Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VI)

10-1-3

EARTHQUAKE INPUT MODELS IN DAM-FOUNDATION INTERACTION STUDIES

P. Léger[1] and M. Boughoufalah[2]

[1]Assistant Professor, Department of Civil Engineering & Applied Mechanics, McGill University, Montreal, Quebec, Canada
[2]Research Assistant, Department of Civil Engineering & Applied Mechanics, McGill University, Montreal, Quebec, Canada

SUMMARY

This study is concerned with the evaluation of four different earthquake input mechanisms that are suitable for time domain analysis of dam-foundation systems. These are A) the standard rigid base input model, B) the massless foundation input model, C) the deconvolved base rock input model, and D) the free-field dam-foundation interface input model. Parametric studies have been conducted by applying the four proposed input mechanisms to simplified two-dimensional finite element models of gravity dam-foundation systems for various site properties. The use of Model A was shown to be inacceptable producing significant artificial amplifications. Models C and D produced very similar results for the complete range of selected site conditions. Model B can be use for practical analyses if a proper modelling of the energy dissipation characteristics of the foundation is provided in the mathematical formulation.

INTRODUCTION

The importance of dam-foundation interaction on the behavior of concrete gravity dams under earthquake ground motions has long been recognized. Previous studies (Refs. 1, 2) have been typically carried out in the frequency domain using foundation models based on analytical half-space solution and two-dimensional linearly elastic dam models in order to identify and quantify the effect of critical parameters. However, the need to represent non-homogeneous geometrical and material foundation properties for which analytical models are not available, and to predict damages due to nonlinear behavior under severe seismic excitation implies that the solution must be determined in the time domain.

The purpose of this paper is to evaluate the relative performance of four different earthquake input models that are suitable for time domain analysis of dam-foundation systems. These are the standard rigid base input model, the massless foundation input model, the deconvolved base rock input model, and the free-field dam-foundation interface input model. Parametric studies have been conducted by applying the four proposed earthquake input mechanisms to simplified 2-D finite element (F.E.) models of gravity dam-foundation systems. Time histories of typical response quantities of interest were computed for various ratios of the modulus of elasticity of the dam and the foundation and various damping ratios in the foundation. Specific range of parameters for which particular input mechanisms are more suitable to be used in order to get reliable time domain seismic response of dam-foundation systems were determined.

MODELS FOR EARTHQUAKE INPUT MECHANISMS

A F.E. discretization is used for both the dam and the foundation rock. A lumped added mass model using incompressible water is used to represent the hydrodynamic interaction effects. The time history input earthquake motions, generally a free-field recorded accelerogram, can be introduced according to one of the four input mechanisms which are shown in Fig.1.

Model A: Standard Rigid base Input
$[M_f]=[0]$, $\ddot{V}_b(t)=\ddot{V}_g(t)$

Model B: Massless Fondation Input
$[M_f]=[0]$, $\ddot{V}_b(t)=\ddot{V}_g(t)$

Model C: Deconvolved Input
$[M_f]=[0]$, $\ddot{V}_b(t)=\ddot{\underset{\sim}{V}}_g(t)$

