Dynamic analysis of concrete arch dams by FE-BE approach including non-uniform ground motion

V. Lotfi
Department of Civil and Environmental Engineering, Amirkabir University, Iran

Abstract

In this paper, a FE-BE procedure is implemented for dynamic analysis of concrete arch dams, which considers the effects of non-uniform ground motion. The technique relies on the finite element method for the discretization of the dam body, while the foundation rock domain is handled by three dimensional boundary element formulations with no restrictions imposed on the geometry of the canyon shape. A previously developed special purpose program is enhanced based on this approach and the response of the Morrow Point arch dam is studied as an example. The efficiency of the analysis is highly influenced by an interpolation scheme, which is used for evaluation of foundation impedance matrix and force vector. The convergence of this method is initially controlled for uniform, as well as non-uniform ground excitations. Subsequently, the effects of non-uniform ground motion are evaluated and discussed for vertically propagating SH, P and SV waves.

1 Introduction

The subject of dam-foundation rock interaction has been one of the main attractions in research conducted in the field of dynamic analysis of concrete arch dams during the past decade.

In one of the earlier studies, i.e., the work of Maeso and Dominguez [1], both dam and foundation rock domains were treated by boundary element formulations (BE-BE method). There is no geometric limitation in their procedure and complications due to non-uniform ground motion are also
introduced in the formulation. However, the method apparently requires enormous computational effort. Furthermore, it is obviously not as convenient to consider different material properties or geometric details in the dam body by the boundary element formulation in comparison to the finite element method.

In other studies, Tan and Chopra [2] proposed a technique in which the dam was modeled by a finite element, while the foundation rock was represented by a two-dimensional (2D) boundary element formulation combined with a series expansion along the canyon axis direction (FE-BE technique). However, the main restriction of their work is that the foundation rock geometry must be that of a uniform canyon extending to infinity. Meanwhile, the ground motion is also assumed uniform.

In an earlier work of the author [3], a FE-BE approach was presented in which the foundation rock domain was treated by a three-dimensional boundary element formulation. Therefore, the geometry of canyon could be quite arbitrary and no restrictions were imposed. It was shown that uniform canyon shape assumption could cause significant departure from the true response in certain cases. The special computer program “MAP-76” [4] was developed in that investigation.

In the present study, that program is enhanced to include the non-uniform ground motion option. The applied concepts and the required changes in the formulation can be found elsewhere in detail [5]. By employing this program, the response of the Morrow Point arch dam is studied herein due to uniform and non-uniform ground excitations. Furthermore, it should be mentioned that in the usual process, most of the computational time is spent for calculations of foundation impedance matrix and force vector at each frequency. However, this could be remedied by calculating the foundation impedance matrix and force vector term only at certain frequency points and interpolating them for intermediate frequencies similar to the work of Tan and Chopra [6]. In the present study, different alternatives of equally spaced frequency points (stations) are considered for the purpose of interpolation. However, in all these cases, a cubic interpolation scheme is implemented. The convergence of this method is initially controlled for uniform, as well as non-uniform ground excitations. Following from that, the effects of non-uniform ground motion are evaluated and discussed.

2 Modeling and basic parameters

As mentioned, the dam body and the foundation rock are treated in this work by finite and boundary elements, respectively. Meanwhile, both domains are considered as linearly viscoelastic materials with isotropic behavior.

2.1 Model

An idealized symmetric model of Morrow Point arch dam is considered. The geometry of the dam may be found in reference [7]. The model is prepared based on the finite and boundary elements discretization for the dam body and
foundation rock respectively, which is depicted in Fig. 1. The dam is discretized by 40 isoparametric 20-node finite elements, while the foundation rock is modeled by 178 isoparametric 8-node boundary elements considered at the foundation surface. In this model, the canyon shape is also assumed uniform.

Figure 1a: Dam-foundation system discretization (FE-BE model).

