EFFECTS OF RESERVOIR LENGTH ON DYNAMIC ANALYSIS OF CONCRETE GRAVITY DAMS

A. Fathi[1] and V. Lotfi[2]

[1] *M.Sc. Student, Dept. of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran.*
[2] *Professor, Dept. of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran.*
Email: arash4wd@yahoo.com , vahlotfi@aut.ac.ir

ABSTRACT :

In dynamic analysis of concrete gravity dams, most engineers consider the water domain as a semi-infinite fluid region. However, there are practical cases that the reservoir cannot be treated as a uniform infinite channel. This is likely to happen when the stream meanders near the dam. In such a case, the reservoir can no longer be considered of infinite length. The purpose of this study is to show that the length of the reservoir affects the response significantly and it should not be modeled as an infinite domain in general.
In this study, dam-reservoir, dam-foundation and reservoir-foundation interactions are all treated rigorously based on a combined finite element-boundary element procedure. A computer program is developed on this basis and results are compared for a triangular dam.

KEYWORDS: Dam-Reservoir-Foundation Interaction, Finite Reservoir Length, Concrete Gravity Dam, Boundary Element

1. INTRODUCTION

An accurate dynamic analysis of concrete gravity dams requires special attention for the interactions involved in this problem [1,2]. These are dam-reservoir, dam-foundation and reservoir-foundation (fluid-foundation) interactions. The analysis can be performed completely either by the boundary element method [2,3] or a combined finite element-boundary element procedure [4].
In most practical cases, reservoir is not located exactly along the dam and it usually meanders. However, most engineers do not consider the exact geometry of the reservoir and treat it as a uniform infinite channel. This may be due to the heavy computational costs of considering the exact geometry of the reservoir and adjacent foundation elements. On the other hand, availability of economical boundary conditions for the upstream face of the reservoir makes it more appealing for analysts to consider it as a semi-infinite domain. Rigorous treatment of dam-infinite reservoir-foundation system is displayed in Fig. 1, while schematic plan and model of the problem of our interest are depicted in Fig. 2.

