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Significance of rigorous fluid-foundation interaction in dynamic analysis of concrete gravity dams

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Abstract. Dynamic analysis of dam-reservoir-foundation system is usually carried out by employing a simplified and approximate one-dimensional model to account for fluid-foundation interaction. The approximation introduced on this basis is examined thoroughly in this paper by comparing the method with the rigorous approach. It is concluded that the errors due to approximate method could be very significant both for horizontal and vertical ground motions.

Key words: rigorous interaction; fluid-foundation interaction; concrete gravity dams; dynamic analysis.

1. Introduction

An accurate dynamic analysis of concrete gravity dams requires special attention for the interactions involved in this problem. These are dam-reservoir, dam-foundation and reservoir-foundation (fluid-foundation) interactions. In the past, there has been extensive research to study the effects of former two interactions, but little attention was devoted to fluid-foundation interaction. Some of these have also led to very efficient softwares (Hall and Chopra 1980, Fenves and Chopra 1984), which are exceptional tools for general investigations related to dynamic response of concrete gravity dams. However, in both of these studies, a simplified and approximate one-dimensional model is utilized to account for fluid-foundation interaction. More recently, Medina *et al.* (1990) developed an analytical procedure based on the boundary element method, which considered all interactions rigorously. They studied the complex frequency response functions of an idealized triangular dam, and concluded that, although the approximate fluid-foundation interaction model was capable of providing a reasonably accurate prediction of the response to vertical excitation, it underestimated the peak value of the response due to harmonic horizontal excitation.

The purpose of this study is to reevaluate the effects of rigorous fluid-foundation interaction more thoroughly by a new technique. The formulation of this method is presented initially and a special computer program "MAP-76" (Lotfi 2001a), is enhanced based on this approach. Utilizing this tool, the significance of rigorous fluid-foundation interaction is investigated and the results are compared with the approximate method for several ratios of foundation rock to dam concrete elastic modulus.

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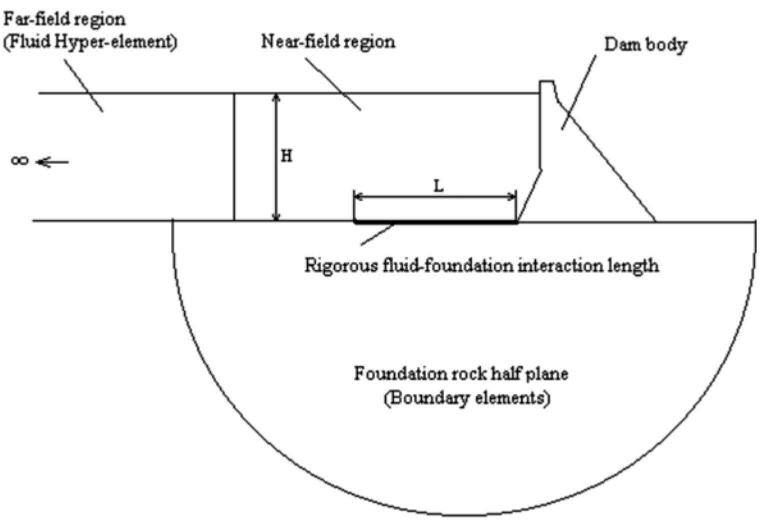


Fig. 1 Dam-reservoir-foundation system (Schematic representation)

2. Method of analysis

The analysis technique utilized in this study is based on the FE-BE-(FE-HE) method, which is applicable for a general dam-foundation-reservoir system (Fig. 1). This means, the dam is discretized by plane solid finite elements, while boundary elements are used for modeling of foundation rock half plane. Meanwhile, the reservoir is divided into two parts, a near field region (usually an irregular shape) in the vicinity of the dam and a far field part (assuming constant depth), which extends to infinity. The former region is discretized by plane fluid finite elements and the latter part is modeled by a two-dimensional fluid hyperelement.

The formulation could be explained much easier, if one concentrates initially on a dam with finite reservoir system (basically the same as a model of dam and reservoir near field), and subsequently add the effects of reservoir far field region and foundation domain for the general case. For this purpose, let us begin with this simpler formulation and then complete it on that basis.

2.1 Dam with finite reservoir system

This is the problem, which can be totally modeled by finite element method. It can be easily shown that in this case, the coupled equations of the system may be written as (Lotfi 2002):

$$\begin{bmatrix} \mathbf{M} & \mathbf{0} \\ \mathbf{B} & \mathbf{G} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{r}} \\ \ddot{\mathbf{p}} \end{bmatrix} + \begin{bmatrix} \mathbf{C} & \mathbf{0} \\ \mathbf{0} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{r}} \\ \dot{\mathbf{p}} \end{bmatrix} + \begin{bmatrix} \mathbf{K} & -\mathbf{B}^T \\ \mathbf{0} & \mathbf{H} \end{bmatrix} \begin{bmatrix} \mathbf{r} \\ \mathbf{p} \end{bmatrix} = \begin{bmatrix} -\mathbf{MJa}_g \\ -\mathbf{BJa}_g \end{bmatrix} \tag{1}$$

M, **C**, **K** in this relation represent the mass, damping and stiffness matrices of the dam body, while **G**, **L**, **H** are assembled matrices of fluid domain. The unknown vector is composed of **r**, which is the vector of nodal relative displacements and the vector **p** that includes nodal pressures. Meanwhile, **J** is a matrix with each two rows equal to a 2×2 identity matrix (its columns correspond to unit rigid body motion in horizontal and vertical directions) and $\mathbf{a}_g$ denotes the vector of ground accelerations. Furthermore, **B** in the above relation is often referred to as interaction matrix.

