On Soil-Structure Interaction Analysis of Concrete Gravity Dams in Frequency Domain

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ABSTRACT:

Extensive construction of gravity dams in developing countries has resulted in a great demand for seismic analysis of these structures based on reliable methodologies. The exhaustive cost of existing time domain solutions for the soil-structure analysis problem as well as the tradition of conducting two-dimensional analysis on dam systems have led to the wide-scale use of two-dimensional analysis routines for seismic demand estimation. The primary goal of this study is to investigate the accuracy of two-dimensional analyses for predicting the seismic demands on concrete gravity dams. A frequency domain analysis approach is used for conducting soil-structure interaction analysis of concrete gravity dams rigorously [1]. A variety of three-dimensional models in different canyons are analyzed and the frequency response functions are obtained. The results from the three-dimensional models obtained in the form of the first mode resonant frequency and the corresponding amplitudes are compared to those of conventional two-dimensional methods. The results of the study show the importance of the consideration of the 3D SSI effects in seismic analysis for the design of new gravity dams as well as the evaluation of existing stock.

KEYWORDS: Gravity Dams, Soil-Structure Interaction, Frequency Domain, Three-Dimensional

1. INTRODUCTION

The dominant effect of a flexible foundation on the seismic behavior of dam structures can be investigated by considering the soil-structure interaction phenomenon [2-4]. The lengthening of the natural vibration periods of the system, introduction of the rocking rigid body motion modes, and the alteration the ground motion due to the wave propagation within the medium are some of the most important results of the presence of a flexible foundation on a dam-foundation system [5, 6]. In order to include the above-mentioned effects in time domain analysis, two alternatives are often selected. Modelling foundation rock with finite elements are possible via either using massless models, where the mass of the foundation system has to be excluded to avoid amplification of ground motion when using conventional boundary conditions. The more rigorous approach is to utilize specially treaded absorbing boundary conditions to simulate the earthquake waves passing through the medium without rebounding as a result of restraint support conditions [7]. However, both approaches have disadvantages: massless models being used with an equivalent calibrated damping is a crude approximation to reality as the damping is calibrated for the first mode response [8].Special absorbing boundaries, such as PMFs on the other hand may be very costly to implement [9].

Another drawback of these approaches as defined in provisions [10, 11] for design and evaluation of concrete gravity dams is the general use of the two-dimensional formulations based on the plane strain or plain stress assumption because of the high computational cost of three-dimensional modelling of a large foundation and dam system. Analysis and design of only arch dams is usually performed with the 3D rigorous formulation of the soil-structure-reservoir interaction [5]. The design and evaluation of gravity dams have been based on the premise of dams in wide valleys with well separated monoliths defined by constructions joints. However, for most systems constructed in the developing world, this premise does not hold [12].

The 2D rigorous approach to the solution of the soil-structure-interaction problem, addressing the radiation effects in the soil medium as well as the dam-reservoir interaction, was developed by Fenves and Chopra [13] based on the assumptions given above. The 3D counterpart of this solution, i.e. the rigorous three-dimensional soil-structure interaction formulation in frequency domain was developed by Chopra et al. [1, 14] using boundary elements in the interface of the dam structure and the foundation rock, implementing Greens functions with rate independent characteristic property of concrete and soil materials.

Within this context, the main goal of this study is to compare 2 and 3D rigorous solutions for the gravity dam SSI problem in order investigate the validity of approaching the seismic analysis for gravity dams in a 2D setting. To this end, 5 gravity dams with different height to valley width ratios are modelled for a typical gravity dam section and the frequency response function of these systems are obtained using rigorous 3D frequency domain analysis. The results are compared with rigorous two-dimensional plain strain analyses and the consistency of the 2D solutions is investigated.