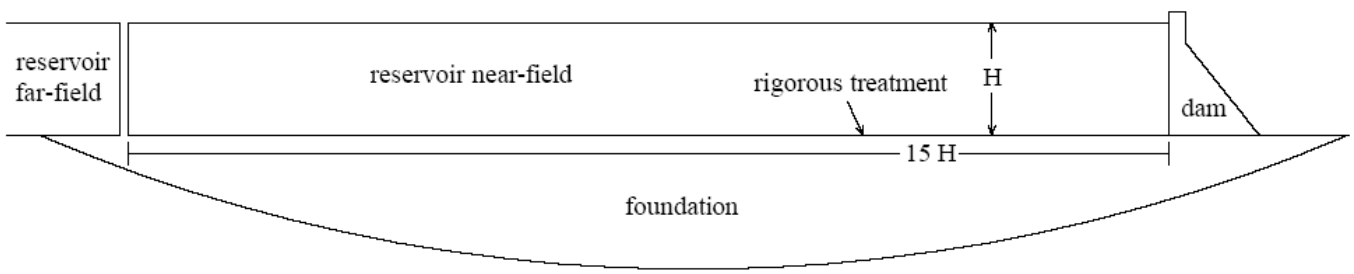

Figure 1 Rigorous treatment of dam-infinite reservoir-foundation system

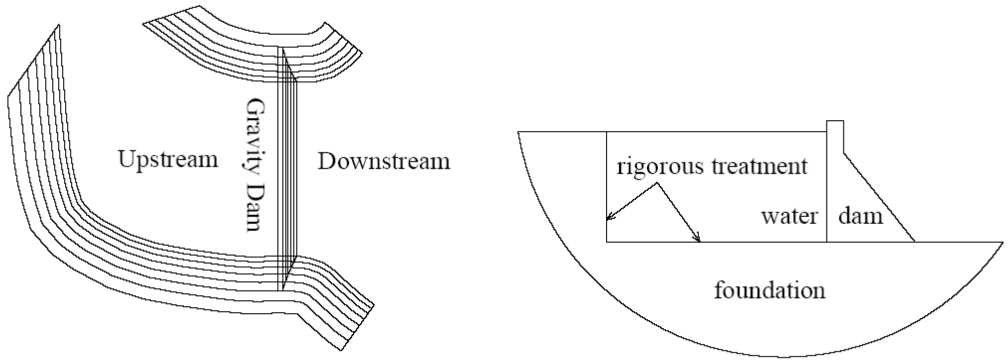

Figure 2 Dam with finite reservoir system, schematic plan and model

The purpose of this study is to evaluate the significance of modeling the specific length of the reservoir rather than considering it as a semi-infinite domain. To this end, frequency response functions of an idealized concrete gravity dam are studied extensively, considering different cases for the length of the reservoir.

2. METHOD OF ANALYSIS

The analysis technique utilized in this study is based on the FE-(FE-HE)-BE method, which is applicable for a general dam-reservoir-foundation system. That means dam body is discretized by plane solid finite elements, while the reservoir domain is considered by a combination of fluid finite elements and a two-dimensional fluid hyper-element. However, fluid hyper-element is used only when the reservoir is treated as a uniform infinite channel and if it is of limited length, this part is omitted. Furthermore, the foundation rock domain is represented by a two-dimensional boundary element formulation. It should be also mentioned that in this approach, the geometry of the foundation rock could be quite arbitrary which leads to different reservoir geometries. However, to avoid complexity in deriving conclusion, only rectangular geometry is considered for the reservoir.
Following details given elsewhere [4,7], the coupled equations of the dam-reservoir-foundation system can be written as:

$$\begin{bmatrix} -\omega^2 \mathbf{M}+\mathbf{K}\,(1+2\,\beta_d\;i\,)+\overline{\mathbf{S}}_f\;(\omega) & -\mathbf{B}^T \\ -\mathbf{B} & \omega^{-2}((-\,\omega^2\,\mathbf{G}+i\,\omega\mathbf{L}+\mathbf{H}\,)+\overline{\mathbf{H}}_h(\omega)) \end{bmatrix} \begin{bmatrix} \mathbf{r} \\ \mathbf{P} \end{bmatrix} = \begin{bmatrix} -\mathbf{M}\mathbf{J}\mathbf{a}_g \\ \omega^{-2}(-\mathbf{B}\mathbf{J}\mathbf{a}_g+\overline{\mathbf{R}}_p(\omega)\mathbf{a}_g) \end{bmatrix} \quad (2.1)$$

$\mathbf{M}$ and $\mathbf{K}$ in this relation represent the mass and stiffness matrices of the dam body while $\mathbf{G}, \mathbf{L}, \mathbf{H}$ are assembled matrices of fluid domain. The unknown vector is composed of $\mathbf{r}$, which is the vector of nodal relative displacements and the vector $\mathbf{p}$ that includes nodal pressure. Meanwhile, $\mathbf{J}$ 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 in the frequency domain. Furthermore, $\mathbf{B}$ in the above relation is often referred to as the interaction matrix. Meanwhile, it is assumed that the damping matrix of the dam is of hysteretic type and β_d is the constant hysteretic factor of the dam body.
In this relation, $\overline{\mathbf{S}}_f(\omega)$ is the extended form of the foundation rock impedance matrix obtained through boundary element formulation [5]. Meanwhile, $\overline{\mathbf{H}}_h(\omega)$, $\overline{\mathbf{R}}_p(\omega)$ are the expanded dynamic stiffness matrix of reservoir hyper-element and its corresponding particular force matrix, respectively [6].
It should be realized that Eqn. 2.1 could be easily transformed to several special cases. Dam-reservoir relation (based on FE-(FE-HE) technique) could be obtained by simply deleting $\overline{\mathbf{S}}_f(\omega)$ matrix in that relation. Dam with a finite reservoir on flexible foundation (FE-FE-BE) could be modeled by eliminating $\overline{\mathbf{H}}_h(\omega)$, $\overline{\mathbf{R}}_p(\omega)$ from that relation, while imposing appropriate boundary condition for the adjacent fluid elements at the upstream end of the reservoir.

