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ANALYSIS OF CONCRETE ARCH DAMS BY FE-BE PROCEDURE IN THE FREQUENCY DOMAIN

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SUMMARY

One of the main complexities in dynamic analysis of concrete arch dams, is the modeling of dam-foundation rock interaction by precise techniques. In this paper, the FE-BE procedure is utilized for this purpose. In this approach, dam body is discretized by finite elements, while foundation rock is handled by three dimensional boundary element formulation. This would allow a rigorous inclusion of dam-foundation rock interaction, with no limitations imposed on geometry of canyon shape. Based on this technique, a previously developed program is modified, and the response of Morrow Point arch dam is studied for various ratios of foundation rock to dam concrete elastic moduli under an empty reservoir condition. Furthermore, the effects of canyon shape on response of dam, is also discussed.

INTRODUCTION

Accurate representation of dam-foundation rock interaction is one of the main challenges in dynamic analysis of concrete arch dams. In the initial studies, this modeling was simplified by using a massless foundation model, such as the work of Fok and Chopra [1]. In that case, the finite element discretization was utilized for both dam body and foundation rock domains (FE-FE approach). Later on, Tan and Chopra [2] improved this methodology and they presented a technique, which considers dam-foundation rock interaction rigorously. In this work, the dam was modeled by finite element, while the foundation rock was represented by a two-dimensional (2D) boundary element formulation combined with a series expansion along the canyon axis direction (FE-BE technique). However, the main limitation of this work, is that the foundation rock geometry must be that of a uniform canyon extending to infinity. In other studies, i.e., the work of Maeso and Dominguez [3], both dam and foundation rock domains were treated by boundary element formulations (BE-BE method).

In this paper, the problem is analyzed by FE-BE technique. That is, dam body and foundation rock domains are discretized by finite and boundary elements, respectively. Meanwhile, the foundation rock is represented by applying a three-dimensional (3D) boundary element formulation. Therefore, the geometry of canyon could be quite arbitrary and no limitations are required to be imposed. A previously developed

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program [4] is modified based on this method and the response of Morrow Point arch dam, is studied as a typical example. The investigation is carried out for various ratios of foundation rock to dam concrete elastic moduli, as well as for two different shapes of canyon.

MODELING AND BASIC PARAMETERS

The computer program "MAP76" [4] was enhanced based on the FE-BE approach which its concepts can be found elsewhere in details [5]. In this program, the dam body and the foundation rock, are treated by finite and boundary elements, respectively. Both domains are considered as linearly viscoelastic materials with isotropic behavior.

Models

An idealized symmetric model of Morrow Point arch dam is considered. The geometry of the dam may be found in reference [6]. The main model is prepared based on the finite and boundary elements discretization for the dam body and foundation rock respectively, which is depicted in Fig. 1.

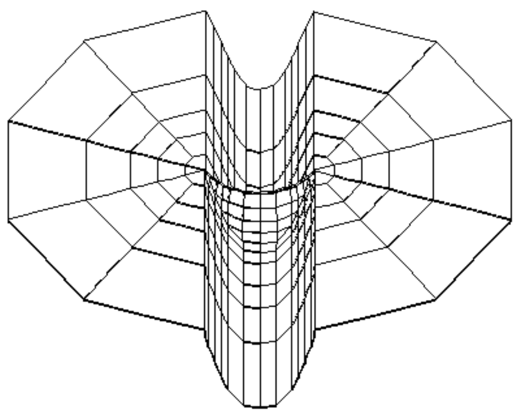


Figure 1. Dam-foundation system discretization (model 1: FE-BE model with uniform canyon shape)

The dam is discretized by 40 isoparametric 20-node finite elements, while the foundation rock is modeled by 178 isoparametric 8-node boundary elements considered at the foundation surface. In this model, the canyon shape is also assumed uniform (FE-BE model with uniform canyon shape).
A second model is also considered which is similar to the first model except that a non-uniform canyon shape is assumed. This could be utilized to study the effects of canyon shape on the response and its geometry will be described further later on.

Basic Parameters

The dam concrete is assumed to be homogeneous with isotropic linearly viscoelastic behavior and the following main characteristics:

Elastic modulus (E_d) = 27.5 GPa.
Poisson's ratio = 0.2
Unit weight = 24.8 kN/m^3
Hysteretic damping factor (β_d) = 0.05

The foundation rock, is idealized by a homogeneous, viscoelastic domain. The basic properties of this region are:

Poisson's ratio = 0.2
Unit weight = 26.4 kN/m^3
Hysteretic damping factor (β_f) = 0.05

As for the foundation rock elastic modulus (E_f), it was varied to cover a wide range of foundation materials. In particular, E_f /E_d ratios of ∞ (rigid foundation), 2, 1, 0.5, and 0.25 are considered in the initial part of the investigations. In later stages, the elastic moduli ratio was fixed as E_f /E_d=1, to study the effects of canyon shape on the response.