2. NUMERICAL MODELLING

2.1. 2D SSI Modelling

The rigorous SSI solution for two-dimensional seismic analysis of gravity dams consists of the formulation of the whole system as discrete substructures, namely as the dam body, foundation rock and the reservoir. The governing equation in the frequency domain can be shown as in Eq. 1:

$$-\omega^2 \begin{matrix} m & \underline{0} \\ \underline{0} & m_b \end{matrix} + (1+i\eta_s) \begin{matrix} k & k_b \\ k_b^T & k_{bb} \end{matrix} \begin{matrix} \bar{r}^l(\omega) \\ \bar{r}_b^l(\omega) \end{matrix} = - \begin{matrix} m\underline{1}^l \\ m_b\underline{1}_b^l \end{matrix} + \begin{matrix} R_h^l \;\omega \\ R_b^l \;\omega \end{matrix} \tag{1}$$

In equation 1, the relative displacements of nodes above the base and the nodal points on the base are represented by $\bar{r}^l$ and $\bar{r}_b^l$, respectively. The scalar η_s denotes the rate independent damping coefficient of soil medium. The vectors R_h^l and R_b^l represent the hydrodynamic forces on the upstream face and the forces due to the soil-structure interaction on the base of the dam, respectively. In this study, the plain strain SSI modelling of a typical gravity dam section is conducted in EAGD-84 [14] based on the general equation given above.

2.2. 3D SSI Modelling

Following the aforementioned 2D SSI formulation, a rigorous 3D SSI model was proposed by Tan and Chopra [16] considering the mixed boundary value problem. The equation of motion in frequency domain including spatially varying ground motion in 3D is given by Eq. 2:

$$\begin{aligned} &-\omega^2 \begin{matrix} m & 0 \\ 0 & m_b \end{matrix} + \; 1 + i\eta_s \begin{matrix} k & k_b \\ k_b^T & k_{bb} \end{matrix} + \begin{matrix} 0 & 0 \\ 0 & S_f \;\omega \end{matrix} \quad \begin{matrix} r \;\omega \\ r_b \;\omega \end{matrix} = \\ &\begin{matrix} R_h \;\;\omega \\ 0 \end{matrix} + \;\omega^2 \begin{matrix} m & 0 \\ 0 & m_b \end{matrix} - \;1 + i\eta_s \begin{matrix} 0 & 0 \\ k_b^T & k_{bb} \end{matrix} \quad \begin{matrix} r^s \;\omega \\ r_f^f \;\omega \end{matrix} \end{aligned} \tag{2}$$

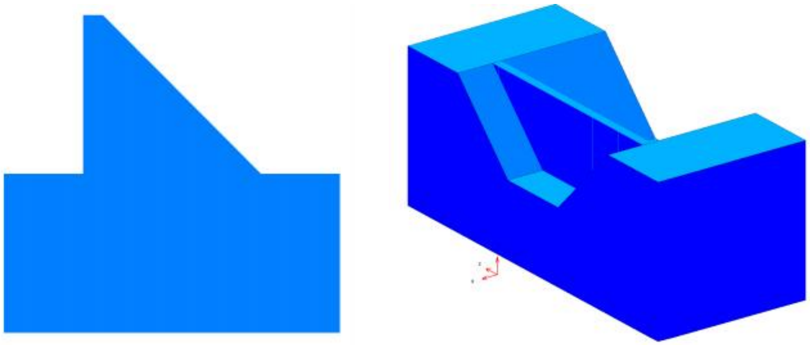
The equation of motion transformed into the frequency domain is partitioned for the nodes of the dam finite element model at the dam-foundation interface ($r_b(\omega)$) and for those not located at the dam-foundation interface ($r(\omega)$). The vector $R_h\,(\omega)$ represents the Fourier transform of hydrodynamic forces at upstream face of dam-body. The static application of the earthquake induced free field displacement $r_f^f\;\omega$ results in the structural displacement vector $r^s(\omega)$. The application of the direct boundary element method for the canyon cut in a visco-elastic half-space as proposed by Zhang and Chopra [17] is used to establish the relation between the forces and displacements at the dam and foundation interface leading to the complex valued impedance matrix of the foundation $S_f\;\omega$. Similar to the Eq. 1, η_s represents the rate independent damping coefficient of the foundation.

The 3D modeling of the gravity dams are conducted using the most recent form of this implementation EACD-2008, which was modified in the due course of this study for gravity dam applications.

