EARTHQUAKE RESPONSE OF CONCRETE GRAVITY DAMS BY COMBINATION OF FINITE ELEMENT AND BOUNDARY INTEGRAL FORMULATIONS

Vahid LOTFI[1] And Mohammad R SHARGHI[2]

SUMMARY

Dynamic analysis of concrete gravity dams in the frequency domain is approached by a combination of different numerical techniques. In this method, the dam body is discretized by finite elements, the water region by a semi-infinite fluid hyperelement, and the foundation rock domain by quadratic boundary elements. A new computer program called "MAP-76" is developed based on this method, and the results for an idealized triangular dam are compared with previous available results from accuracy point of view.

INTRODUCTION

There has been extensive research to examine the effect of dam-water-foundation interactions in case of concrete gravity dams which could be idealized as a two dimensional model. In most of these works, the behavior of dam concrete and foundation rock are considered as linearly viscoelastic material, and the fluid domain is treated based on compressible fluid theories. In some of these cases [Hall and Chopra, 1982b], and [Fenves and Chopra, 1984], the dam is discretized by finite elements, while the fluid domain is treated by semi-infinite hyperelement, and the foundation rock dynamic stiffness is considered by integration of closed formed half plane solutions. In other studies [Dominguez and Medina, 1989], the dam body, the foundation region, and the fluid domain have been handled by applications of boundary integral methods for all media and combining these regions by appropriate interaction conditions.

In this paper, the problem is approached by a sub-structuring technique, taking advantages of both methods mentioned above. In this method, the dam is discretized by finite elements, the fluid region by a hyperelement taking into account the reflection boundary condition at reservoir bottom, and the foundation domain by boundary integral formulation. The dynamic behaviour of an idealized triangular dam with vertical upstream face is considered as a controlling example.

[1] *Assistant Professor of Civil Eng. Dept., Amirkabir University, Tehran, Iran.*
[2] *Ph.D. Candidate of Civil Eng. Dept., Amirkabir University, Tehran, Iran*

The problem can be divided into three domains of concrete dam body, foundation rock, and impounded water (Fig. 1). The domains are interacting at the boundaries.