Figure 1b: Boundary element discretization of foundation rock.
2.2 Basic parameters

The dam concrete is assumed to be homogeneous with isotropic linearly viscoelastic behavior and the following main characteristics:

- Elastic modulus \( (E_d) \) = 27.5 GPa.
- Poisson’s ratio = 0.2
- Unit weight = 24.8 kN/m³
- Hysteretic damping factor \( (\beta_d) \) = 0.05

The foundation rock, is idealized by a homogeneous, viscoelastic domain. The basic properties of this region are:

- Elastic modulus \( (E_f) \) = 27.5 GPa.
- Poisson’s ratio = 0.2
- Unit weight = 26.4 kN/m³
- Hysteretic damping factor \( (\beta_f) \) = 0.05

3 Results

The FE-BE model (Fig. 1) is prepared based on the discretization and basic parameters explained in previous section. The responses of the dam crest are initially obtained for this model with the assumption of uniform ground motion due to upstream, vertical and cross-stream excitations (Fig. 2).

The response quantities plotted are the amplitudes of the complex valued radial accelerations for two points located at dam crest. These are either the mid-crest point \( (\theta = 0^0) \) selected for upstream or vertical excitations or a point located at \( (\theta = 13.25^0) \) which is used for the case of cross-stream excitation. This is due to the fact that radial acceleration is diminished at mid-crest for the cross-stream type of ground motion.

In each case, the amplitude of radial acceleration is plotted versus the dimensionless frequency for a significant range. The dimensionless frequency for upstream and vertical excitation is defined as \( \omega / \omega_1^S \) where \( \omega \) is the excitation frequency and \( \omega_1^S \) is the fundamental frequency of the dam on rigid foundation with empty reservoir for a symmetric mode. For the cross-stream excitation cases, the dimensionless frequency is defined as \( \omega / \omega_1^A \), where \( \omega_1^A \) is the fundamental resonant frequency of the dam on rigid foundation with empty reservoir for an anti-symmetric mode.

It should be noted that for each type of excitation, the response is obtained by utilizing the interpolated foundation impedance matrix as well as the case where that matrix is calculated directly without interpolation. In the former condition, the foundation impedance matrix is initially calculated at certain frequency
Figure 2: Responses at dam crest due to harmonic upstream, vertical and cross-stream ground motions (uniform ground motion).
points, and thereafter, the impedance matrix is calculated at each intermediate frequency value based on a cubic interpolation scheme. In this alternative, three cases are considered by employing 7, 13 and 25 frequency points, respectively. In each case, these stations are assumed to be spaced equally and the numbers mentioned include \( \omega = 0 \) as the first point. In other words, there are 6, 12 and 24 equal frequency intervals for these cases, respectively.

It is observed (Fig. 2) that response for cases utilizing interpolation are the same as the direct analysis case (with no interpolation) for the whole frequency range considered. This is true for all three cases of upstream, vertical and cross-stream excitations. It is worthwhile to mention that calculation of foundation impedance matrix in the direct method required approximately 40, 20, 10 times more execution time, if it is compared with the other three cases utilizing 7, 13 and 25 frequency points, respectively.

Overall, this means that assuming uniform ground motion, the interpolation procedure is completely successful as far as accuracy and efficiency is concerned and great accuracy can be achieved even with a relatively low number of frequency stations (7 points) for the interpolation purposes.

In the next stage, the same convergence study is performed under the condition of non-uniform ground motion. It should be noted that for these cases, interpolation must be carried out both for foundation impedance matrix and foundation force vector. Meanwhile, it should be mentioned that for this condition (non-uniform ground motion), the free field motions are defined as vertically propagating SH, P and SV waves [8], which produce unit acceleration at the uniform half space surface (in the absence of dam-canyon system). These will correspond to upstream, vertical and cross-stream excitations, respectively.