3. MODEL DEFINITION

3.1. Model Definition and the Solution of the Eigen Value Problem

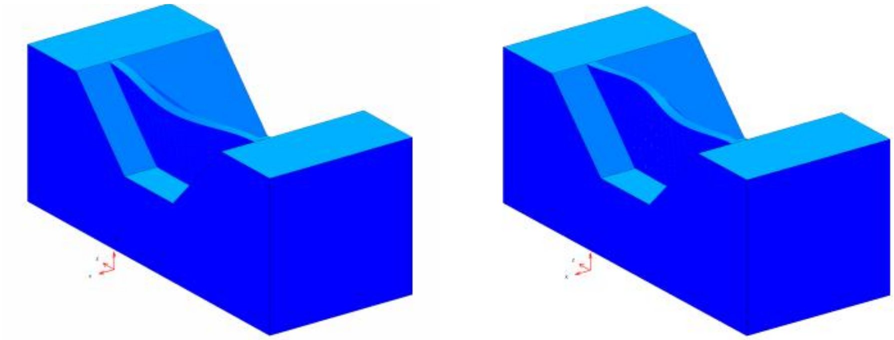
A typical gravity dam section having a height of 80 meters and downstream slope of 1V/1H is selected as the case study, the 2D representation of which is shown in Figure 1a. Three-dimensional realizations of this typical section is chosen with the dam located in a variety of valley lengths, namely at 180, 240, 320, 480, and 960 meters. Hexahedral and quadrilateral quadratic elements are used in the discretization of the dam and foundation respectively. The 3D realization in a 180m wide valley is shown in Figure 2b.



(a) 2D (b) 3D

Figure 1. Finite element idealization of gravity dams

In order to obtain accurate results, the size of the boundary elements used for the foundation rock discretization is chosen to be smaller than half of the shear wavelength of the soil medium. The Young's modulus of dam concrete and foundation soil medium are chosen as 20 and 10 GPa, respectively. A rate independent damping coefficient of 0.1 is used for both materials. The dynamic stiffness matrix of the foundation substructure is computed at discrete frequency values starting from zero frequency representing the static stiffness matrix to 50 Hz. Following the assembly of the dam body stiffness matrix and foundation rock impedance matrices, Eigen Value problem is solved for determining the natural frequencies and the mode shapes using generalized coordinates. The first two modes of the dam system shown in Figure 3b is presented in Figure 4. Two-dimensional SSI analysis is performed using the same assumptions for modelling of the gravity dam.



(a)Fundamental Frequency f1=4.1 Hz. (b)Second Frequency f2=5.7 Hz

Figure 4. First and second mode shapes of the 3D model with foundation interaction

3.2. Frequency Response Functions

Comparison of the results of the 2 and 3D models are conducted in the frequency domain given the comparison of the modal effects are readily obtained. For investigating the effect of the 3D SSI formulation on the equivalent damping ratio, the traditional half-power bandwidth method is utilized [18, 19]. However, exact formulation of the aforementioned method is applied in this study (Eq. 3) considering the large amount of damping obtained in the analyses (i.e. flatter response curves) as a consequence of the traveling of the seismic waves [20] towards infinity.

$$\frac{\omega}{\omega_n} = 1 - 2\zeta^2 \pm 2\zeta \; \overline{1 - \zeta^2} \tag{3}$$

Acceleration at the midpoint of the crest of the dam is selected as the response quantity defining the overall behaviour of the system as it can be easily used to compare the 2 and 3D response of the gravity dams. Transfer function representing the frequency response function for the dam-foundation system is obtained using the fast Fourier transform of the crest acceleration response at the midpoint of the dam for a very short duration pulse excitation as the input motion to the system. This transfer function includes all modes' contributions and can be used as a convenient tool in calculation of the desired response for different earthquake records by simply multiplying FFT of ground motion and the obtained transfer function. The elimination of the repetition of the impedance matrix calculation of a model for different ground motions and the ease of the comparison of the response amplitudes of different models at different frequency values are the two predominant advantages of the transfer function approach as outlined in Figure 5.

Figure 6. General procedure in obtaining transfer functions

The analyses in this study are conducted without including the reservoir given the investigation/comparison of the 2 and 3D soil-structure interaction is the primary goal of this study.

4. THE RESPONSE OF CONCRETE GRAVITY DAMS

4.1. Transfer Function Comparison

The transfer function response of the 3D models and the 2D counterpart are compared in Figure 4. Three-dimensional models with valley widths of 180, 240, 320, 480, and 960 meters are shown as 0X, 1X, 2X, 4X, and 10X models, respectively, in this figure. A decreasing trend of the amplitude of the response at the fundamental mode is observed as expected as the canyon becomes wider. The substantial amplitude at higher frequencies are also of concern, as the models do not represent a single predominant modal response expected for the fixed base systems. The fundamental frequency of a 3D system converges to the 2D system only for a canyon width of 980m, which is 12 times the height of the dam. A large difference in the response is observed even for a canyon width of 480m, which can be considered easily as a wide canyon for design and evaluation purposes. Furthermore, the amplitude of the response in the fundamental mode is also very different and changes substantially compared to the 2D response as the canyon width decreases.

