Dam-reservoir interaction effects on the elastic dynamic response of concrete and earth dams

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Abstract

The relative effects of dam-reservoir interaction on the dynamic response of concrete and earth dams are studied. The amplification of accelerations at the dam crest is explored under harmonic acceleration load. For certain cases of concrete dams the accelerations can be significantly affected by the upstream reservoir, whereas this influence is smaller for earth dams.

Keywords: dam, reservoir, interaction, finite elements, earthquake

1. Introduction

The early studies for modelling dams and reservoirs considered undeformable [1] or simple flexible dams [2] and concentrated on predicting the hydrodynamic pressures on dams. Various closed-form solutions were proposed [1] for simplified problems and hydrodynamic pressures were considered as "added mass". Numerical models [3] using finite element (FE) [4, 5] or boundary elements (BE) [6] considered complicated dam-reservoir interaction (DRI) by discretising the reservoir using "solid" [4] or "fluid" (Eulerian or Lagrangian) [7] elements with relevant boundary conditions (BCs) [8].

Previous studies [1, 2] showed that DRI effects are more pronounced in concrete dams than earth dams. These are mainly focused on (a) the fundamental period of vibration of the dam-reservoir system (DRS), T_d, and (b) the magnitude of its dynamic response. DRI causes the DRS to soften, elongating its T_d, and alters its response by amplifying the seismic motion. However, DRI effects have traditionally been considered as insignificant for earth dams [3] and were therefore neglected in their analysis [9, 10].

This note studies the effects of DRI on the dynamic response of concrete and earth dams using 2860 parametric analyses for different dynamic characteristics of the load, the dam and the reservoir. The dam and reservoir domains are discretised with 8-noded isoparametric displacement-based quadrilateral solid elements, following Pelecanos et al. [4] and Pelecanos [11]. Dynamic two-dimensional plane-strain analyses in time-domain are performed using ICFEP [12] and the generalised α-time-integration scheme [13].

2. Rectangular concrete dam

A simple rectangular concrete dam (B=0m) (Figure 1) is considered with dimensions as: H=60m, W=18m, L=300m, T=18m and $L/H = 5$ [4].

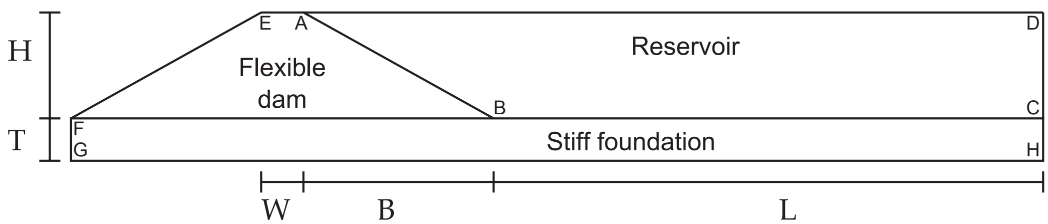

Figure 1: Geometry of the dams considered.

2.1. Dam with empty reservoir

The reservoir (A-B-C-D) is not discretised. The dam properties are: elastic modulus E = 35 GPa, Poisson's ratio ν=0.3 and mass density ρ=2500 kg/m^3. Rayleigh damping, $\xi = 5\%$ with ω_1 and ω_2 equal to the fundamental circular frequency of the dam, ω_d, and the circular frequency of the harmonic load, ω respectively. The foundation is rigid with bulk modulus, $K = 10^8$ kPa and ν=0.4. The BCs along (G-H) are: zero displacements in the vertical and a harmonic acceleration in the horizontal direction ($a(t) = a_0 \cos \omega t$). 65 different values of ω are considered for $a_0 = 1$ m/s^2 to 40 cycles.

The black dashed line in Figure 2 shows the amplification spectrum, i.e. the amplification of accelerations at the dam crest, $|F|$, versus ω/ω_d. Peak values of $|F|$ occur at $\omega/\omega_d = 1$ and 4.7, i.e. at the first two natural modes of dam vibration. The analytical value of ω_d, based on Euler-Bernoulli beam theory, is larger (by 16%) than the calculated FE value. This is attributed to the stocky geometry (H/W=3.333) of the examined dam for which shear effects become significant and that the bending theory does not consider.