For harmonic ground excitations $\mathbf{a}_g(t) = \mathbf{a}_g(\omega)e^{i\omega t}$ with frequency ω, displacements and pressures will all behave harmonic, and the Eq. (1) can be expressed as:

$$\begin{bmatrix} -\omega^2\mathbf{M} + \mathbf{K}(1 + 2\beta_d i) & -\mathbf{B}^T \\ -\omega^2\mathbf{B} & -\omega^2\mathbf{G} + i\omega\mathbf{L} + \mathbf{H} \end{bmatrix} \begin{bmatrix} \mathbf{r} \\ \mathbf{p} \end{bmatrix} = \begin{bmatrix} -\mathbf{MJa}_g \\ -\mathbf{BJa}_g \end{bmatrix} \tag{2}$$

In this relation, it is assumed that the damping matrix of the dam is of hysteretic type. This means:

$$\mathbf{C} = \frac{2\beta_d}{\omega}\mathbf{K} \tag{3}$$

Where β_d is the constant hysteretic factor of the dam body. Relation (2) is the coupled equations of a dam with finite reservoir system in frequency domain which can be made symmetric by multiplying the lower partition matrices by a factor of ω^{-2}.

2.2 Pseudo-symmetric technique

Considering the coupled Eq. (2), it is noticed that unsymmetric terms are due to **B** matrix and its transpose appearing in this relation. This matrix is usually obtained by assemblage of contributing submatrices of interface elements located at fluid-solid contact, or even surfaces where fluid elements are adjacent to rigid or absorbing boundaries. However, to make it more convenient from programming point of view, one can eliminate these interface elements and consider its effect as part of adjacent fluid element matrices. In that case, matrices of the *i*th fluid element which contribute to the corresponding total mass, damping and stiffness matrices of the system would be generally as follows, respectively:

$$\mathbf{Q}_i^M = \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{B}_i & \mathbf{G}_i \end{bmatrix}, \quad \mathbf{Q}_i^C = \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{L}_i \end{bmatrix} \quad \text{and} \quad \mathbf{Q}_i^K = \begin{bmatrix} \mathbf{0} & -\mathbf{B}_i^T \\ \mathbf{0} & \mathbf{H}_i \end{bmatrix} \tag{4}$$

In the present work, interface elements are excluded and their effects are considered as part of fluid element matrices similar to the above explanation. However, everything is made symmetric from the very beginning. This means that fluid element matrices are considered symmetric artificially as below:

$$\mathbf{Q}_i^M = \begin{bmatrix} \mathbf{0} & \mathbf{B}_i^T \\ \mathbf{B}_i & \mathbf{G}_i \end{bmatrix}, \quad \mathbf{Q}_i^C = \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{L}_i \end{bmatrix} \quad \text{and} \quad \mathbf{Q}_i^K = \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{H}_i \end{bmatrix} \tag{5}$$

This presumption makes the method very convenient from programming point of view. However, it would yield to a coupled relation in the frequency domain, which is not really satisfied completely:

$$\begin{bmatrix} -\omega^2\mathbf{M} + \mathbf{K}(1 + 2\beta_d i) & -\omega^2\mathbf{B}^T \\ -\omega^2\mathbf{B} & -\omega^2\mathbf{G} + i\omega\mathbf{L} + \mathbf{H} \end{bmatrix} \begin{bmatrix} \mathbf{r} \\ \mathbf{p} \end{bmatrix} \triangleq \begin{bmatrix} -\mathbf{MJa}_g \\ -\mathbf{BJa}_g \end{bmatrix} \tag{6}$$

It is noticed that a special notation $\hat{=}$ is utilized in this relation. This is to emphasize that equality is slightly damaged due to an extra ω^2 factor appearing in the second term of the upper partition of this relation in comparison to Eq. (2). When this term is corrected, it is noticed that the lower partitions are also required to be multiplied by ω^{-2} to preserve symmetry. Of course, it must be mentioned that in actual programming, the total dynamic stiffness matrix (i.e., the resulting left hand side matrix of Eq. (6)) could be stored based on symmetric skyline technique and the two above-mentioned steps would be simply performed by multiplying the columns corresponding to pressures degree of freedom by a factor of ω^{-2}, while the same factor is also applied to the lower partition of right hand side vector. In this manner, the final coupled equations of the dam with finite reservoir system in the frequency domain would be:

$$\begin{bmatrix} -\omega^2\mathbf{M} + \mathbf{K}(1 + 2\beta_d i) & -\mathbf{B}^T \\ -\mathbf{B} & \omega^{-2}(-\omega^2\mathbf{G} + i\omega\mathbf{L} + \mathbf{H}) \end{bmatrix} \begin{bmatrix} \mathbf{r} \\ \mathbf{p} \end{bmatrix} = \begin{bmatrix} -\mathbf{MJa}_g \\ -\omega^{-2}\mathbf{BJa}_g \end{bmatrix} \tag{7}$$

The above approach could be visualized as the frequency domain extension of the Pseudo-Symmetric technique originally explained elsewhere for time domain (Lotfi 2002).

In this manner, the usual interface elements are excluded and their effects are considered as part of the adjacent fluid finite element matrices. Meanwhile, all these matrices are made symmetric artificially from the very beginning. Therefore, usual symmetric memory allocation and efficient symmetric skyline solvers could be employed. Of course, slight adjustments are required to be implemented as discussed above, before the actual equations solving routine is started.

