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STRUCTURE-FOUNDATION INTERACTION EFFECTS ON SEISMIC LOAD REDUCTION OF CONCRETE GRAVITY DAMS

Gao LIN, Ruifeng ZHANG and Fuming WANG

Department of Civil Engineering, Dalian University of Technology
Dalian, China

SUMMARY

A semi-analytical procedure for evaluating the compliance functions of semi-infinite viscoelastic multi-layered foundation is developed. The complex frequency response functions and the earthquake response of typical concrete gravity dams resting on multi-layered foundation are studied. Based on these investigations, it is found that the foundation flexibility tends to reduce the earthquake response of concrete gravity dams in general, and the higher the exciting frequency , the more significant the interaction effect becomes. Moreover, the stiffness of the surface layer plays the most important role in dam-foundation interaction, the softer the surface layer, the more obvious the tendency of reduction appears.

INTRODUCTION

The structure-foundation interaction and its effects on the earthquake response of dams and other important buildings is a problem of great concern in the engineering design. Besides, it also represents an active field of earthquake engineering research. However, the establishment of dynamic impedance functions of half plane foundation associates with some difficulties in mathematics. Up to the present time , very few of analytical solutions such as the viscoelastic half plane and layered foundation have been obtained (Ref. 1,2). For these reasons, many researchers are engaged in creating some approximate approaches to calculate the dynamic stiffness matrixes of complex foundation , while others devoted to work out wave transmitting boundaries in order to directly evaluate the response of structure-foundation systems subjected to earthquake excitation . Although these efforts have achieved good results, to a certain degree, they are still time consuming. Therefore, only limited number of quantitative results dealing with structure-foundation interaction problems are obtained. In order to get a clearer understanding of the structure-foundation interaction effect on the earthquake response of dam structure, in this paper, a semi-analytical procedure for evaluating the compliance functions of viscoelastic half-plane with inhomogeneities along the depth , by virtue of the cubic spline functions, is presented. It has the advantages of transforming the solution of a two- or three-dimensional problem into that of a one-dimensional problem. Thus, the computational efforts are reduced to a great extent , while it ensures the required precisions. On this basis, the response characteristics of concrete gravity dams taking into account the foundation flexibility is studied.

COMPUTATIONAL MODEL FOR VISCOELASTIC LAYERED FOUNDATION

The dynamic compliance functions of viscoelastic half plane foundation with vertical inhomogeneities are derived semi-analytically in the following manner. First, the domain to be analyzed is defined as part of the foundation with boundaries placed far enough from the base of the structure. The domain in the vertical direction is partitioned into N equal parts with node points located at the interface between two layers of different nature. Then, the displacement field of foundation excited by a uniformly-distributed harmonic load with a unit resultant acting upon the surface of the foundation within a lenth b is expressed as given in formula (1).

$$u(x,\ y)=\sum_{m=1}^{M}[\phi]\ X_m\ \{a\}_m \quad ; \qquad v(x,\ y)=\sum_{m=1}^{M}[\phi]\ Y_m\ \{b\}_m \tag{1}$$

where $[\phi]=[\phi_{-1}\,\phi_0\,\phi_1\ \ldots\ \phi_{N-1}]$; $\{a\}_m=[a_{-1}\,a_0\,a_1\ldots a_{N-1}]^T$; $\{b\}_m=[b_{-1}\,b_0\,b_1\ldots b_{N-1}]^T$

$\phi_i=\phi_i(y)$ are base vectors consisting of cubic B-spline functions $\varphi_3(y)$; a and b are corresponding parameters of the splines; and X and Y are Fourier series (Ref. 3). Writing it in the matrix form, We have

$$\{\delta\}=\left\{\begin{matrix}u\\v\end{matrix}\right\}=[N]\{r\} \tag{2}$$

where $[N]=[[N]_1\ [N]_2\ \ldots\ [N]_m]$

$$\{r\}=[\{r\}_1\ \{r\}_2\ \ldots\ \{r\}_m]^T$$

$$[N]_m=\begin{bmatrix}[\phi]X_m & 0\\ 0 & [\phi]Y_m\end{bmatrix}$$

$$\{r\}_m=[\{a\}_m\quad \{b\}_m]^T$$

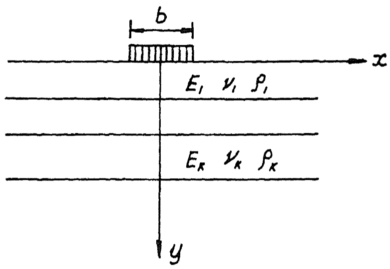

Fig. 1

Following the procedure of finite element method, we get the generalized stiffness, and mass matrixes of the foundation [K], [M] respectively. Eventually, the dynamic compliance coefficients are obtained by solving the equation of motion in the frequency domain.