RESULTS

The FE-BE model with uniform canyon shape (Fig. 1) is considered initially. The responses of dam crest are obtained due to upstream, vertical and cross-stream excitations (Fig 2) and in each case for several ratios of foundation rock to dam concrete elastic moduli (E_f / E_d).

The response quantities plotted are the amplitudes of the complex valued radial accelerations for two points located at dam crest. These are either the mid-crest point $(\theta = 0^o)$ selected for upstream or vertical excitations or a point located at $(\theta = 13.25^o)$ which is used for the case of cross-stream excitation. This is due to the fact that radial acceleration is diminished at mid-crest for the cross-stream type of ground motion.

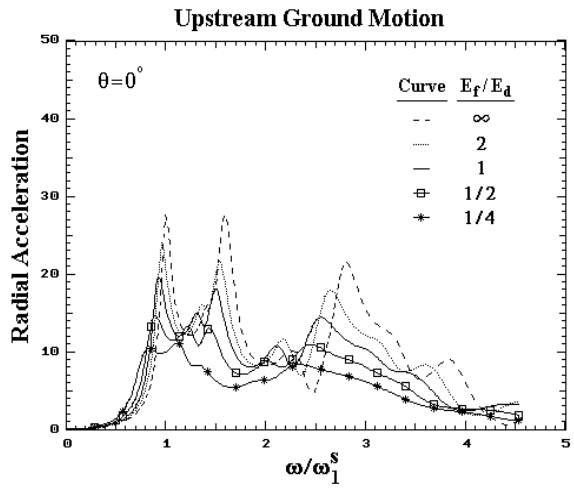
In each case, the amplitude of radial acceleration is plotted versus the dimensionless frequency for a significant range. The dimensionless frequency for upstream and vertical excitation is defined as ω / ω_1^S where ω is the excitation frequency and ω_1^S is the fundamental frequency of the dam on rigid foundation with empty reservoir for a symmetric mode. For the cross-stream excitation cases, the dimensionless frequency is defined as ω / ω_1^a, where ω_1^a is the fundamental resonant frequency of the dam on rigid foundation with empty reservoir for an anti-symmetric mode.

It is observed that the natural frequencies of the system, as well as the magnitude of the peaks of the response decrease as the ratio of foundation rock to dam concrete elastic moduli (E_f / E_d) reduces. The decrease in the response is due to radiation damping phenomena, which is caused by energy taken from system and traveling to far-field.

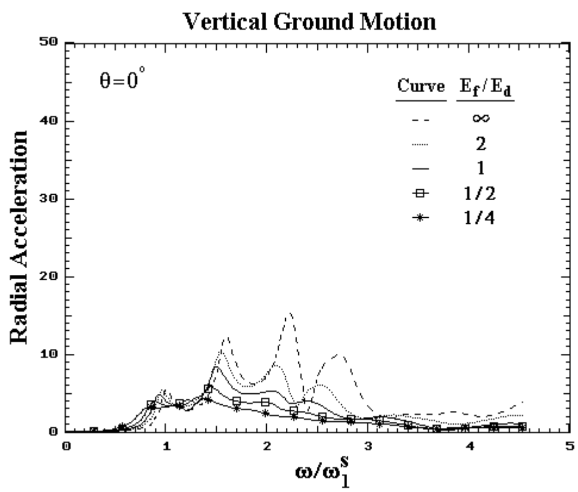
Similar results taken from work of Tan & Chopra [2], are also illustrated in Fig. 3 for comparison purposes in the case of upstream ground motion. These results could be compared with the corresponding results of the present study (Fig. 2a).

It is noticed that trend is similar and relatively good agreement exists between the results obtained herein and the ones taken from the above mentioned reference. The main difference is the amplitude of the peaks which are slightly higher in the work of Tan and Chopra (Fig. 3) in comparison with the present study results (Fig. 2a). This is mainly due to the fact that in that work, the foundation impedance matrix is obtained by applying a fine mesh and implementing static condensation to condense the extra degrees of freedom.