Model D: Free-Field Interface Input
$[M_f]=[0]$, $\ddot{V}_b(t)=0$

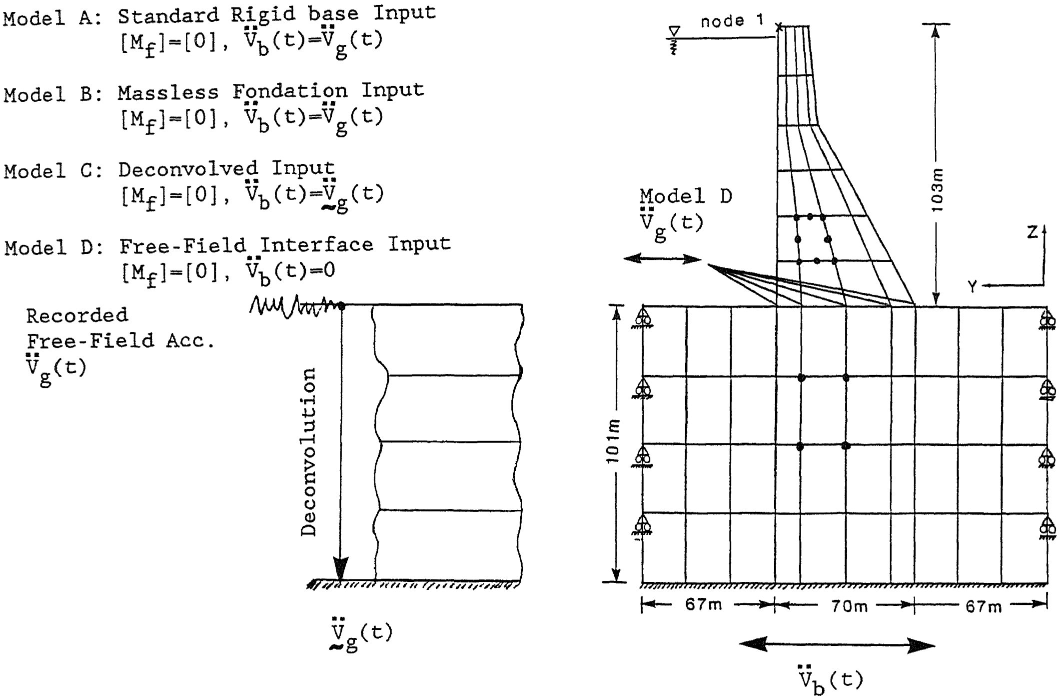

Fig. 1 Dam-Foundation System and Earthquake Input Mechanisms

<u>Model A</u> This is the standard rigid base input model where the free-field motions recorded at the ground surface are applied directly at the base of the deformable foundation rock. For this model the equations of dynamic equilibrium can be written as

$$[M]\{\ddot{V}\} + [C]\{\dot{V}\} + [K]\{V\} = -[M][r]\{\ddot{V}_b(t)\} \qquad (1)$$

in which [M], [C] and [K] are the F.E. mass, damping and stiffness matrices for the complete dam-foundation-reservoir system, $\{\ddot{V}_b(t)\}$ is the specifed bas acceleration time history and [r] is the influence coefficient matrix, expressing nodal displacements resulting from a uniform unit value of base rock displacements. The application of the rigid base input model is very simple. However, this model is not expected to give accurate results knowing that when the surface free-field motions are applied at the base rock level their frequency content and intensity will be modified by propagation through the deformable rock thus producing different surface motions than those obtain from the real rigid base input which has its focus beneath the local base rock.

<u>Model B</u> This is the massless foundation input model which has been proposed by Clough (Ref. 3) in the late seventies and has been used extensively for seismic

analysis of concrete dams since then (Refs. 4,5). The only difference with model A, is that only the flexiblity of the foundation rock is taken into account. This model which is still able to accuratly represent the stress concentrations that may develop at the rock-concrete interface presents several advantages. The problem of artificial amplification of the free-field accelerogram as discussed for model A will be eliminated, there will also be a reduction in the number of dynamic DOF and the vibration properties of the complete model will be representative of the dam. However, the idealized foundation rock without mass does not totally model the dam-foundation interaction mechanisms and the system frequencies obtain from this model will be different than those where the foundation inertia is represented. The damping of the foundation in the absence of mass is usually taken as zero but this will neglect the radiation damping of the foundation. A certain amount of damping can thus be included in the foundation for that purpose.

Model C This is the deconvolved base rock input model where the base rock motions at the deformable foundation rock are derived from the specified free-field motions by the inverse application of the wave propagation equations (Ref. 6) . The results obtained from this model are obviously dependent upon the quality of the deconvolution process. The seismic response of the system should theoretically be more accurate than those given by models A and B since the dam-foundation interaction mechanisms are well represented and the earthquake motions are treated in a more realistic manner. The main disadvantages of this model is that it is rather tedious since it involves the use of specialized computer programs and a separate analysis of the free-field system. Furthermore, the deconvolution process generally involves restrictive assumptions on the nature and direction of seismic waves and a reliable implementation of the decovolution technique requires some form of sensitivity analysis.