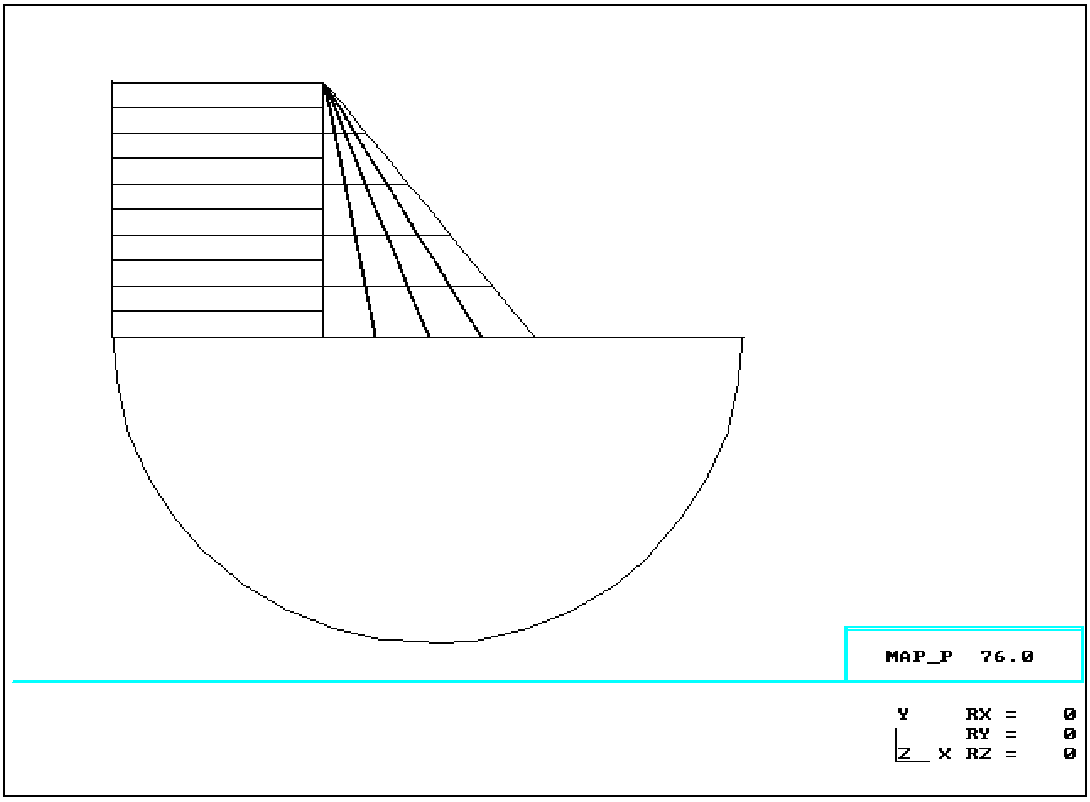


Fig. 1. Dam-reservoir-foundation system

Dam

The dam body is assumed as linearly viscoelastic material. It is more generally discretized by finite elements. In this case, 20 isoparametric 8 noded elements are used. The dynamic stiffness matrix of this domain is formed in the frequency domain as usual. Apart from the inertia force vector corresponding to dam body, the interacting forces of foundation and impounded water are also present for this domain.

Foundation Rock

The rock domain is idealized as a semi-infinite linearly viscoelastic half plane. Boundary element idealization is more appropriate for this region. Herein, quadratic isoparametric boundary elements are utilized. It is also more efficient numerically to define a dynamic stiffness matrix for this region likewise. This relates interacting forces and displacements of the foundation domain at the dam-foundation interface.

Impounded Water

This domain, in its most general form is subdivided into two regions, a part near the dam body with an irregular geometry, and a regular region extending to infinity in the upstream direction. The first region is discretized by fluid finite elements, while the latter is usually included by utilizing a fluid hyperelement [Hall and Chopra, 1982b]. However, if the reservoir has a regular geometry as the case considered in this work, then the first region can be excluded and the whole domain can be modeled by a fluid hyperelement alone.
The formulation of this hyperelement is based on the invisid, and compressible fluid theory. Meanwhile, an absorptive boundary condition is applied for this domain to model partial reflection of waves at reservoir's bottom due to presence of sediments and flexible foundation at that boundary. This is

introduced by the wave reflection coefficient α, defined as the ratio of the amplitude of the reflected hydrodynamic pressure wave to the amplitude of a vertically propagating pressure wave incident on the reservoir bottom.

Similar to the foundation rock domain, it is possible to define a dynamic stiffness matrix for the fluid region which relates interacting forces and displacements at dam-water boundary.

Solution Strategy

Dynamic stiffness matrices of different domains can be combined convenintly by direct method in frequency domain. However, it is much more efficient to use an approach based on the Ritz concept. The displacements are expressed as linear combination of Ritz vectors, chosen as the normal modes of an associated undamped dam-foundation system similar to the work of Ref. 2 [Fenves and Chopra, 1984]. The final equations obtained are in terms of generalized Ritz coordinates. The solution of these equations at an arbitrary exitation frequency would readily define displacements or accelerations at each node.

BASIC PARAMETERS

The dam body is assumed to be homogeneous and isotropic with linearly viscoelastic properties for mass concrete : Elastic modulus (E_d)= 27.5 Gpa. , Poisson's ratio = 0.2 , unit weight =24.8 kN/m^3, and hysteretic damping factor η_d= 0.10 .