3. MODELING AND BASIC DATA

An idealized triangular dam with vertical upstream face and a downstream slope of 1:0.8 is considered on a flexible foundation under a full reservoir condition.
For models that the reservoir is treated as a uniform infinite channel, the dam is discretized by 20 isoparametric 8-node finite elements, while the foundation rock is modeled with 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 375 isoparametric 8-node fluid finite elements [4]. The reservoir far-field is treated by a fluid hyper-element having 11 nodes.
The same model of dam is used for cases that their reservoir has a limited length. However, the number of fluid finite elements and foundation boundary elements depends on the length of the reservoir and its specific geometry. Fig. 3 shows one of these cases that the length of the reservoir is twice the height of the dam (L/H=2). It should be noted that in these cases, upstream face of the reservoir is also in contact with foundation boundary elements that makes rigorous treatment of fluid-foundation interaction possible.

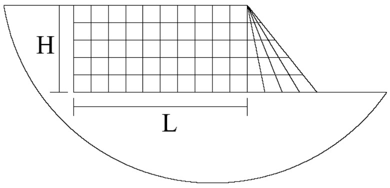

Figure 3 Discretization of dam-finite reservoir-foundation system for the case of L/H=2

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 $\mathrm{kN/m^3}$, and hysteretic damping factor β_d = 0.05.
The impounded water is taken as inviscid, and compressible fluid with unit weight = 9.81 $\mathrm{kN/m^3}$, and pressure wave velocity = 1440. m/sec.
The foundation rock is idealized as a homogenous and isotropic viscoelastic media. The material properties of this region are: Poisson's ratio = $1/3$, and unit weight = 26.4 $\mathrm{kN/m^3}$. The foundation rock elastic modulus (E_f) is varied to cover a wide range of foundation materials. The hysteretic damping factor β_f = 0.05 is also specified for this material.

4. RESULTS

The response of horizontal acceleration at dam crest due to horizontal and vertical harmonic ground excitations are obtained for different values of reservoir length and foundation rock elastic modulus. Different lengths for the reservoir can be represented simply by the value of L/H where in this case, L represents the length of the reservoir which is bounded and treated by fluid finite elements and H is water depth. In particular, L/H ratios of 1 to 15 are studied. The results for this part are presented in Figs. 4-7 while the response for the infinite reservoir is also shown as a reference in each case.
Response functions of horizontal acceleration at dam crest due to horizontal harmonic ground excitation are presented in Figs. 4-5. It is noticed that the nature of the amplitude of response is quite oscillatory with respect to frequency. This is due to partial reflection of pressure waves at the upstream face of the reservoir. Meanwhile, the oscillation in response generally begins at the first natural frequency of the reservoir and keeps its presence even for very high values of L/H. This is the frequency that pressure waves start to propagate in the reservoir. It is worthwhile to mention that in the presence of fluid hyper-element, when the reservoir is treated as a uniform infinite channel, these waves could pass that boundary completely.
Concentrating on $E_f/E_d = 2$, the response for L/H=1 through 3 is substantially lower than the infinite case at the fundamental frequency of the system. However, as L/H increases, the difference decreases at this frequency but is still significant at other frequency regions. For higher values of L/H, there is no significant difference in the vicinity of the

fundamental frequency of the system. However, significant oscillation can be observed for other frequency regions even for very high values of L/H.

Response functions for other values of E_f/E_d are also presented. It is seen that as the foundation becomes softer, the oscillation in the response tends to disappear. Although response functions for reservoirs with finite domain behave oscillatory, they slowly converge to the response of a dam with an infinite reservoir as the value of L/H is increased and E_f/E_d is decreased.