This approach is very convenient as a technique for general-purpose finite element programs in regard to their fluid-structure module in frequency domain, since the program would not even feel the slightest non-symmetry even at the element level, while the interface elements are also excluded.

2.3 Reservoir near field boundary conditions

As mentioned in the previous section, the boundary conditions for reservoir near field (except at the water surface which is easily applied), are usually implemented by the help of interface elements. However, these elements could be excluded and their effects could be incorporated in the adjacent fluid elements. On that basis, the fluid element matrices are in general as shown in relations (5), and depending on the type of condition utilized, either one of the matrices $\mathbf{L}_i$, $\mathbf{B}_i$ or both will be generated. Of course, it is clear that if the fluid element is not adjacent to boundary, there is no need for these matrices and displacement degrees of freedom are excluded for those elements. In the case of perimetral fluid elements (adjacent to reservoir near field boundary), there are three types of conditions as listed in Table 1, which could be imposed.

It should be mentioned that in relations of Table 1, the constants ρ, c are mass density and compression wave velocity of water, respectively. Furthermore, n is the reservoir near field outward normal direction, a_g^n, the free field ground acceleration in the n-direction and q is the admittance or a damping coefficient for the corresponding boundary (Fenves and Chopra 1984). The coefficient q is also related to a more meaningful wave reflection coefficient α,

$$\alpha = \frac{1 - qc}{1 + qc} \tag{8}$$

Table 1 Conditions for reservoir near field Boundary

Type	Relation	Generation of Matrices	
		$\mathbf{L}_i$	$\mathbf{B}_i$
I	$\frac{\partial p}{\partial n} = -\rho \ddot{u}_n$	No	Yes
II	$\frac{\partial p}{\partial n} = -\rho a_g^n - q\frac{\partial p}{\partial t}$	Yes	Yes
III	$\frac{\partial p}{\partial n} = -\frac{1}{c}\frac{\partial p}{\partial t}$	Yes	No

which is defined as the ratio of the amplitude of the reflected hydrodynamic pressure wave to the amplitude of a propagating pressure wave incident on the reservoir' boundary in the normal direction.

The condition of type I, is considered for the contact of fluid with flexible solid, such as the dam-reservoir interface or even fluid-foundation interface, if the interaction is going to be treated rigorously. The second type of condition is the so-called approximate boundary condition. This can be imposed at the reservoir bottom for an approximate treatment of fluid-foundation interaction. The last type of condition (III) is referred to as Sommer-feld boundary condition. This is usually applied at the reservoir near field upstream boundary (in cases which far field region is not modeled), as a substitute for a precise transmitting boundary. However, when a fluid hyperelement is utilized, this condition is not required and waves are transmitted exactly through that semi-infinite element.

2.4 Dam-foundation-reservoir system

In regard to the formulation for a general dam-foundation-reservoir system, one can start from relation (7), which is for a system of dam with finite reservoir. Then, add the effects of incorporated foundation and the reservoir far field region extending to infinity. It can be easily shown (following steps similar to other studies (Lotfi and Sharghi 2001, Lotfi 2001b)) that the resulting relation can be written as follows:

$$\begin{bmatrix} -\omega^2\mathbf{M} + \mathbf{K}(1+2\beta_d i) + \bar{\mathbf{S}}_r(\omega) + \bar{\mathbf{S}}_f(\omega) & -\mathbf{B}^T \\ -\mathbf{B} & \omega^{-2}(-\omega^2\mathbf{G} + i\omega\mathbf{L} + \mathbf{H}) \end{bmatrix} \begin{bmatrix} \mathbf{r} \\ \mathbf{p} \end{bmatrix} = \begin{bmatrix} -\mathbf{MJa}_g \\ -\omega^{-2}\mathbf{BJa}_g \end{bmatrix} + \begin{bmatrix} \bar{\mathbf{F}}_p(\omega)\mathbf{a}_g \\ \mathbf{0} \end{bmatrix} \tag{9}$$

Where $\bar{\mathbf{S}}_f(\omega)$ is the expanded form of the foundation rock impedance matrix obtained through boundary element formulation. Meanwhile, $\bar{\mathbf{S}}_r(\omega), \bar{\mathbf{F}}_p(\omega)$ are the expanded dynamic stiffness matrix of the reservoir hyperelement and its corresponding particular force matrix, respectively (Lotfi 2001b).

It must be mentioned that the hyperelement is assumed to be formulated in terms of relative horizontal displacement of the nodes and one relative vertical displacement degree of freedom located at the base. Therefore, type I condition must be used for adjacent fluid elements in the reservoir near field region to provide the appropriate coupling at that contact surface.

2.5 Special cases

The formulation for dam-foundation-reservoir system was presented in the previous section. However, it should be realized that the general relation (9) could be easily transformed to several special cases. Dam-reservoir relation (based on FE-(FE-HE) technique) could be obtained by simply deleting $\bar{\mathbf{S}}_f(\omega)$ matrix in that relation. Dam-foundation with a finite reservoir could be modeled (FE-BE-FE) by eliminating $\bar{\mathbf{S}}_r(\omega)$, $\bar{\mathbf{F}}_p(\omega)$ from that relation, while imposing type I or II condition (depending on interaction treatment) for the adjacent fluid elements at the upstream end of the reservoir. Moreover, in the special case of dam-foundation with a regular shape reservoir system and assuming an approximate fluid-foundation interaction model, one can eliminate the rows and columns corresponding to pressure degrees of freedom in relation (9), which results in the following relation based on a FE-BE-HE technique used in other studies (Lotfi 2001b):

$$[-\omega^2\mathbf{M} + \mathbf{K}(1 + 2\beta_d i) + \bar{\mathbf{S}}_r(\omega) + \bar{\mathbf{S}}_f(\omega)][\mathbf{r}] = [-\mathbf{MJa}_g + \bar{\mathbf{F}}_p(\omega)\mathbf{a}_g] \tag{10}$$