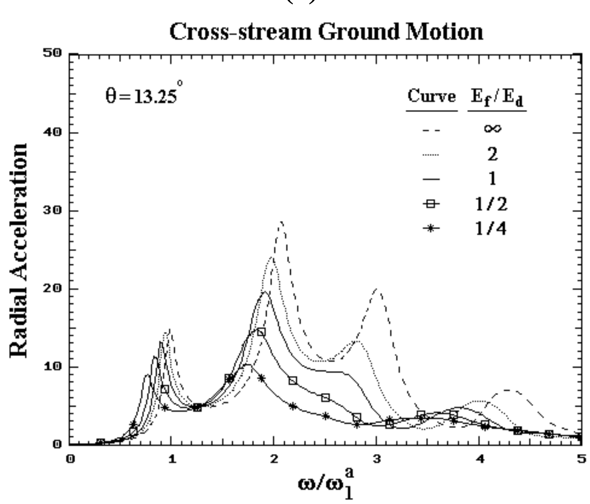
Finally, it was decided to show the effects of canyon shape on the response. For this aim, the second model is defined (FE-BE model with non-uniform canyon shape). This model is exactly similar to the first model, except from the geometry of canyon standpoint (Fig. 4). In this case, it is assumed that the topography at the crest level makes an angle of 60° with the stream direction. This is in both upstream and downstream directions at both left and right banks. At lower elevations, this angle is reduced based on a quadratic function of height, such that it becomes zero at the base of the dam.



(a)



(b)



(c)

Figure 2. Influence of moduli ratio E_f / E_d on response of dam due to harmonic upstream, vertical and cross-stream ground motions.

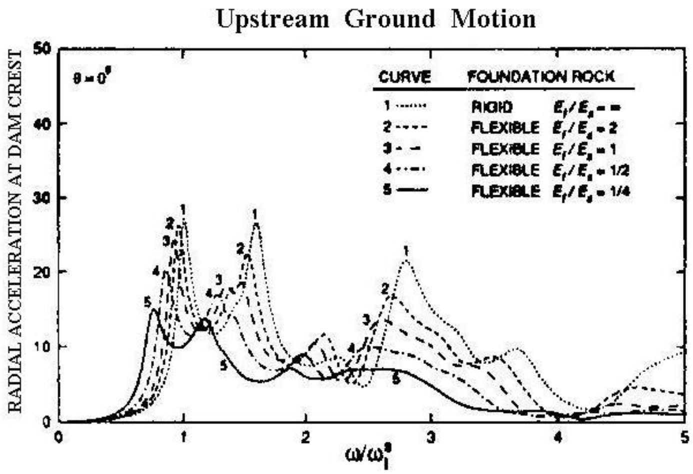


Figure 3. Influence of moduli ratio E_f / E_d on response of dam due to harmonic upstream ground motion (result taken from the work of Tan and Chopra [2] for comparison)

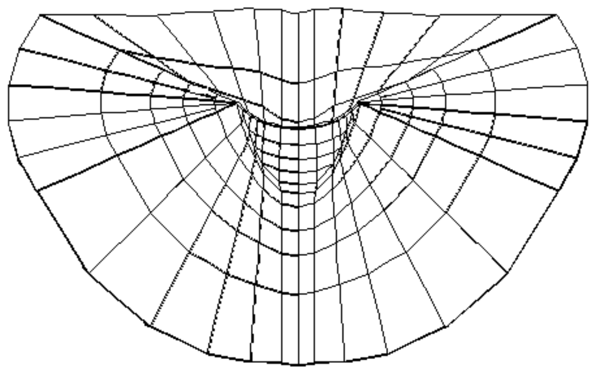


Figure 4. Dam-foundation system discretization (model 2: FE-BE model with non-uniform canyon shape)

The results for uniform and non-uniform canyon shapes (model 1 versus model 2 for $E_f / E_d = 1$) are compared in Fig. 5 for different types of excitation. This figure displays the effects of canyon shape on the responses, and the response for the rigid foundation case is also given as a reference in each type of ground motion.

It is observed that the response is significantly effected due to change in canyon shape. The peaks of the response for the non-uniform canyon shape is lower than for the uniform canyon shape, and the natural frequencies of the system are also reduced. This is because, the foundation domain has become more flexible as a result of thinner abutment, and the behavior is similar to reducing the foundation elastic modulus for fixed dam properties or decreasing the elastic moduli ratio (E_f / E_d). Of course, this decrease in the magnitude of the peaks is more pronounced for the upstream and cross-stream excitations than for vertical ground motion.