Figs. 6-7 show horizontal acceleration at dam crest due to vertical harmonic ground motion. Considering the case of $E_f/E_d = 2$, significant differences are observed between cases of L/H=1 through 3 and the infinite case. Meanwhile, response functions behave oscillatory similar to the case of horizontal ground motion. However, as the value of L/H increases, oscillations tend to lessen in the vicinities of the first three natural frequencies of the reservoir. It is also noticed that oscillation in response tends to decrease faster than the cases of horizontal ground motion as L/H increases. Considering other values of foundation rock to dam concrete elastic modulus, as foundation becomes softer, oscillation decreases. However, slight oscillation can be seen at the fundamental frequency of the system even for very high values of L/H and soft foundations.

5. CONCLUSION

A formulation was briefly discussed for dynamic analysis of concrete gravity dams in the frequency domain based on the FE-(FE-HE)-BE method. A computer program was developed by this technique, and the response of an idealized dam-reservoir-foundation system was studied. All interactions were treated rigorously. Overall, the following conclusions are obtained:

It is important to model the reservoir as a bounded domain for low values of L/H and hard foundations. Specific length of the reservoir in the lower range influences the response significantly. As pressure waves cannot pass through the reservoir's upstream face completely, reflection of these waves contributes to the oscillatory nature of the response. The oscillation begins at the first natural frequency of the reservoir and for horizontal ground motion; this is considerable even for very high values of L/H. On the contrary, for vertical ground excitation, oscillation disappears slowly as L/H increases. Generally, as L/H increases and foundation becomes softer, the oscillation tends to disappear.

For both horizontal and vertical ground motions, it is observed that for very high values of L/H, response functions for a bounded and unbounded reservoir are in good agreement. One may also conclude that as E_f/E_d decreases, the response for the dam-reservoir system with lower L/H values would also resemble the one for a dam with infinite reservoir domain.

Finally, it is worthwhile to mention that the main disadvantage of the presented procedure is heavy computational costs of obtaining the impedance matrix of the foundation region especially for large L/H values.

REFERENCES

[1] 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.*

[2] Medina, F., Dominguez, J. and Tassoulas, J.L. (1990). Response of dams to earthquakes including effects of sediments. *Journal of Structural Eng. ASCE*, **116**, 3108-3121.

[3] Maeso, O., Aznarez, J. J., Dominguez, J. (2002). Effects of space distribution of excitation on seismic response of arch dams. *Journal of Engineering Mechanics*, **128:7**, 759-768.

[4] Lotfi, V. (2005). Significance of rigorous fluid-foundation interaction in dynamic analysis of concrete gravity dams. *Journal of Structural Engineering and Mechanics*, **21:2**, 137-150.

[5] Lotfi, V., and Sharghi, M.R. (2001). Direct frequency domain analysis of concrete gravity dams based on FE-BE procedure. *Journal of Dam Engineering*, **XI:4**, 273-291.

[6] Lotfi, V. (2001). Frequency domain analysis of concrete gravity dams including hydrodynamic effects. *Journal of Dam Engineering*, **XII:1**, 33-53.

[7] Fathi, A., Lotfi, V. (2008). Effects of reservoir length and rigorous fluid-foundation interaction on the frequency response functions of concrete gravity dams. Submitted to the *Journal of Structural Engineering and Mechanics*.