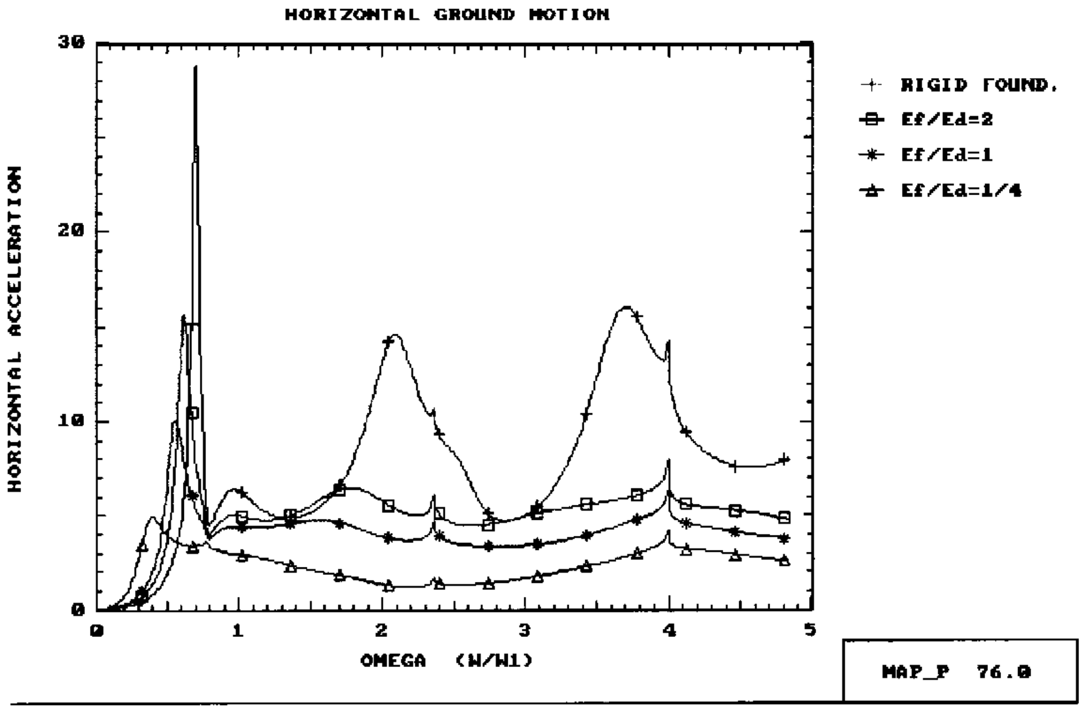
The impounded water is taken as invisid, and compressible fluid with unit weight = 9.81 kN/m^3 , and pressure wave velocity = 1440. m/sec.

The foundation rock is idealized by a homogeneous, isotropic, viscoelastic half plane. The material properties of this region are: Poisson's ratio= 1/3 , unit weight=26.4 kN/m^3, and the elastic modulus E_f is varied to cover a wide range of foundation materials. In particular, E_f/E_d ratios of ∞ (rigid foundation), 2, 1, and 1/4 are considered in the analyses presented here. The hysteretic damping factor η_f =0.10 is also specified for this material.

RESULTS

To verify the solution procedure, the response of horizontal acceleration at dam crest due to horizontal and vertical harmonic ground excitations are obtained for several ratios of foundation rock to dam concrete elastic modulus. These ratios are selected as mentioned previously and are similar to the values considered in Ref. 3 [Fenves and Chopra, 1985]. Two different alternatives of reservoir bottom absorption coefficient α = 1, and 0.5 were also considered. α = 1 represents full reflection, while α = 0.5 allows for partial refraction of waves impinging at reservoir's bottom.

The results obtained are plotted in Figs. 2,and 3. Similar graphs taken from Ref. 3 [Fenves and Chopra, 1985] are also shown in Fig. 4 for comparison purposes. However, It should be noticed that eventhough similar properties are used in both studies, there are still slight differences. These are mainly, types of finite elements, two dimensional behavior assumed (plane stress versus plane strain), and the formulation to obtain the dynamic stiffness of half plane. In the present study, boundary element method is employed which is much more general and versatile than the technique based on integration of closed formed solution applied in the above mentioned reference. In particular, it can be easily modified for general cases of complicated boundaries at the foundation surface, eventhough it is limited to straight line for the present study.