The results for non-uniform ground motion condition are presented in Fig. 3. It is observed that the response for low number of frequency stations utilized (7 points) is significantly different from the response obtained for direct method (no interpolation) at certain frequency ranges. The results for the 13 frequency points case are very close to the direct method except for vertical ground motion in the vicinity of the peak corresponding to the first symmetric natural frequency of the system. However, even this slight error is diminished in the case of 25 frequency points and it is noticed that the response is now perfectly matched with the one corresponding to direct method (no interpolation) for the whole frequency range considered. Therefore, it can be concluded that the interpolation scheme is still successful under the condition of non-uniform ground motion. However, a moderate number of initial frequency stations must be used for the interpolation purposes. This is due to the fact that foundation force vector terms are less smooth functions of frequency in comparison with the terms of foundation impedance matrix.

Finally, the response for different forms of excitation, are compared for uniform and non-uniform ground motions in Fig. 4. These graphs can be used to evaluate the effects of non-uniform ground motion on the response of the dam. The response of rigid foundation case is also provided in these plots as a reference.
Figure 3: Responses at dam crest due to harmonic upstream, vertical and cross-stream ground motions. (non-uniform ground motion; corresponding to vertically propagating SH, P and SV waves, respectively).
Figure 4: Comparison of response at dam crest for uniform and non-uniform ground motions due to upstream, vertical and cross-stream excitations.
It is observed that natural frequencies of the system reduce for flexible foundation cases in comparison with corresponding characteristics of the dam on rigid foundation. The amount of these reductions, is the same for both uniform and non-uniform ground motion cases. Meanwhile, the responses for low frequencies are practically the same for both uniform and non-uniform ground motions. This is noticed up to the first symmetric natural frequency of the system for the upstream excitation, and near the first symmetric or anti-symmetric natural frequency of the system for vertical and cross-stream ground motions, respectively. Of course, it should be mentioned that it was expected to have a similar response at low frequencies for uniform and non-uniform ground excitations. This is due to the fact that at low frequencies, existing wavelengths are actually changing between infinity (for \( \omega = 0 \)) and a finite large number. As long as the wavelengths are much higher than the characteristic geometric length of the arch dam, the effects of non-uniform ground motion are not expected to be significant.

It is also observed that for moderate frequencies, the response is mainly higher for uniform ground motion. While at high frequencies, the opposite behavior is noticed. This is true independent of the type of excitation.

4 Conclusions

A formulation was implemented for dynamic analysis of concrete arch dam–foundation rock systems based on FE-BE procedure including the effects of non-uniform ground motions. Following this methodology, an existing computer program [4] was modified and the response of Morrow Point arch dam was studied due to uniform and non-uniform ground excitations. The efficiency of the program is greatly influenced by an interpolation scheme, which is used for evaluation of foundation impedance matrix and force vector. The convergence of this method is initially controlled and discussed for uniform, as well as non-uniform ground excitations. Following from that, the effects of non-uniform ground motion are evaluated and changes in response are also specified in comparison with uniform ground excitation.

Overall, the main conclusions obtained by the present study can be listed as follows:

- The convergence study for uniform ground motion reveals that the interpolation procedure is completely successful as far as accuracy and efficiency is concerned. It is noted that great accuracy can be achieved even with relatively low number of frequency stations (7 points) for the interpolation purposes.
- From similar convergence study in the case of non-uniform ground excitations, it is apparent that the interpolation scheme is still successful. However, a moderate number of initial frequency stations must be used for the interpolation purposes. This is due to the fact that foundation force vector terms are less smooth functions of frequency in comparison with the terms of the foundation impedance matrix.
Finally, the responses were compared for uniform and non-uniform ground motions for different types of excitation direction. It is observed that the response for low frequency is practically the same for both uniform and non-uniform ground motions. This is due to the fact that at low frequencies existing wavelengths are actually changing between infinity (for \( \omega = 0 \)) and a finite large number. As long as the wavelengths are much higher than the characteristic geometric length of the arch dam, the effects of non-uniform ground motion are not expected to be significant.

It is also observed that for moderate frequencies the response is mainly higher for uniform ground motion in comparison with non-uniform ground motion, while at high frequencies the opposite behavior is noticed. This is true for all three types of excitation direction being considered.

References