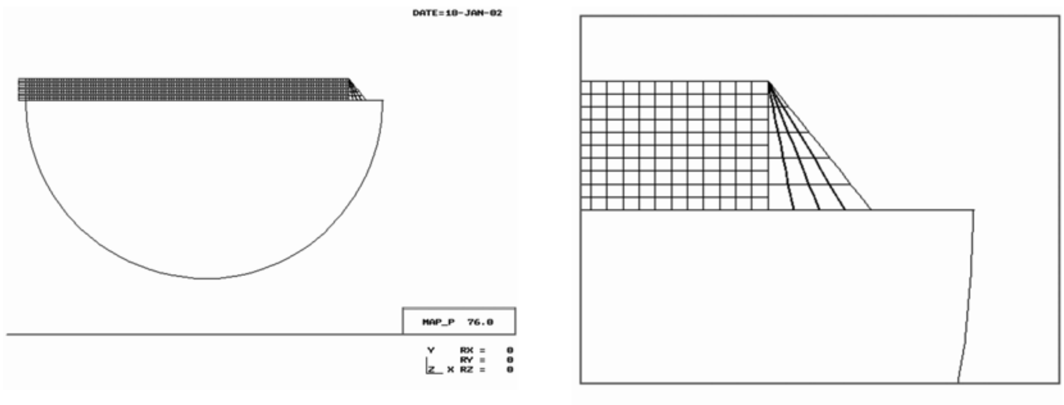
As mentioned before, the hyperelement is formulated in terms of relative horizontal displacements and the base relative vertical displacement degrees of freedom. Therefore, its coupling with the dam is easily possible as shown in relation (10) for that special case.

3. Modeling and basic parameters

A special computer program “MAP-76” (Lotfi 2001a) is used as the basis of this study. The program was originally based on the FE-BE-HE technique. That is the dam body and the foundation rock are treated by finite and boundary elements respectively, while a hyperelement was considered for modeling of the reservoir.

In this study, the program is modified such that plane fluid finite elements could be introduced in the reservoir near field. By employing type I condition on the upstream and downstream faces of this region, the fluid elements could be readily coupled with the hyperelement and the plane solid finite elements. Meanwhile, two types of conditions are generally imposed at the base of the reservoir near field region. Type I condition is considered for a distance L (specified by the user) near the dam heel, which allows for rigorous fluid-foundation interaction on that range, and the remaining length of the base is considered as a type II condition (approximate interaction). By changing the value of L, one can easily transform the whole base of the reservoir near field to a rigorous fluid-foundation interaction condition or alternatively an approximate one.

It should be noted that the problem is also assumed in a state of plane strain and both dam body and the foundation rock domains are assumed as linearly viscoelastic materials with isotropic behavior.



(a) (b)

Fig. 2 Dam-reservoir-foundation system: (a) Complete model, (b) Close-up view

3.1 Model

An idealized triangular dam with vertical upstream face and a downstream slope of 1:0.8 is considered on a flexible half plane under a full reservoir condition. The discretization of the complete system is displayed in Fig. 2(a), while a close-up view for the neighborhood of dam body is also depicted in Fig. 2(b).

The dam is discretized by 20 isoparametric 8-node finite elements, while the foundation rock is modeled by 72 isoparametric 3-node boundary elements considered at the foundation surface. A length of 15H (H = water depth) is considered as the reservoir near field region, which is modeled by 1200 isoparametric 4-node fluid finite elements. The reservoir far field is treated by a fluid hyperelement having 11 nodes with only a horizontal displacement degree of freedom at each node, except at the base where both horizontal and vertical displacement degrees of freedom exist.

3.2 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 β_d = 0.05.

The impounded water is taken as inviscid, 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, and 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 foundation rock elastic modulus (E_f), which was initially chosen to be equal to the concrete elastic modulus. However, in the second part of the investigations, it was varied to cover a wide range of foundation materials. The hysteretic damping factor β_f = 0.05 is also specified for this material.

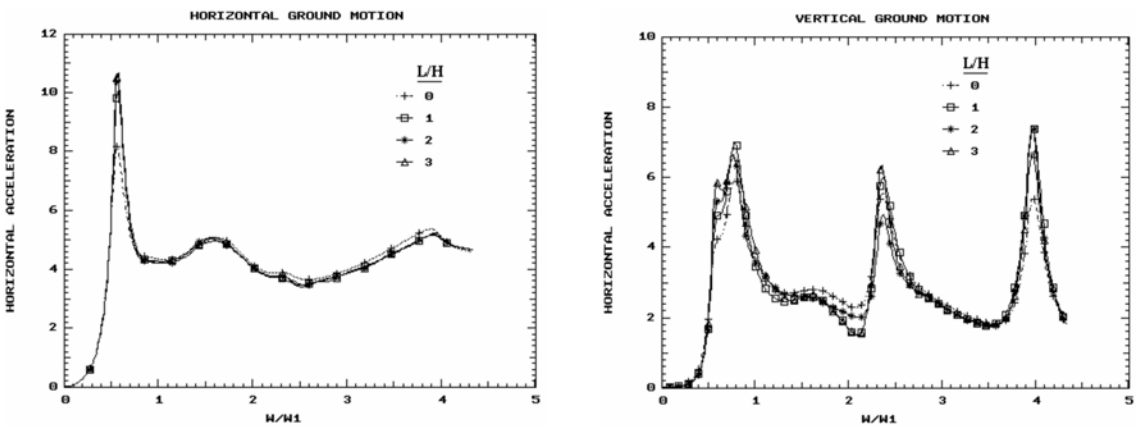


Fig. 3 Horizontal accelerations at dam crest due to horizontal and vertical ground motions for low values of normalized rigorous fluid-foundation interaction length