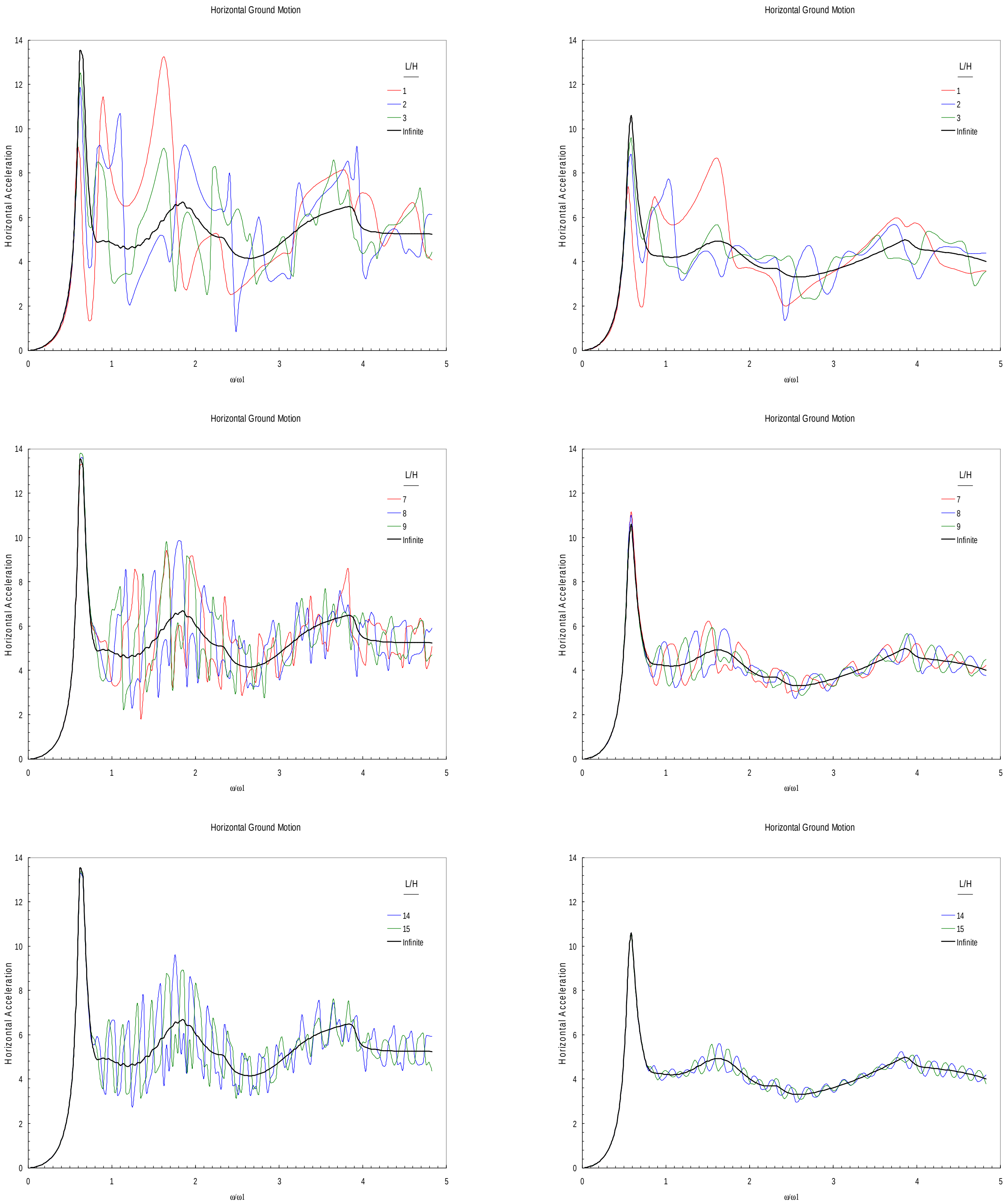

Figure 4 Horizontal acceleration at dam crest due to horizontal ground motion for different values of L/H

($E_f/E_d = 2$ is depicted on the left column and $E_f/E_d = 1$ on the right)