The significant change in the frequency response functions for the higher frequencies is also evident in the figure. For narrow canyons, the response in higher frequencies is considerably higher than the larger canyons. The effects from these modes are damped out as the canyon width increases. The shape of the frequency response function also shows that the frequency content of the motion can be significantly effective on the final response of the dam. Motions with higher frequency content may lead to significantly different response in a 3D analysis compared to an analysis conducted with a 2D idealized model.

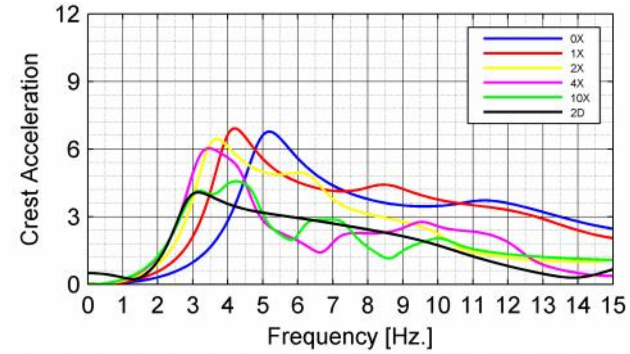


Figure 7. Transfer functions of the 2 and 3D models

4.2. Equivalent Damping Ratio

The behaviour of the gravity dams is greatly influenced by the effect of foundation rock as a source of energy dissipation. The contribution of the damping characteristics of the soil medium (besides the radiation of the seismic waves), introduces higher levels of energy dissipation compared to the modelling alternatives of these structures using the conventional massless foundation finite element models or the simplified 2D analysis procedures [21]. The geometry of the valley also seems to significantly affect the response: as given in Figure 4, the amplitudes of the peak response for different models are significantly different for different valley configurations. Wider valleys induce smaller amplitudes and higher damping contribution to the response compared to narrow valleys. The peak response for the same gravity dam section located in a 320m valley is greater than the 2D response by over 50%.

In order to quantify the damping effect on the system response, the widely used half-power bandwidth method is applied to the first mode frequency response of all models as discussed before. The equivalent damping ratios for the first mode are obtained (Table 1). The results presented in the table imply that:

1) The natural frequency of a dam in even a relatively wide valley can be significantly larger compared to a 2D idealization commonly utilized in the design and evaluation of dam,
2) The damping ratios for narrower valleys are significantly lower than the damping observed in an idealized 2D response.

Table 1. Fundamental frequency and equivalent damping ratio

model size	3D models					2D model
	0X	1X	2X	4X	10X	plain strain
ζ_1 %	15.1	16.7	20.2	26.1	41.7	32.4
F_1 Hz.	5.2	4.1	3.4	2.9	2.6	2.6

5. CONCLUSION

The effects of the rigorous consideration of the 3D SSI on the performance of gravity dams are investigated in this study. The differences with the use of the 2D SSI formulation, the general idealization with which the design and evaluation of dams are conducted, are determined. The following conclusions are drawn from this study:

> There is a considerable dispersion in the fundamental frequency values for dams constructed in valleys with different widths. The 2D idealization can only represent the resonant frequency of the 3D models with valley widths at least six times larger than the height of the dam. Consequently, dams constructed in narrow canyons are more susceptible to high frequency ground excitations whereas the dams in larger canyons are sensitive to the earthquakes with low frequency wave content.

The evaluation of the peak displacement response of the structure, which directly influences stresses developed at critical locations of dam body [21], shows the implied damping for dams in narrow canyons is considerably lower than the 2D idealizations. The equivalent damping ratio for dams constructed in narrow canyons is almost 50% of the value obtained for the 2D idealization.

The factors above, as well as the changes observed in the general shape of the frequency response function for dams built in narrow canyons shows the importance of performing full 3D SSI analysis instead of conventional 2D SSI analysis for gravity dams. The results from the 3D analyses can be quite different compared to their counterparts with 2D idealization even for an 80m high dam built in a 480m wide valley which would easily be characterized as a 2D system in design or evaluation.

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