4. Results

The first stage of the study is concentrated on the effects of parameter L (rigorous fluid-foundation interaction length (Fig. 1)) in the response of the dam. For this purpose, three sets of low, moderate and high values of L are considered.

In this part, the foundation rock elastic modulus is set equal to the dam concrete elastic modulus. Based on this selection and the properties mentioned before, the wave reflection coefficient is obtained as α = 0.71. This is only utilized for type II condition, which is imposed over the remaining length of the reservoir base where the fluid-foundation interaction is not treated rigorously. Therefore, for L = 0, the interaction is completely treated approximately, while for high values of L, one can expect results similar to the case where the rigorous interaction length is infinite.

The response of horizontal acceleration at dam crest due to horizontal and vertical harmonic ground excitations are presented in Fig. 3 for low values of interaction length.

It is noticed that for horizontal ground motion, the main difference in response is occurring near the fundamental frequency of the system. Meanwhile, the responses for L/H (rigorous fluid-foundation interaction length normalized with respect to water depth) values of 2 and 3 are very close for the whole range of considered frequencies.

As for the vertical ground motion, it is observed that the responses differ at several frequency regions. These are intervals in the vicinities of fundamental frequency of the system and the reservoir natural frequencies. Furthermore, the difference between the results corresponding to L/H values of 2 and 3 are significant at these frequency intervals.

For higher values of normalized rigorous interaction lengths, the results for horizontal ground motion are practically the same as for L/H = 3 presented. Therefore, it is not shown anymore, and the results for L/H = 3 can be considered as the converged solution. However, for vertical ground motion, the trend is quite different. For this type of excitation, the results are compared in Fig. 4 for two sets of moderate and high values of normalized rigorous interaction length, while the response for L/H = 0 is also shown as a reference in each case. It is noticed that for moderate L/H values,

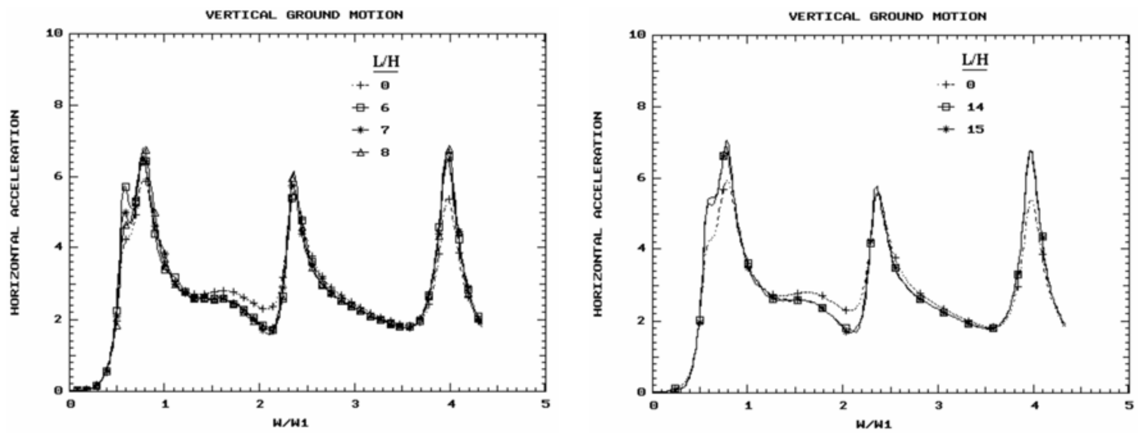


Fig. 4 Horizontal accelerations at dam crest due to vertical ground motion for two sets of moderate and high values of normalized rigorous fluid-foundation interaction length

the differences occurring at natural frequencies of the reservoir become negligible. However, there are still significant differences among the responses near the fundamental frequency of the system. For very high values of L/H, the difference in response becomes negligible even near the fundamental frequency of the system. Therefore, the result for L/H = 15 can be considered as the converged solution for vertical ground motion. Moreover, comparing the results for L/H = 0 and 15, it is noticed that there are significant differences in response occurring near the fundamental frequency of the system, as well as the peaks corresponding to the first and third natural frequencies of the reservoir.

It is worthwhile to mention that in other studies (Medina *et al.* 1990), it was concluded that effect of rigorous fluid-foundation interaction is not significant for vertical ground motion. This was in spite of the fact; they had noticed some differences in comparison with an earlier study that fluid-foundation interaction was treated approximately. This judgment is not correct and it was partially induced because; they attributed the differences in response mainly to the coarse mesh of finite elements employed in the earlier study. This can be claimed by the fact that in this study, the model is totally the same in both rigorous and approximate cases as far as discretization or other basic assumptions are concerned, and the only difference is the type of condition utilized at reservoir-foundation interface, and still significant differences are noticed for vertical ground motion results.