$$(-\omega^2[M]+(1+i\eta)[K])\{r\}=\{P\} \tag{3}$$

where η is the hysteretic damping factor; {P} is the generalized load vector and {r} are the unknown generalized displacements we are seeking for. It is interesting to note that because of the orthogonal properties of functions X and Y , [K] and [M] turn to diagonally block-banded matrixes and Eq. (3) becomes

$$(-\omega^2[M]_{mm}+(1+i\eta)[K]_{mm})\{r\}_m=\{P\}_m \qquad (m=1,2,\ \ldots\ ,M) \tag{4}$$

Each set is only composed of 2(N+1) equations. Owing to the excellent interpolation characteristics of spline functions, 5 to 8 terms for N are enough to ensure appropriate accuracy of the results. Thereby, the computational effort for determining the impedance matrix (the inverse of the compliance matrix) of the foundation is reduced to a great extent. It is worth noting here that the proposed method can be easily extended to three dimensional cases (Ref. 3).

For elastic media, the wave reflecting effects at artificial boundaries can not be disregarded. However, the phenomena are quite different for viscoelastic media. If artificial boundaries are located far enough from the loading points, the reflected waves attenuate rapidly during the transmission process, and become insignificant, so that an infinite domain can be approximated by a domain with limited size.

In order to develop an understanding of the effectiveness of the method, the calculated compliance coefficients for homogeneous viscoelastic half-plane are compared to the analytical solution. In table 1, the first and second rows denote the results obtained by the present method and those by the analytical solution of A.K. Chopra (Ref. 1) respectively. They agree fairly well.

Table 1 Dynamic Compliance Coefficients for Homogeneous Viscoelastic Halfplane

$\nu=1/3$ $a_o=\omega b/c_s=0.5$ $\eta=0.25$								
x/b	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5
f_m^{xx}	0.3593	0.0687	-0.0291	-0.0767	-0.0970	-0.0891	-0.0817	-0.0667
	0.3548	0.0707	-0.0296	-0.0787	-0.0957	-0.0929	-0.0806	-0.0667
g_m^{xx}	-0.3946	-0.2925	-0.2205	-0.1537	-0.0958	-0.0539	-0.0241	-0.0081
	-0.3902	-0.2899	-0.2193	-0.1502	-0.0932	-0.0501	-0.0215	-0.0052
f_m^{yy}	0.2544	-0.0489	-0.1225	-0.1344	-0.1071	-0.0404	0.0144	0.0647
	0.2385	-0.0473	-0.1320	-0.1452	-0.1115	-0.0531	0.0085	0.0566
g_m^{yy}	-0.3546	-0.2208	-0.1116	-0.0103	0.0664	0.1032	0.1070	0.0793
	-0.3553	-0.2259	-0.1142	-0.0129	0.0620	0.1008	0.1029	0.0761
$\nu=1/3$ $a_o=1.0$ $\eta=0.25$								
f_m^{xx}	0.2091	-0.0641	-0.1006	-0.0794	-0.0616	-0.0482	-0.0426	-0.0136
	0.2127	-0.0540	-0.0931	-0.0745	-0.0549	-0.0484	-0.0392	-0.0125
g_m^{xx}	-0.3363	-0.1789	-0.0674	-0.0085	0.0122	0.0232	0.0451	0.0630
	-0.3400	-0.1838	-0.0719	-0.0131	0.0062	0.0184	0.0394	0.0581
f_m^{yy}	0.1030	-0.1472	-0.0798	0.0336	0.0743	0.0448	-0.0242	-0.0436
	0.0955	-0.1385	-0.0812	0.0317	0.0784	0.0398	-0.0220	-0.0432
g_m^{yy}	-0.2921	-0.0628	0.0792	0.0883	0.0122	-0.0547	-0.0502	-0.0039
	-0.2906	-0.0636	0.0811	0.0897	0.0116	-0.0530	-0.0498	-0.0027