2.2. Dam with full reservoir

The reservoir domain is modelled as a linear material with bulk and shear moduli as: $K_w = 2.2 \cdot 10^6$ kPa and $G_w = 100$ kPa [4]. The elastic dam modulus is altered to provide 22 values of ω_r/ω_d ($\omega_r = 0.25V_p/H$) [1] ($V_p = 1483$ m/s is the p-wave velocity of water). Interface elements [12] are placed along the reservoir-dam (A-B) and dam-foundation (B-C) interfaces, with normal and shear stiffnesses: $K_N = 10^8$ kN/m^3, $K_S = 1$ kN/m^3. The reservoir (C-D) BCs are: zero displacements in the vertical and viscous dashpots [8] in the horizontal directions. Figure 3 shows $|F|$ with respect to ω/ω_d and ω_r/ω_d and the dashed line refers to the empty reservoir case.

The $|F| - \omega/\omega_d$ spectrum is similar for all ω_r/ω_d: two peak values of $|F|$, of which the magnitude and the value of ω/ω_d at which they occur vary with ω_r/ω_d. Maximum $|F|$ occurs where $\omega/\omega_d \approx \omega_r/\omega_d \approx 1$, i.e. where $\omega \approx \omega_d \approx \omega_r$, due to reasonance between the harmonic load, the dam and the reservoir. There are also large values of $|F|$ for $\omega/\omega_d \approx \omega_r/\omega_d$ (shown diagonally), i.e. where $\omega \approx \omega_r$. The $|F|$ value for the latter case ($\omega \approx \omega_r$) can be larger than that corresponding presumably to the second mode of dam vibration (i.e. close to $\omega/\omega_d \approx 4.7$). However, in some cases (e.g. close to $\omega/\omega_d \approx \omega/\omega_r \approx 3$) there is a combined effect of $\omega \approx \omega_r$ and the second mode of dam vibration. Figure 2 shows the amplification spectra for a dam with empty and full ($\omega_r/\omega_d = 1$) reservoir. DRI results in higher $|F|$ for the first mode, but smaller for the second mode and maximum $|F|$ occurs at smaller ω/ω_d.

Figure 4 shows the value of ω/ω_d for which the maximum $|F|$ occurs at various values of ω_r/ω_d. The maximum $|F|$ occurs at ω/ω_d equal or lower than that of an empty reservoir case, therefore, both natural periods of a DRS are larger than those of a dam with an empty reservoir. The variation in the T_d of the DRS depends on ω_r/ω_d. Regarding the first mode, the deviation of T_d from the empty reservoir case is larger when $\omega_r/\omega_d \approx 1$. Regarding the second mode, T_d increases close to the second frequency of vibration of the reservoir, $\omega_r/\omega_d \approx 2 \sim 3$. Peak $|F|$ values also occur for $\omega_r/\omega_d \approx \omega/\omega_d$ as observed earlier in Figure 3. However, peak $|F|$ values at $\omega/\omega_d \approx 2 \sim 4$ could be a combination of (a) $\omega/\omega_d \approx \omega_r/\omega_d$ (resonance between the load and the reservoir) and (b) the second mode of dam vibration.

Figure 5 shows the maximum value of $|F|$ with ω_r/ω_d for the two modes. Regarding the first mode, the maximum $|F|$ value of a DRS is larger than that of a dam with an empty reservoir, for $\omega_r/\omega_d \gtrsim 0.8$. Regarding the second mode, the $|F|$ of a dam with a full reservoir is larger than that for an empty reservoir for $\omega_r/\omega_d \gtrsim 2.7$ (i.e. $T_{r2} > T_d$).

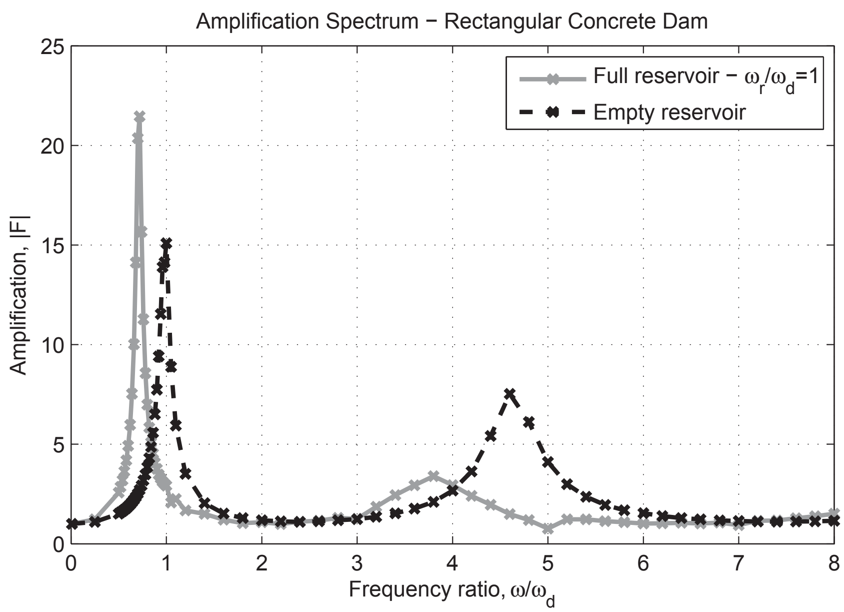

Figure 2: Amplification spectra of the concrete dam with full and empty reservoir.