In the second part of the investigations, 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. In particular, E_f/E_d ratios of 2, 1, and ¼ are considered. The results for this part are presented in Figs. 5-7. In each graph, three cases are compared. These are curves related to cases which fluid-foundation interactions are excluded, treated approximately and considered rigorously.

It must be mentioned that results for excluding interaction cases are obtained similar to approximate cases (Type II condition implemented at the reservoir base) except that wave reflection coefficient is specified as $\alpha = 1$ in these cases (total reflection condition). Further, the approximate cases correspond to models where rigorous interaction length are taken as zero (L = 0), while in the actual rigorous cases, these lengths are chosen equal to a large value (L = 15H). Moreover, the consistent α values for the approximate cases corresponding to E_f/E_d ratios of 2, 1, and ¼ (taking

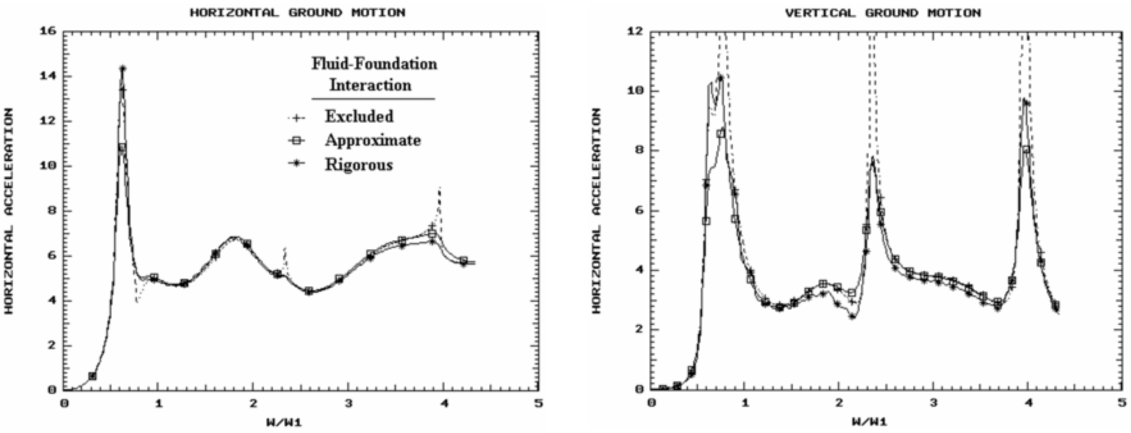


Fig. 5 Horizontal accelerations at dam crest due to horizontal and vertical ground motions (E_f/E_d = 2)

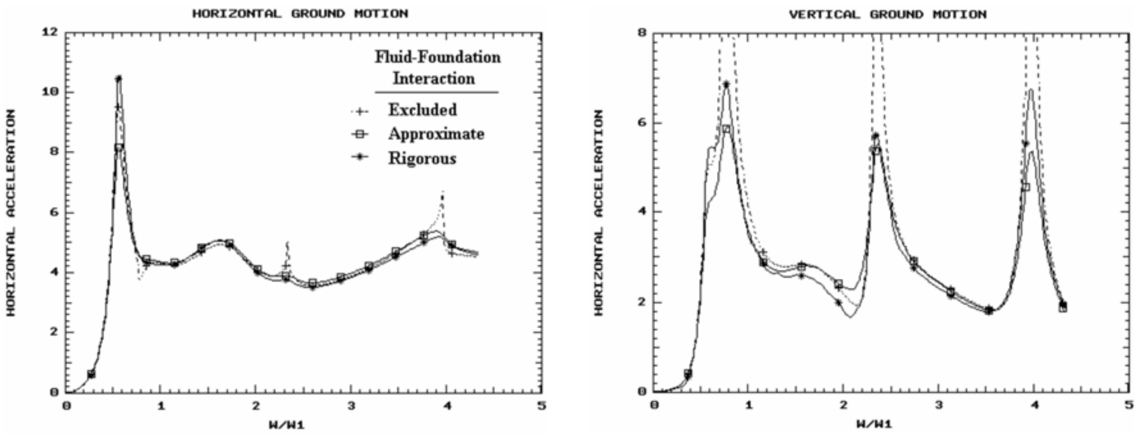


Fig. 6 Horizontal accelerations at dam crest due to horizontal and vertical ground motions (E_f/E_d = 1)

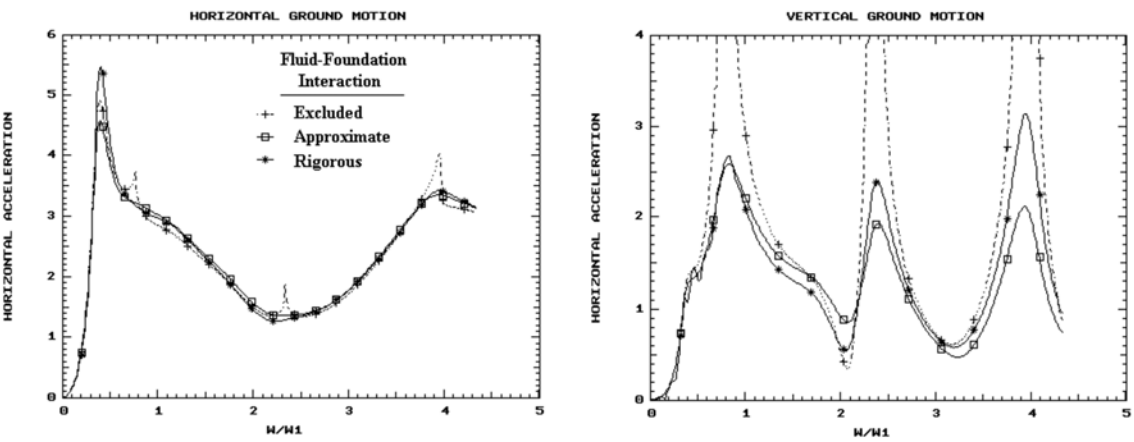


Fig. 7 Horizontal accelerations at dam crest due to horizontal and vertical ground motions (E_f/E_d = 1/4)

into account the other parameters previously mentioned) work out to be 0.787, 0.710 and 0.495, respectively.