EARTHQUAKE RESPONSES OF GRAVITY DAMS INCLUDING STRUCTURE-FOUNDATION EFFECTS

Based on the foundation impedance matrix $[S_f(\omega)]$ obtained above , the earthquake response of concrete gravity dams resting on the foundation with inhomogeneities along the depth can be determined by the equation of motion of the system.

$$([M_d]+[M_r])\{\ddot{U}\}+[C_d]\{\dot{U}\}+([K_d]+[S_f])\{U\}=-([M_d]+[M_r])\{e\}a_g(t) \tag{5}$$

where $[M_d]$, $[C_d]$, $[K_d]$ are the mass , damping and stiffness matrixes of the dam respectively, $a_g(t)$ is the time history of earthquake ground acceleration, $[M_r]$ is the matrix of added mass exerted by the reservoir water. For simplicity, the compressibility of water has been neglected. However, by employing the generalized boundary element method suggested by the authors (Ref. 4), it is not difficult to take into consideration the water compressibility and energy absorption effect at reservoir bottom.

As the dynamic impedance matrixes of the foundation being a function of the exciting frequency, Eq.(6) is convenient to solve in the frequency domain. First, the complex frequency response functions of the system are calculated in accordance with the equation of motion due to a unit harmonic excitation.

$$(-\omega^2[M_d+M_r]+(1+i\eta)[K_d]+[S_f(\omega)])\{U(\omega)\}=-([M_d]+[M_r])\{e\} \tag{6}$$

Then, the displacement response in the time domain can be determined through Fourier transform.

$$U(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}U(\omega)\ A_g(\omega)\ e^{i\omega t}d\omega \qquad A_g(\omega)=\int_0^T a_g(t)\ e^{-i\omega t}dt \tag{7}$$

Where T is the duration of the earthquake.

Based on the procedures explained above, numerical analysis of a 100^m high concrete gravity dam including dam-foundation interaction has been implemented. The dam is modelled by an assemblage of 4 node isoparametric finite elements as shown in Fig. 2. Three cases of inhomogeneous foundations with variable stiffness along the depth are investigated to illustrate the foundation nature on the earthquake response of gravity dams. Fig. 3 demonstrates the complex frequency response function for the absolute values of horizontal acceleration at dam crest due to the unit horizontal earthquake excitation. Cases of rigid foundation and currently used foundation model with massless springs are also presented in the figure for comparison.

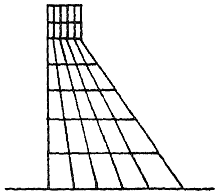

Fig.2

It can be proved that for concrete gravity dams other than 100^m in height but having similar geometrical shapes and similar discretization of finite element meshes, the following relations between their values of complex frequency response of acceleration exist.

$$A_H(\omega_\lambda) = A_{100}(\omega) \qquad \omega_\lambda = \frac{1}{\lambda}\omega = 100\,\omega/H \tag{8}$$

Where A_H and A_{100} are complex frequency response functions of acceleration for dams H^m and 100^m high respectively; λ is the scale factor. So the numerical results for dams 100^m high may easily be extended to dams other than 100^m high.

Fig. 5 shows the time history of horizontal displacement at the crest of a 100^m high concrete gravity dam due to the May 18,1940 El Centro Earthquake excitation ($a_{max.}$=341 cm/sec.), the response spectrum of which covers a quite wide range of frequency content.

In a previous paper of the authers (Ref. 5,6) the stationary random response of concrete gravity dams supported on homogeneous viscoelastic half-plane with various stiffness properties has been studied. In comparison with the average values of horizontal base shear response for typical gravity dams 50^m, 100^m, and 200^m in height on the rigid foundation, those values for dams resting on homogeneous flexible foundations subjected to six actual earthquake waves and two narrow band white noise are shown in Fig. 6.