Model D This is the free-field concrete rock interface input model where the equations of motion of the complete dam-foundation rock system are rewritten so that the effective seismic input is expressed directly in terms of the free-field motions, $\{\ddot{V}_g(t)\}$, recorded at the ground surface (Refs. 7,8). The equations of dynamic equilibrium can be written as

$$[M]\{\ddot{\underline{V}}\} + [C]\{\dot{\underline{V}}\} + [K]\{\underline{V}\} = - [M][\underline{r}] + \begin{bmatrix} M_{gd} \\ M_{gg} \\ 0 \end{bmatrix} \{\ddot{V}_g(t)\} \qquad (2)$$

where [M], [C], and [K] are the usual F.E. system matrices of the complete sytem, $[M_{gd}]$ represents the dam-foundation mass coupling terms and $[M_{gg}]$ the dam-foundation interface DOF, $[\underline{r}]$ is the matrix of influence coefficient expressing the nodal displacements of the dam due uniform unit dispalcements applied at the base of the dam (not the base rock). In this formulation the displacements $\{\underline{V}\}$ are the added motions with respect to the free-field response. The main asumptions used in this model are that the input motions at the level of the base rock are not considered to be affected by the presence of the dam and that all interface nodes will be subjected to the same free-field accelerogram. In theory any desired spatial variation of the free-field components could be considered at the interface, however there is seldom sufficient information to specify such variation.

DAM-FOUNDATION-RESERVOIR SYSTEM ANALYSED AND GROUND MOTION

Figure 1 shows the dam-foundation-reservoir system analysed. The concrete of the dam is assumed to be linearly elastic (plane stress) with a modulus of elasticity, E_d, of 24,000 MPa, a mass density of 2640 kg/m^3, a Poisson's ratio of 0.20, and 5% damping. The dam rest on a lineraly elastic foundation block (plane stress) with a Poisson's ratio 0.33 and a mass density of 2643 kg/^{3} for earthquake input models A,C,D. For the foundation rock, the modulus of elasticity, E_f, is varied such that E_f/E_d= 4, 2, 1, 1/2, 1/4, 1/8. The damping ratio for the foundation rock is specified as 5, 10 and 15 % critical. The global damping matrix is most effectively constructed by applying separately the concept of Rayleigh damping to the dam and the foundation (Ref. 9). In the case of proportional damping the global damping matrix may be computed from

$$[C] = a_0\ [M] + a_1\ [K] \tag{3}$$

where [M] and [K] are the combined system matrices and a_0, a_1 are proportionality constants selected to control the damping ratios of the lowest and highest mode expected to contribute significantly to the response. In the case of non-proportional damping the following matrices will be computed for the dam and for the foundation:

$$[C_d] = a_{0,d}\ [M_d] + a_{1,d}\ [K_d] \tag{4}$$

$$[C_f] = a_{0,f}\ [M_f] + a_{1,d}\ [K_f] \tag{5}$$

or

$$[C_f] = a_{1,f}\ [K_f] \tag{6}$$

The ground motions selected for this study are the horizontal components of the El Centro 1940, Pacoima Dam 1971, and Parkfield 1966 earthquakes. The maximum amplitudes of all ground motions have been normalized to 0.35g.The deconvolved accelerograms required for input model C were obtain using the computer program SHAKE (Ref. 10) A direct step-by-step integration of the equations of motions expressed in geometric coordinates has been selected to deal effectively with non-proportionally damped systems.

RESPONSE RESULTS

The earthquake response of the system was determined in terms of a global response parameter, the dam-foundation interface base shear, and local response parameters such as nodal displacements, accelerations (computed relative to a common reference, the base of the dam), and elements stresses. Time histories, maximum (Max.) and root mean square values (RMS) were used to quantify the magnitudes and variations of the response quantities of interest. A summary of important numerical results are presented below in order to illustrate the relative performance of the proposed input models.