From comparison of the results related to horizontal ground motion for E_f/E_d = 2, it is observed that there is significant difference in the peak response at the fundamental frequency of the system between the rigorous and approximate cases. Meanwhile, the response for rigorous case is even higher than the one where interaction is excluded. For other frequencies, the response of all three cases are very similar, and there are no major changes, except near natural frequencies of the reservoir, where some dips are noticed in the case related to excluding interaction, which are diminished in the other two cases. Similar behavior is consistently noticed for other ratios of E_f/E_d as well.

For vertical ground motion, it is clear that response becomes infinite at reservoir natural frequencies when the reservoir-foundation interaction is excluded ($\alpha = 1$). However, for approximate, as well as rigorous cases, it is noticed that response is bounded at these frequencies, while the peaks corresponding to rigorous cases are higher than approximate cases, except at the first natural frequency of the reservoir related to E_f/E_d = 1/4, where the peak for rigorous case is slightly lower than the approximate case. It is also observed that at the fundamental frequency of the system, the trend is similar to the response for horizontal ground motion. That is, the response for rigorous case is higher than approximate case and even set slightly over the case where interaction is excluded. However, contrary to horizontal ground motion, this increase in response becomes negligible for low ratio of foundation rock to dam concrete elastic modulus (E_f/E_d = 1/4).

To evaluate the importance of rigorous fluid-foundation interaction more precisely, percent increase in response for rigorous cases with respect to approximate ones are also calculated and summarized in Table 2. These quantities are determined at peaks corresponding to fundamental frequency of the system and the first three natural frequencies of the reservoir.

It is noticed that for horizontal ground motion, the maximum value is 32% corresponding to E_f/E_d = 2, occurring at the fundamental frequency of the system. This increase in response, decreases slowly as the foundation becomes softer.

For vertical ground motion, the maximum increase at the fundamental frequency of the system is 40% related to E_f/E_d = 2, which is even more significant than the corresponding value for horizontal excitation. However, contrary to horizontal ground motion results, this increase in response decreases very rapidly as the foundation becomes softer. Significant increases in response

Table 2 Increase in response for rigorous interaction method in comparison to approximate case

Ground Motion	E_f/E_d	Increase in response (%)			
		At the fundamental frequency of the system	At the natural frequencies of the reservoir		
			First	Second	Third
Horizontal	2	32	*	*	*
	1	30	*	*	*
	1/4	20	*	*	*
Vertical	2	40	22	*	23
	1	28	17	*	27
	1/4	*	*	24	50

Note: * stands for negligible increase or even slight decrease in response

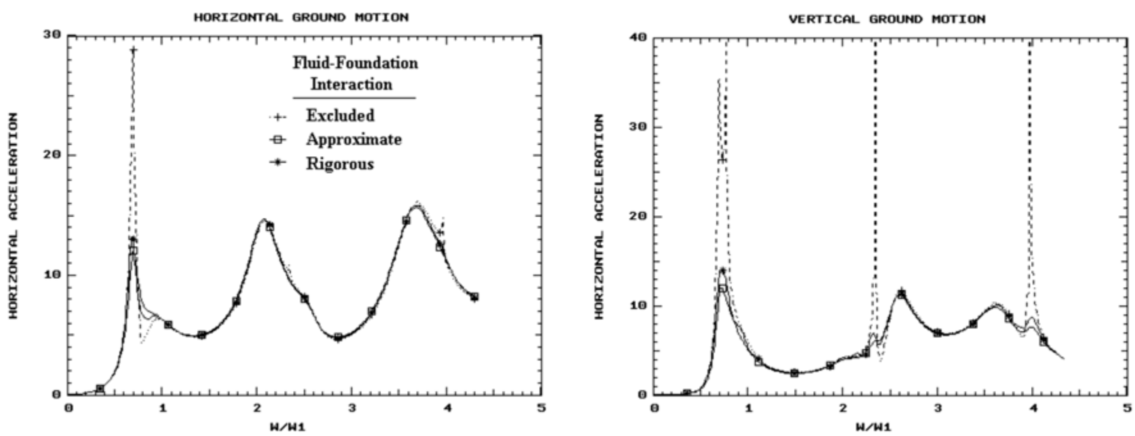


Fig. 8 Horizontal accelerations at dam crest due to horizontal and vertical ground motions (Fictitious cases: $E_f/E_d = 1$ and rigid dam base)

are also noticed at natural frequencies of the reservoir with a maximum value of 50% occurring for E_f/E_d = 1/4. Therefore, it can be concluded that rigorous fluid-foundation interaction could also become important for vertical ground motion, and in some cases increase in response with respect to approximate case would be much higher than what is obtained for horizontal ground motion.