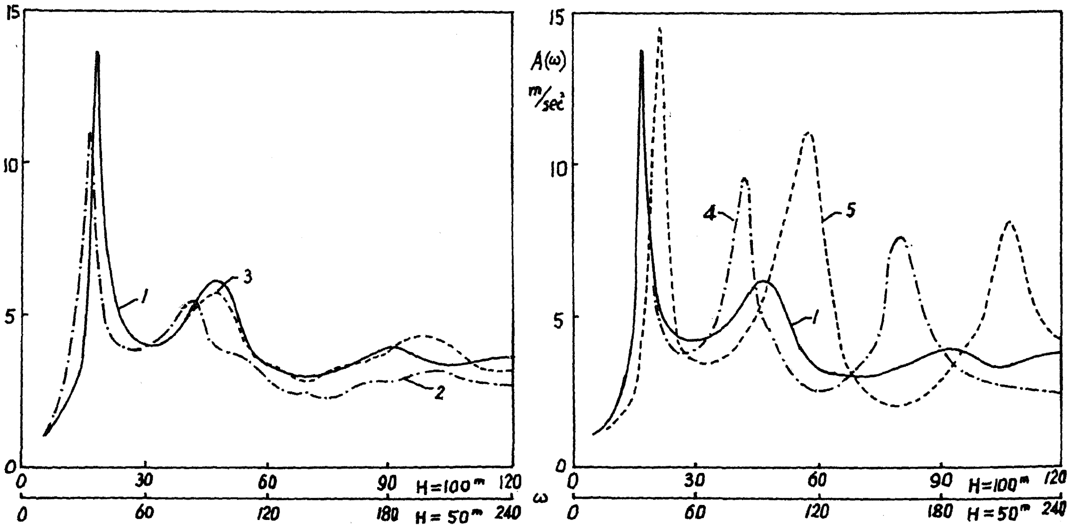

Fig.3 Complex Response Function of Absolute Acceleration

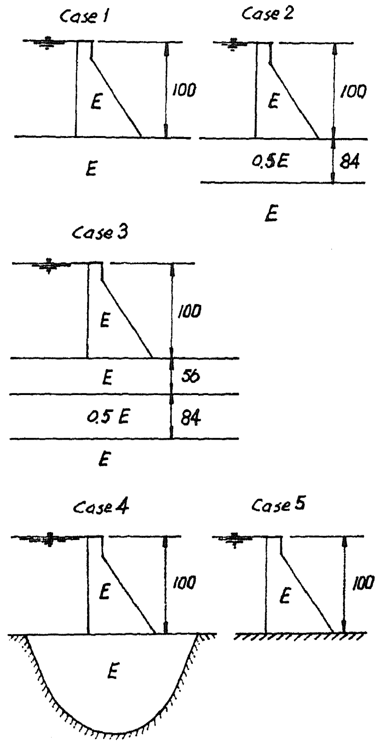

Fig.4 Cases Studied

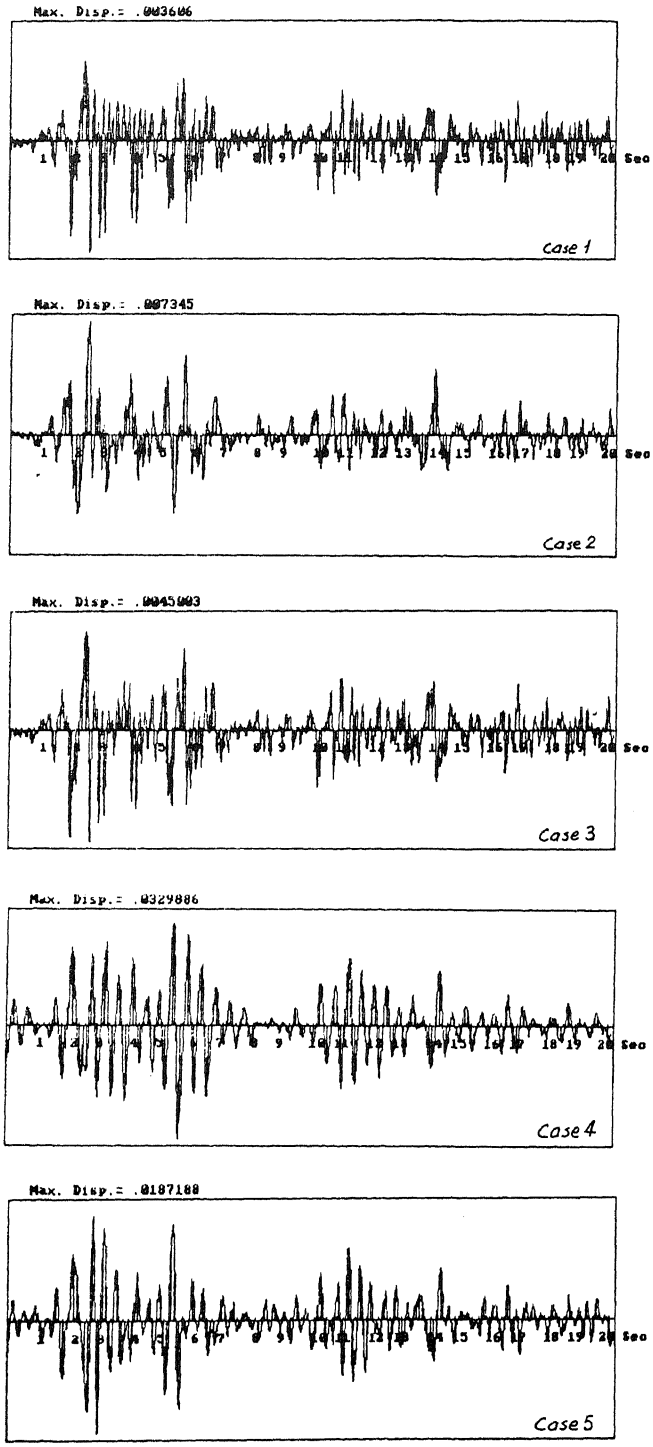

Fig.5 Horizontal Displacement Response of Point No. 1

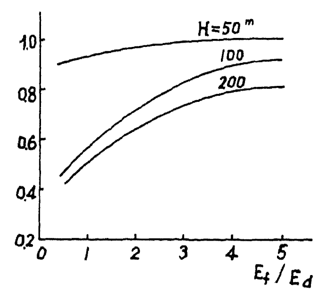

Fig. 6

BASIC CONCLUSIONS

From all the results presented above, some conclusions about dam-foundation interaction effects may be drawn:

(1) The foundation flexibility tends to reduce the earthquake response of concrete gravity dams in general, because a greater part of vibration energy is being radiated into the infinite foundation medium.

(2) The reduction of the complex frequency response of the dam is remarkable when the exciting frequency is greater than the fundamental frequency of the dam-foundation system, and the higher the exciting frequency, the clearer the tendency of reduction can be found. However, the interaction effect becomes less important when the exciting frequency is close to the fundamental frequency of the system.

(3) For concrete gravity dams about equal or higher than 100m in height, the dam-foundation interaction becomes significant, on the contrary, for dams equal or lower than 50m in height, the interaction effect becomes less apparent. As a matter of fact, in the later case, the predominent frequencies of earthquakes for rock foundation coincide appoximately with the fundamental frequency of the system, while in the former case, the predominent frequencies of earthquakes appoach the second frequency of the system, where dam-foundation interaction becomes significant.

(4) The dam-foundation interaction lowers the vibration frequencies of the system in comparison with those on the rigid foundation. In this aspect, the currently used massless spring model of the foundation behaves the same nature as the real dam-foundation system. However, the massless spring model fails to simulate the energy dissipation characteristics due to radiating damping, it leads to different complex frequency response functions and different earthquake response of dams.

(5) The foundation inhomogeneity has great influences on the foundation compliance matrixes, hence it affects the earthquake response of dams considerably. Nevertheless,the flexibility of the surface layer plays the most important role in the dam-foundation interaction. The softer the surface layer, the more apparent the interaction effect appears.

(6) In case of the top layer foundation stiffness being five times greater than that of the dam, the interaction effect becomes insignificant, and the earthquake responses of dam are close to that on the rigid foundation.

(7) The interaction effects depend on height of the dam, stiffness ratio of foundation to dam, position of weak layer in foundation, frequency spectrum characteristics of input seismic ground motion and many other factors.

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