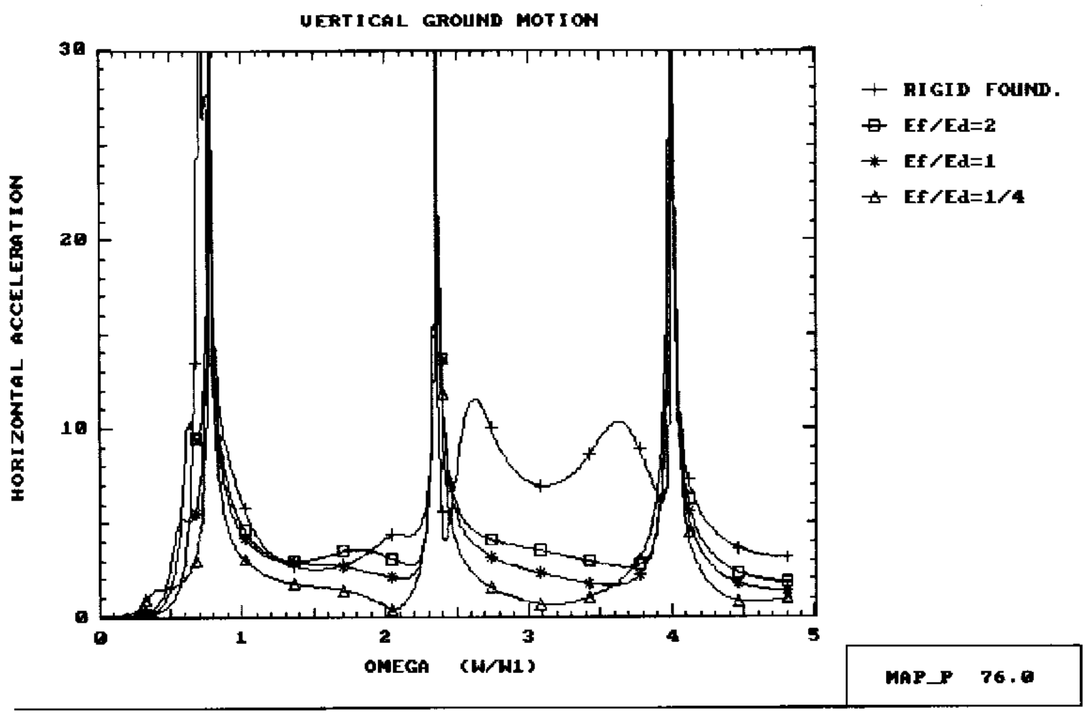
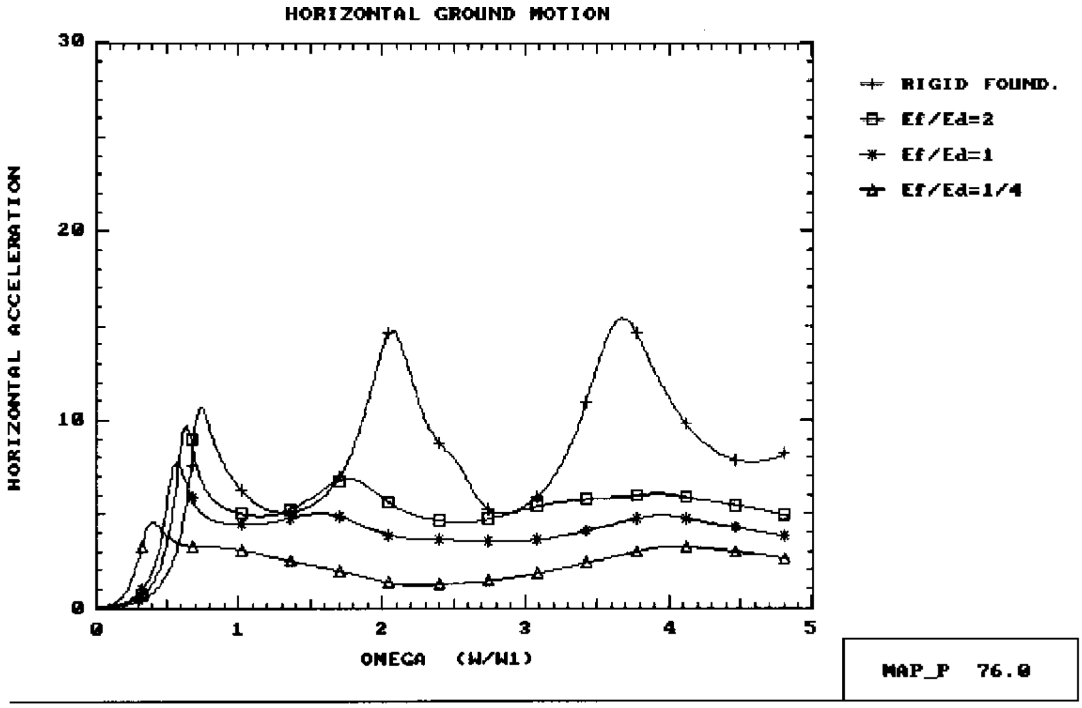