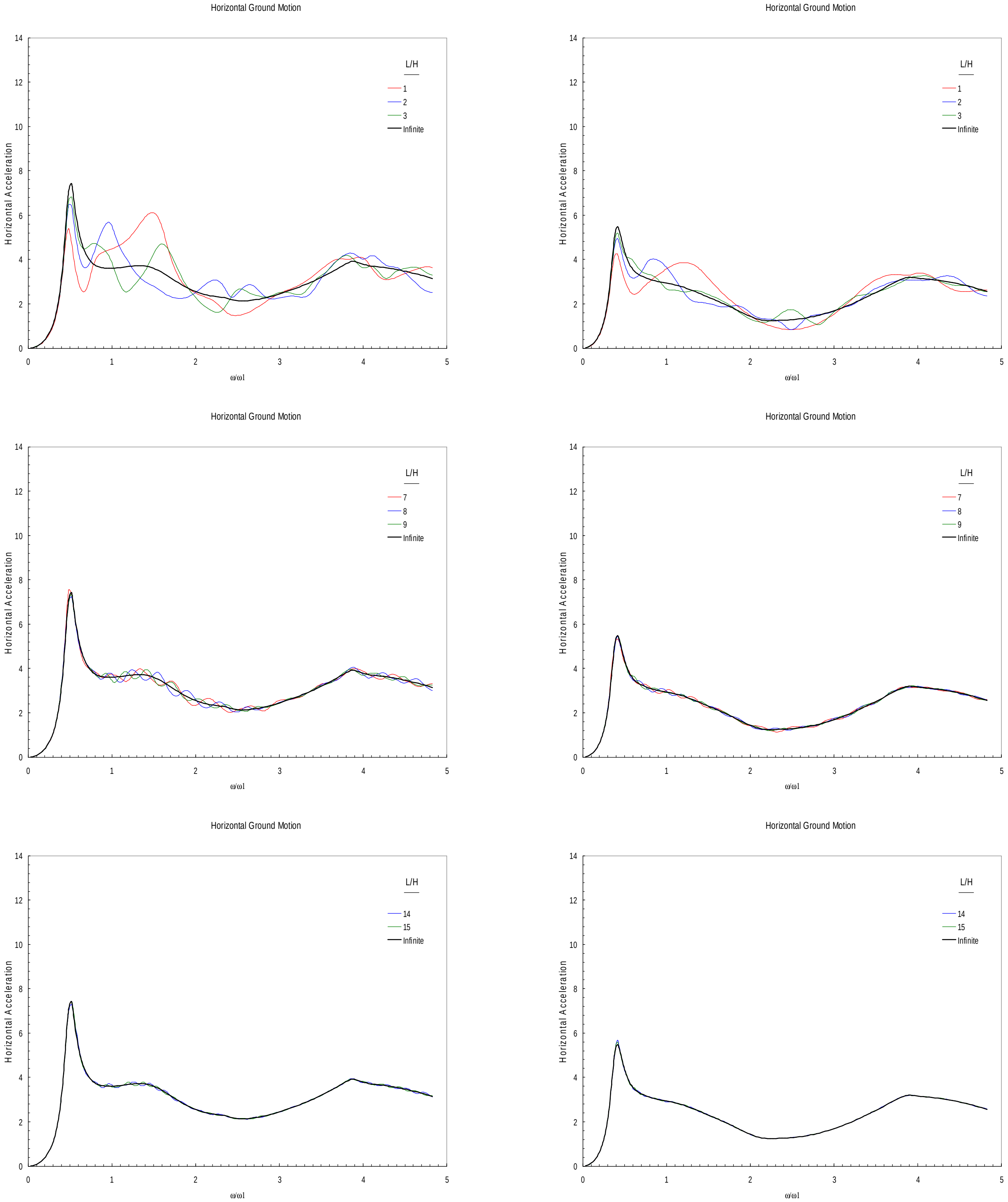

Figure 5 Horizontal acceleration at dam crest due to horizontal ground motion for different values of L/H

($E_f/E_d = 1/2$ is depicted on the left column and $E_f/E_d = 1/4$ on the right)