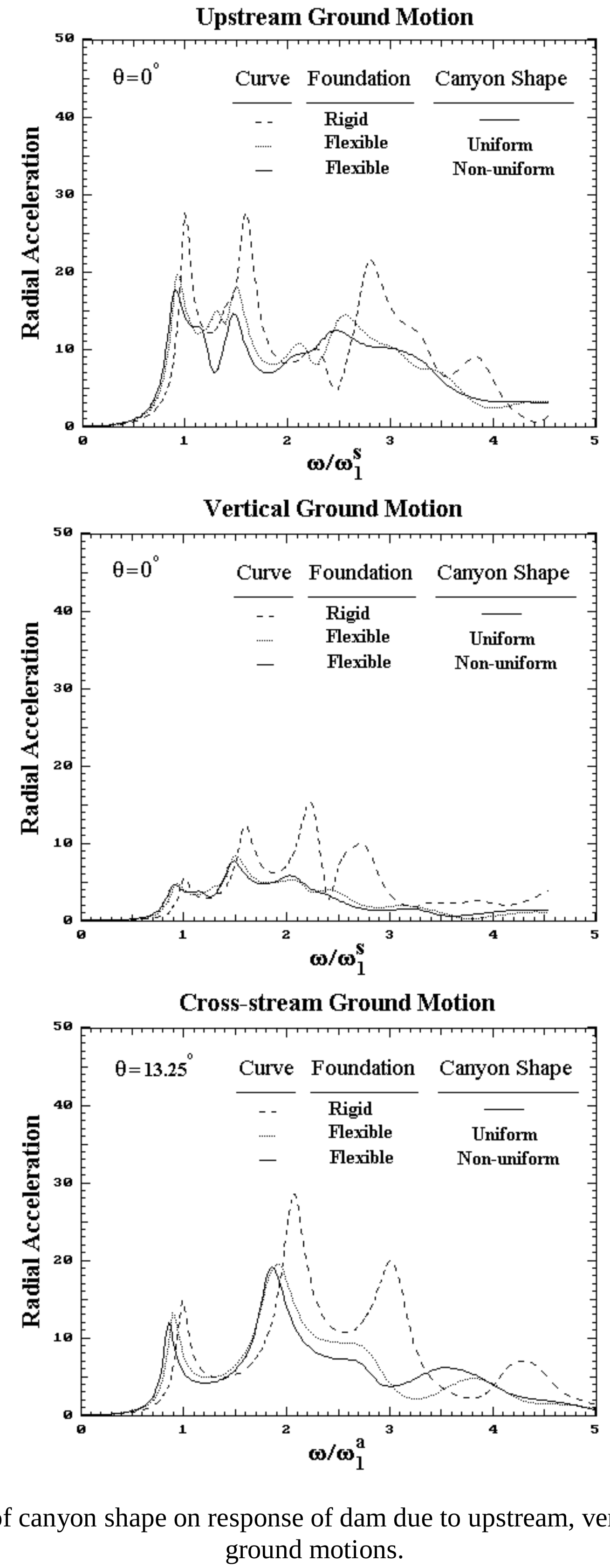


Figure 5. Influence of canyon shape on response of dam due to upstream, vertical and cross-stream ground motions.

CONCLUSIONS

The formulation based on FE-BE procedure for dynamic analysis of concrete arch dam-foundation rock systems, was implemented. A computer program based on this methodology was prepared and the response of Morrow Point arch dam was studied for various ratios of foundation rock to dam concrete elastic moduli, as well as different shapes of canyon. Overall, the main conclusions obtained by the present study can be listed as follows:

- The initial results obtained herein shown to be in relatively good agreement with the work of Tan and Chopra [2]. Meanwhile, similar observations as to previous studies due to effects of dam-foundation rock interaction are also noticed in the present results.
- The main advantage of the FE-BE procedure of the present study over the method of Tan and Chopra [2] is that there are no restrictions imposed as to the geometric shape of the canyon.
- The results are also compared for two cases having uniform and non-uniform canyon shapes. It is observed that the response is significantly effected due to change in canyon shape. The peaks of the response for the non-uniform canyon shape (thinner abutment) is lower than for the uniform canyon shape, and the natural frequencies of the system are also reduced. The behavior is similar to reducing the foundation elastic modulus for fixed dam properties or decreasing the elastic moduli ratio (E_f / E_d). Of course, this decrease in the magnitude of the peaks is more pronounced for the upstream and cross-stream excitations than for vertical ground motion.

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