Fig. 2. Horizontal responses at dam crest due to horizontal and vertical ground motions for the case of rigid reservoir bottom ($\alpha = 1$).



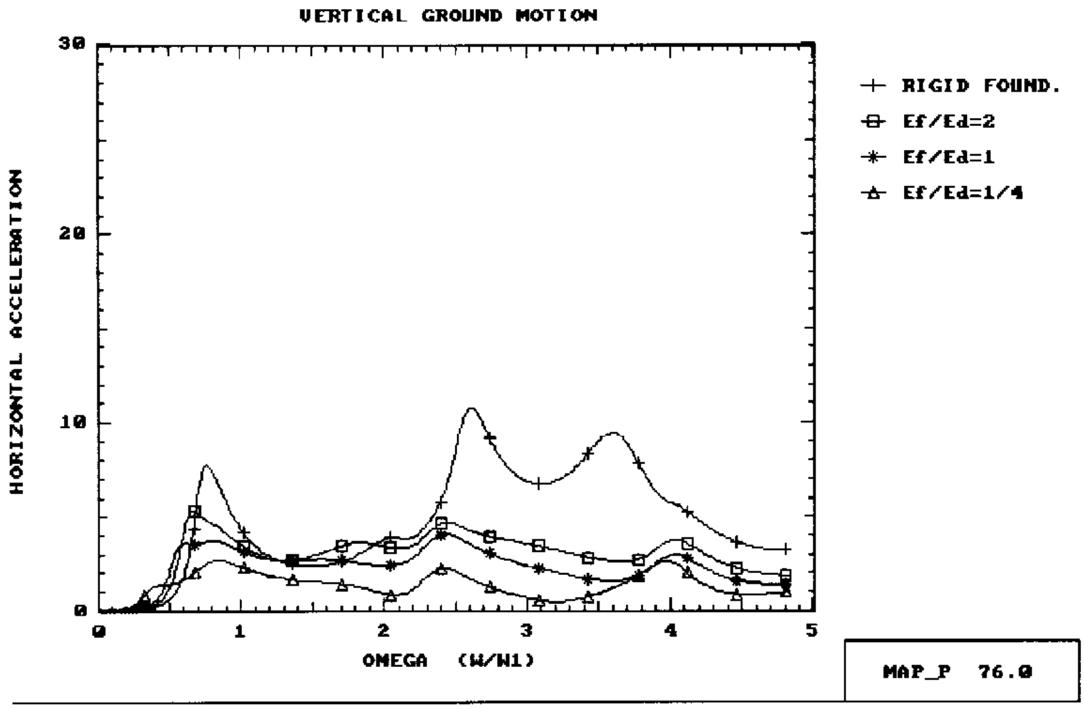


Fig. 3. Horizontal responses at dam crest due to horizontal and vertical ground motions for the case of absorptive reservoir bottom ($\alpha = 0.5$).