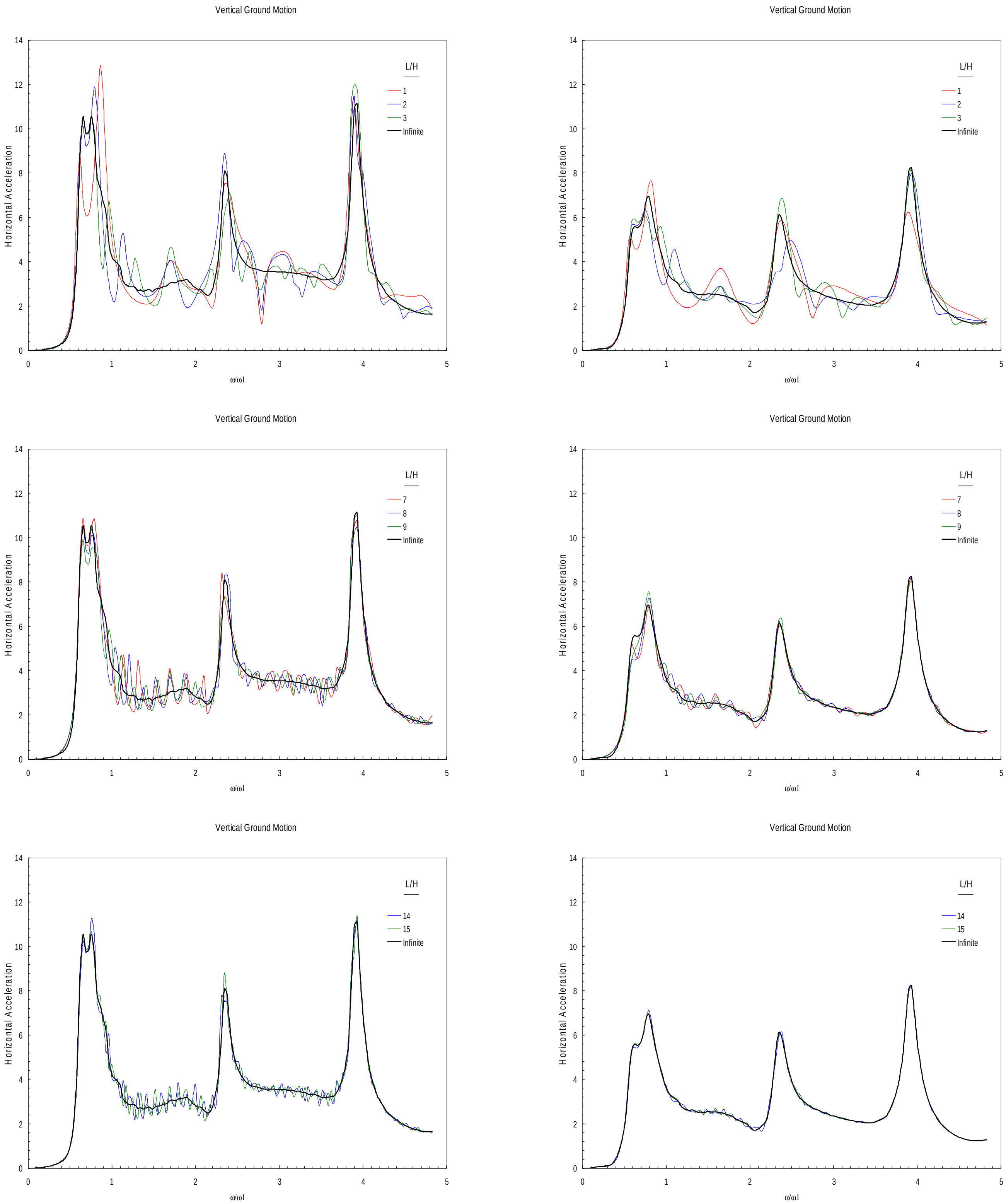

Figure 6 Horizontal acceleration at dam crest due to vertical ground motion for different values of L/H

($E_f/E_d = 2$ is depicted on the left column and $E_f/E_d = 1$ on the right)

