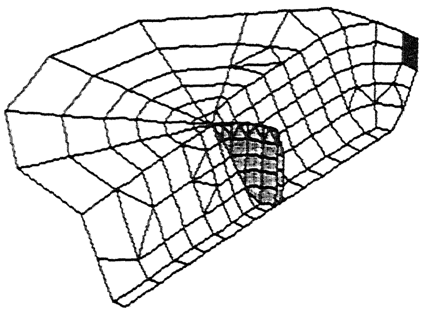

Fig.9. Geometry and boundary element discretization of the partially open reservoir.

infinite channel ($\omega/\omega_1{}^s$ = 1.45). For higher frequencies the response functions of the three reservoirs present differences; however, that part of the response functions do not include high amplifications of the ground motion.

4 CONCLUSIONS

A B.E. approach for the seismic analysis of arch dams has been presented. The following important effects are included together in a rigurous manner in a three-dimensional model: Dam-foundation rock interaction, dam-water interaction, water-foundation rock interaction and traveling waves in the foundation rock. To validate the approach an analysis of the Morrow Point dam with several assumptions for the reservoir geometry and foundation rock properties has been done. The following conclusions can be drawn:

1. The foundation rock compliance produces a decrease in the main peaks of the dam response for all the excitations and reservoirs geometries considered.

2. Existing models which do not include the traveling wave effect and make an approximation of the dam-foundation rock and the water-foundation rock interactions produce results with significant errors.

3. The fact that the reservoir is completely or partially close at a distance from the dam several times its height has an important influence on the dam respose.

4. A good representation of the actual geometry of the reservoir is very important. The proposed B.E. approach permits such a representation up to a significant distance from the dam.

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REFERENCES

Dominguez,J. and Maeso, O. 1993. "Earthquake analysis of arch dams. Part.II: Combine dam-water-foundation rock interaction and traveling wave effects", J.of Eng.Mech. (On review).

Fok,K., and Chopra, A.K. 1986. "Frequency response functions for arch dams: Hidrodynamic and foundation flexibility effects", Earthquake Eng.Struc.Dyn., 14, 769-795.

Hall,J.F., and Chopra, A.K. 1983. "Dynamic analysis of arch dams including hydrodynamic effects", J.Eng.Mech.Div.ASCE, 109, 149-163.

Maeso,O., and Dominguez,J. 1993."Earthquake analysis of arch dams. Part.I: Dam-foundation rock interaction and traveling wave effects", J.of Eng.Mech. (On review).

Zhang,L., and Chopra, A.K. 1991. "Impedance functions for three-dimensional foundations supported on an infinitely-long canyon of uniform cross-section in a homogeneous half-space", Earthquake Eng. and Struct.Dyn., 20, 1011-1027.