Table 1 Max. and RMS Values of Base Shear Normalized to Model C with E_f/E_d = 1 (Foundation damping = 10% for Models A,B,C,D, and 0% for B') EL Centro Earthquake

Ef/Ed	1/8		1/4		1/2		1		2		4	
Models	RMS	MAX	RMS	MAX	RMS	MAX	RMS	MAX	RMS	MAX	RMS	MAX
A	2.42	1.52	2.03	1.71	2.13	2.26	1.84	1.89	1.64	1.64	1.45	1.37
B'	1.73	1.01	1.51	1.28	1.64	1.55	1.24	1.15	1.20	1.11	1.10	0.99
B	1.09	0.87	1.03	1.16	1.11	1.28	0.98	1.05	0.96	1.01	0.94	0.97
C	1.19	0.85	0.98	0.82	1.22	1.20	1.00	1.00	0.94	0.87	1.04	0.86
D	1.09	0.72	1.03	0.85	1.25	1.24	1.04	1.06	1.02	0.95	1.02	0.90

Table 1 presents the MAX and RMS values of the dam-foundation interface base shear for the complete range of elastic site properties retained in the analysis assuming 10% foundation damping and using the El Centro earthquake. The results have been normalized with respect to input model C with E_f/E_d= 1. It is shown that the application of model A, the rigid base rock input model, induced very significant artificial amplifications in the response quantities of interest. The magnitudes of these artificial amplifications are shown to increase with the level of foundation flexibility. Model A is therefore recognized inadequate to evaluate time domain seismic responses of dam-foundation systems and should not be used in practice. The use of model D, the free-field input model, yielded results which are very similar (within 10% in average) of those derived from the theoretically more accurate deconvolved input model (C). This is shown to be independent of the level of flexibility and damping of the foundation rock. Model D can thus be considered the most efficient to evaluate the time domain responses of gravity dam-foundation systems considering the inertial properties of the foundation since it is much easier to implement than model C.

The performance of model B, the massless foundation input model, is shown to be dependent on the foundation flexibility, on the level of damping of the massless foundation rock, and the computational technique used to form the global damping matrix [C]. It should be noted however that any differences in the response quantities computed from model B and those of models C and D are also due to the fact that the behavior of the massless foundation model in free-vibration is somewhat different than the free-vibration response of the mass foundation model. The massless foundation input model with no damping tends to overestimate quite significantly the response as compared to models C and D and this for the complete range of site conditions except in the case of a stiff lightly damped foundation where the effects of soil-structure interaction are not significant (Fig.2). The performance of model B as compared to models C and D is significantly improved by considering some radiation damping provided by the foundation as shown in Fig. 3. The results of models B, C and D are then within 10% in average but it is shown that the massless foundation input model tends to consistently underestimate the response as compared to models C and D as the stiffness of the foundation is increased. This can be explained by the fact that the foundation damping for non-proportional massless foundation models was controlled only for the first mode of vibration, higher modes receiving significantly larger damping ratios. The relative contribution of the first mode of vibration to the total response depends on the flexibility of the foundation rock. The more flexible the foundation, the higher is the contribution of the fundamental mode such that stiffness proportional foundation damping is satisfactory. For relatively more rigid foundations, one should expect that the effective damping will be higher than the assigned value, since the individual modal contributions will be spread over many modes. This explains some of the discrepancies shown between models B and C, D for the stiffer foundation models.

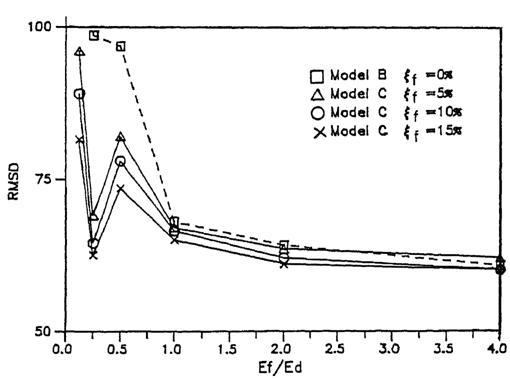

Fig. 2 Comparisons of Y-Displacements at node 1 (El Centro Earthquake)