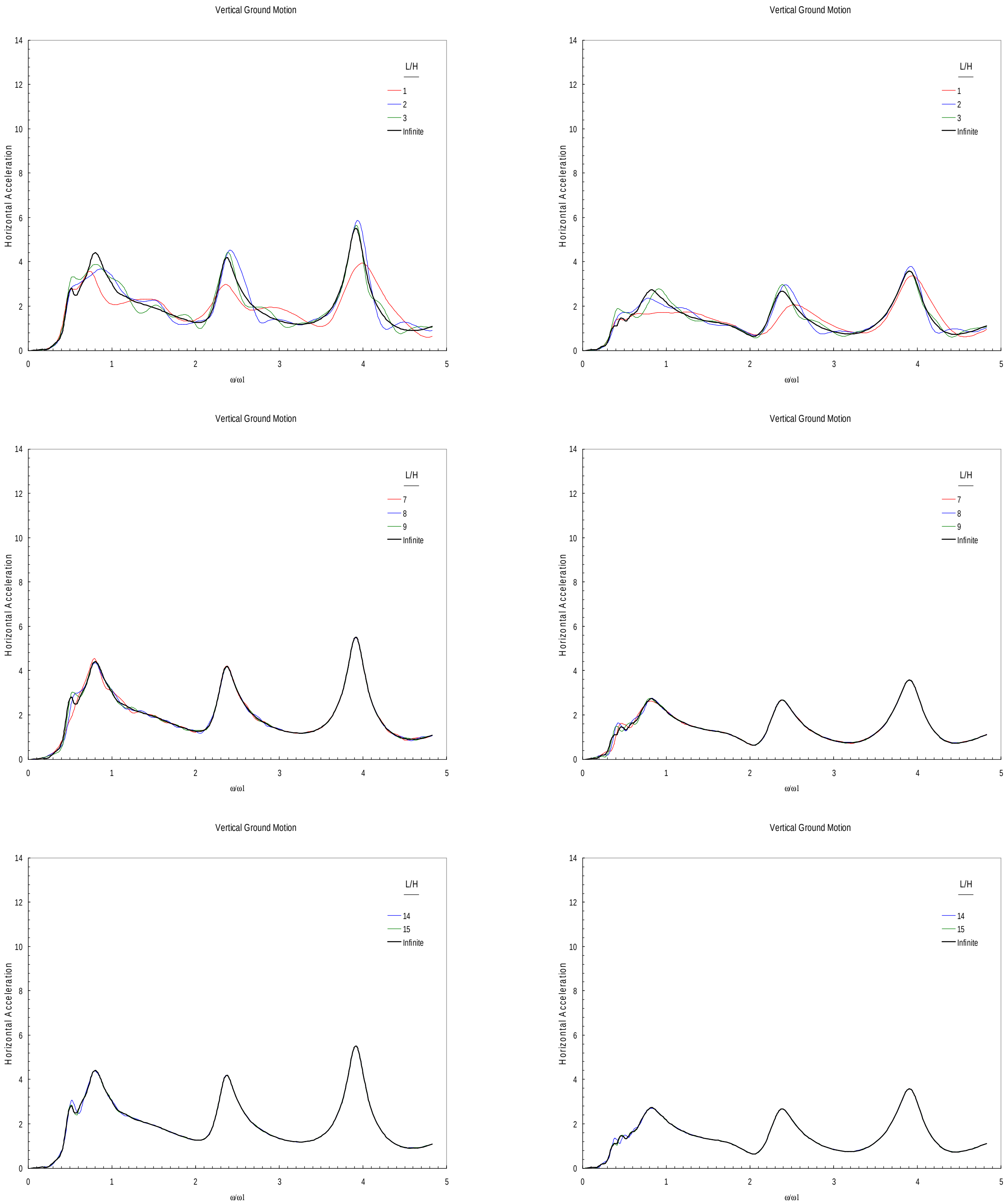

Figure 7 Horizontal acceleration at dam crest due to vertical ground motion for different values of L/H

($E_f/E_d = 1/2$ is depicted on the left column and $E_f/E_d = 1/4$ on the right)