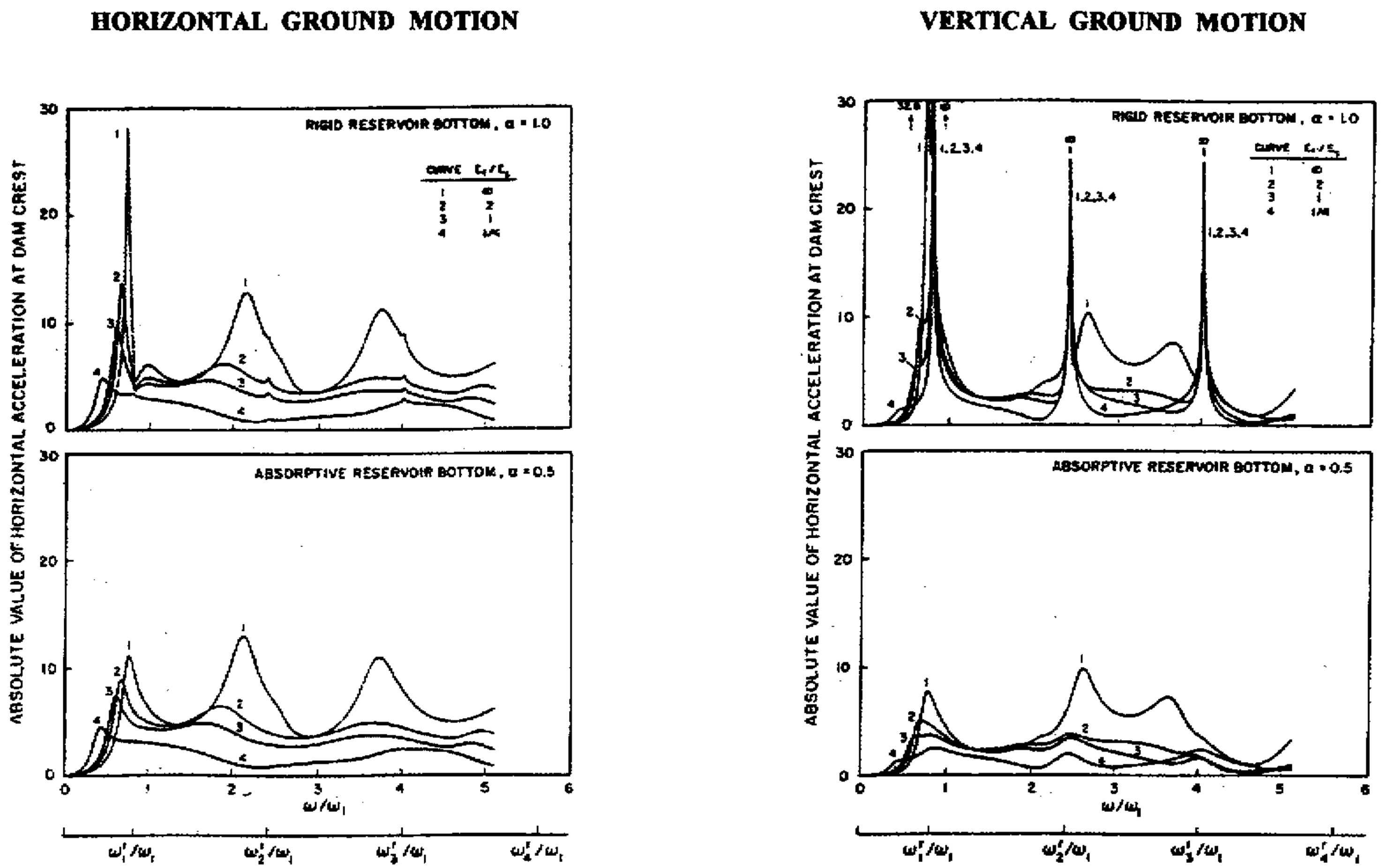


Fig. 4. Horizontal responses at dam crest due to horizontal and vertical ground motions. Results taken from reference 4 [Fenves and Chopra, 1985].

Having the above comments in perspective, it is noticed that very good agreement exist between the results obtained based on present study (Figs. 2,and 3) and the ones taken from the reference mentioned above (Fig. 4). It is observed that for the case of $\alpha = 1$ (Fig. 2), as foundation becomes more flexible for a fixed dam properties, the fundamental resonant frequency of the system decreases, the amplitude of the fundamental resonant peak lowers and frequency band width at resonance increases. Meanwhile, for low values of foundation rock to dam concrete modulus, response decreases significantly due to additional radiation damping occuring in foundation. It is also noticed that sharp peaks are occuring at cut-off frequencies of the reservoir. These peaks are singularities of the response for vertical ground motion. However, they are bounded in the case of horizontal excitation.

For cases of $\alpha = 0.5$ (Fig. 3), similar observations are noticed, with the exception that sharp peaks are limited at cut-off frequencies even for vertical ground motion. Meanwhile, the response for both excitations are generally much lowered in comparison with the cases of rigid reservoir bottom assumption ($\alpha = 1$).

CONCLUSIONS

Possibility of a new numerical tools for dynamic analysis of concrete gravity dams are investigated. In this approach, the dam body is discretized by finite elements, the water region by a semi-infinite fluid hyperelement, and the foundation rock domain by quadratic boundary elements. The interactions are considered through a substructuring technique and a new computer program is developed. The dynamic behaviour of an idealized triangular dam with vertical upstream face is considered as a controlling example. Specifically, this investigation leads to the following conclusions:

- The procedure based on combinations of finite elements, hyperelement, and boundary elements with a substructuring technique is proved to be an efficient method for dynamic analysis of concrete gravity dams.
- A new computer program called " MAP-76" is developed based on this procedure and the results are controlled with previous studies published by employing EAGD-84 computer program. The horizontal response at dam crest due to both horizontal and vertical ground motion are seen to be in perfect agreement between the two programs for different ratios of foundation rock to dam concrete elastic moduli. This is controlled for two different alternative values of wave reflection coefficient specified at reservoir bottom.
- Similar observations as to previous works, for the effects of dam-foundation interaction, dam-water interaction, and the effect of absoptive boundary condition on the dynamic response of concrete gravity dams are verified in this study.

REFERENCES

Dominguez, J. and Medina, F. (1989), "Boundary elements for the analysis of the seismic response of dams including dam-water-foundation interaction effects. II", *Engr. Anal.*, Vol.6, pp 158-163.

Fenves, G. and Chopra, A.K. (1984), "Earthquake analysis of concrete gravity dams including reservoir bottom absorption and dam-water-foundation rock interaction", *Earthquake Eng. and Struct. Dyn.,* Vol. 12, pp 663-680.

Fenves, G. and Chopra, A.K. (1985), "Effects of reservoir bottom absorption and dam-water-foundation rock interaction on frequency response functions for concrete gravity dams", *Earthquake Eng. and Struct. Dyn*., Vol. 13, pp 13-31.

Hall, J.F. and Chopra, A.K. (1982b), "Hydrodynamic effects in the response of concrete gravity dams", *Earthquake Eng. and Struct. Dyn*., Vol. 10, pp 333-345.