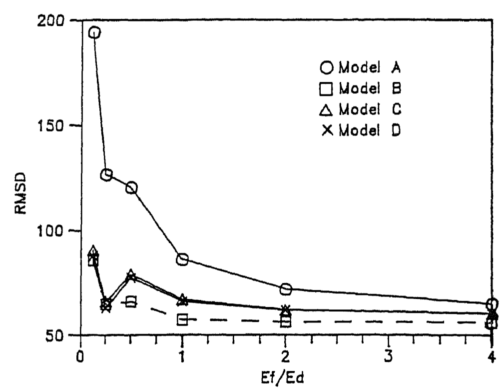

Fig. 3 RMS of Y-Displacements at node 1 (Foundation Damping = 10%, El Centro Eq)

CONCLUSIONS

The results derived from the application of the four proposed earthquake input mechanisms to a simple two-dimensional gravity dam-foundation-reservoir system have clearly shown that the use of different input models lead to significant differences in the structural response of this type of structure. The main conclusions were that model A induced very significant amplification in the response quantities of interest. The use of model D, yielded results which were very similar to those derived from the theoretically more accurate model C and that was shown to be independent of the levels of flexibility and damping of the foundation rock. Model D can thus be considered more efficient than model C to evaluate the time domain response of gravity dam-foundation systems since it is much easier to implement than model C.

The performance of model B, the massless foundation input model, was shown to be dependent on the foundation flexibility, on the level of radiation damping of the massless foundation rock and on the computational procedure retained to form the global damping matrix. In order to obtain a good correlation with models C, D, the damping matrix should be constructed by considering the foundation damping characteristics to be stiffness proportional only, even when similar damping ratios are assigned to the dam and the foundation. For very flexible foundation cases ($E_f/E_d \leqslant 1/4$), similar results in typical response quantities of interests have been observed between model B, in which the damping was controlled only for the first mode of vibration, and models C, D. For stiffer foundation cases, the numerical results indicate that the damping ratio assigned to the foundation in model B should be smaller than the one that would have been retained for the application of models C, D, in order to get an accurate response from this massless foundation model. Model B was thus shown to be able to produce numerical results with an acceptable level of confidence for typical engineering applications if a proper modelling of the energy dissipation characteristics of the foundation is provided in the F.E. model. This is significant for practical applications since Model B is very simple to implement numerically using standard commercial finite element packages.

REFERENCES

1. Chopra, A.K. and Gupta S., "Hydrodynamic and Foundation Interaction Effects in Frequency Response Functions for Concrete Gravity Dams", Earthquake Eng. Struct. Dynamics, 10, 89-106, (1982)
2. Fenves, G. and Chopra A.K., "Effects of Reservoir Bottom Absorption and Dam-Water-Foundation Rock Interaction on Frequency Response Functions of Concrete Gravity Dams", Earthquake Eng. Struct. Dynamics, 13, 13-31, (1985)
3. Clough, R.W., "Non-Linear Mechanisms in the Seismic Response of Arch Dams", Proceedings of the International Research Conference on Earthquake Eng. Skopje, Yugoslavia, June/July, 669-684, (1980)
4. Hall, J.F., "Study of the Earthquake Response of Pine Flat Dam", Earthquake Eng. Struct. Dynamics, 14, 281- 295, (1986)
5. Chopra, A.K., "Earthquake Analysis, Design and Safety of Concrete Dams", Proceedings of the Fifth Canadian Conference on Earthquake. Eng., Ottawa, July, 39-62, (1987)
6. Reimer, R.B., "Deconvolution of Seismic Response for Linear Systems", Earthquake Engineering Research Center, Report EERC 73-10, University of California, Berkeley, (1973)
7. Clough, R.W. and Penzien J., "Dynamics of Structures", McGraw-Hill, (1975)
8. Clough, R.W. and Chopra A.K., "Earthquake Response Analysis of Concrete Dams", In Structural and Geotechnical Mechanics, W.J. Hall, Editor Prentice-Hall, (1977)
9. Clough, R.W. and Mojtahedi, S., "Earthquake Response Analysis Considering Non Proportional Damping", Earthquake Eng. Struct. Dynamics, 4, 489-496, (1976)
10. Schnabel, P.B., Lysmer J. and Seed H.B., "SHAKE a Computer Program for Earthquake Response of Horizontally Layered Sites", Earthquake Engineering Research Center, Report EERC 72-12, University of California, Berkeley, 1972.