At this point, the importance of rigorous fluid-foundation interaction has become clear. However, a question remains to be answered. That is why the responses at the fundamental frequency of the system are higher in rigorous cases than cases where interactions are excluded. To examine this behavior, it was decided to study three cases similar to the cases corresponding to $E_f/E_d = 1$, already considered. Everything in these new cases, are the same as the ones mentioned previously, except that the displacement degrees of freedom at the dam base are fixed. This would create three fictitious cases, which dam-foundation rock interactions are excluded, even though the foundation is present in the models. It should be noted that this would actually eliminate the coupling of the foundation impedance matrix with the rest of the system for the first two cases which fluid-foundation interactions are excluded or treated approximately. However, the coupling still exists for the rigorous interaction case through the reservoir-foundation interface.

The results for these three fictitious cases are presented in Fig. 8. It is noticed that for horizontal excitation, the response at the fundamental frequency of the system for the rigorous fluid-foundation interaction case is much closer to the case which interaction is treated approximately in comparison to real cases. Meanwhile, both of these responses are significantly lower than the response related to the case which interaction is excluded. Similar observations are noticed for responses due to vertical excitation.

This change in trend for the fictitious cases in comparison to the real cases reveals the importance of a factor, which is missing when the fluid-foundation interaction is excluded or treated approximately. This factor relates to the fact that hydrodynamic pressures are not exerted over the foundation surface at the reservoir base when the fluid-foundation interaction is excluded or treated approximately. Therefore, it is believed that in real cases, these hydrodynamic pressures cause the additional increase in response at the fundamental frequency of the system for the rigorous cases in comparison to approximate cases, such that the responses are even higher than those corresponding to excluding interaction cases. These pressures influence the response of the dam mainly through its base, which was artificially disrupted in fictitious cases. Of course, for low ratios of foundation rock to dam concrete elastic modulus (E_f/E_d = 1/4), the increase in response at the fundamental frequency of the system due to vertical ground motion is negligible as already mentioned.

5. Conclusions

A formulation was presented for dynamic analysis of concrete gravity dams in the frequency domain based on the FE-BE-(FE-HE) method. The special computer program "MAP-76" was enhanced by this technique, and the response of an idealized dam-foundation-reservoir system was studied taking into account the fluid-foundation interaction rigorously. Overall, this investigation leads to the following conclusions:

- In general, rigorous fluid-foundation interaction effects could be important for both horizontal and vertical ground motions.

For the horizontal ground motion, it was observed that:

- The effective rigorous fluid-foundation interaction length is in the order of L = 3H.
- The main difference in the response utilizing rigorous interaction in comparison to approximate one, occur near the fundamental frequency of the system.
- The maximum increase in the peak response for rigorous case in comparison to approximate case is 32% and it corresponds to E_f/E_d = 2. As the ratio E_f/E_d decreases, the increase in the peak response is lowered. However, even for low ratios of foundation rock to dam concrete elastic modulus (E_f/E_d = 1/4), the increase is still significant.

For the vertical ground motion, the following observations were noted:

- A rigorous fluid-foundation interaction length in the order of L = 15H is required for the solution to converge.
- The response utilizing rigorous interaction in comparison to approximate one, differ at several frequency regions. These are intervals in the vicinities of the fundamental frequency of the system and the reservoir natural frequencies.
- The maximum increase in the response at the fundamental frequency of the system is 40% for the rigorous case in comparison to the approximate case and it corresponds to E_f/E_d = 2, which is even more significant than the corresponding value for horizontal excitation. However, contrary to horizontal ground motion results, this increase in response decreases very rapidly as the foundation becomes softer.
- Significant increases in response are also noticed at the natural frequencies of the reservoir for the rigorous cases in comparison to the approximate cases with a maximum value of 50% occurring for E_f/E_d = 1/4.
- Although the difference between the response of the rigorous and approximate models due to vertical excitation becomes negligible near the fundamental frequency of the system or first natural frequency of the reservoir for the soft foundation case considered (E_f/E_d = 1/4), it increases appreciably at higher natural frequencies of the reservoir.

Moreover, for both excitations, it could be claimed that:

- An important factor, which is missing when the fluid-foundation interaction is treated approximately, relates to the fact that hydrodynamic pressures are not exerted over the foundation surface at the reservoir base. Therefore, it is believed that in real cases, these pressures cause the additional increase in response at the fundamental frequency of the system for the rigorous case in comparison to approximate case, such that the response is even higher than the one corresponding to excluding interaction case. These pressures influence the response of the dam mainly through its base.

References

Fenves, G. and Chopra, A.K. (1984), "Earthquake analysis and response of concrete gravity dams", Report No. UCB/EERC-84/10, University of California, Berkeley, CA.

Hall, J.F. and Chopra, A.K. (1980), "Dynamic response of embankment, concrete gravity and arch dams including hydrodynamic interaction", Report No. UCB/EERC-80/39, University of California, Berkeley, CA.

Lotfi, V. (2001a), "MAP-76: A program for analysis of concrete dams", Amirkabir University of Technology, Tehran, Iran.

Lotfi, V. (2001b), "Frequency domain analysis of concrete gravity dams including hydrodynamic effects", *Journal of Dam Engineering*, **XII**, Issue 1.

Lotfi, V. (2002), "Seismic analysis of concrete dams using Pseudo-Symmetric technique", *Journal of Dam Engineering*, **XIII**, Issue 2.

Lotfi, V. and Sharghi, M.R. (2001), "Direct frequency domain analysis of concrete gravity dams based on the FE-BE procedure", *Journal of Dam Engineering*, **XI**, Issue 4.

Medina, F., Dominguez, J. and Tassoulas, J.L. (1990), "Response of dams to earthquakes including effects of sediments", *J. Struct. Eng.*, ASCE, **116**, 3108-3121.