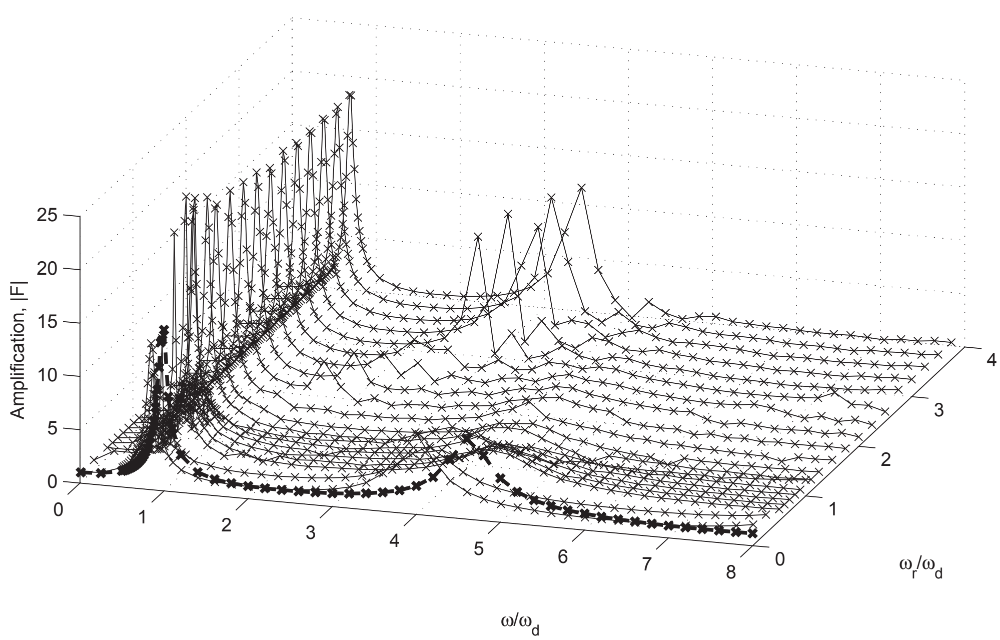

Figure 3: Amplification at the crest of the concrete dam against ω/ω_d and ω_r/ω_d.

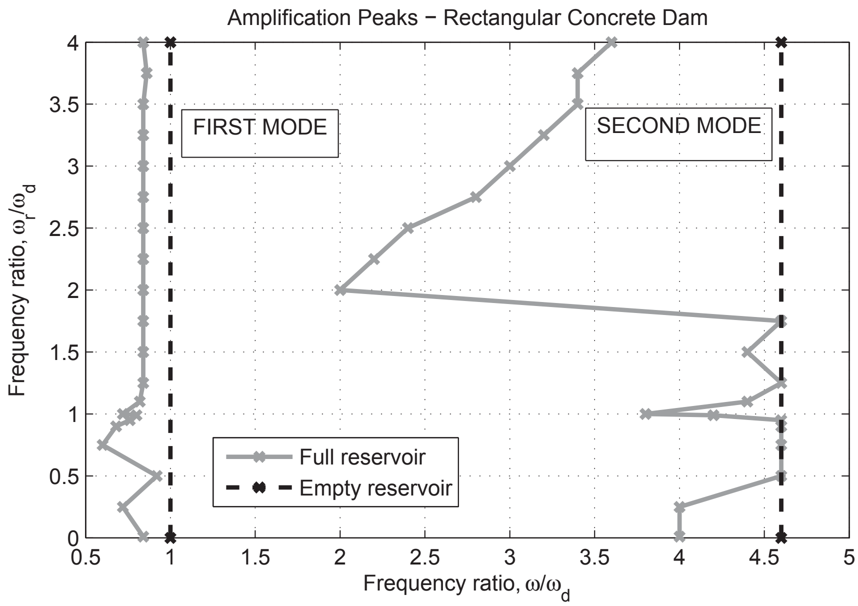

Figure 4: Amplification peaks of the concrete dam with full and empty reservoir.

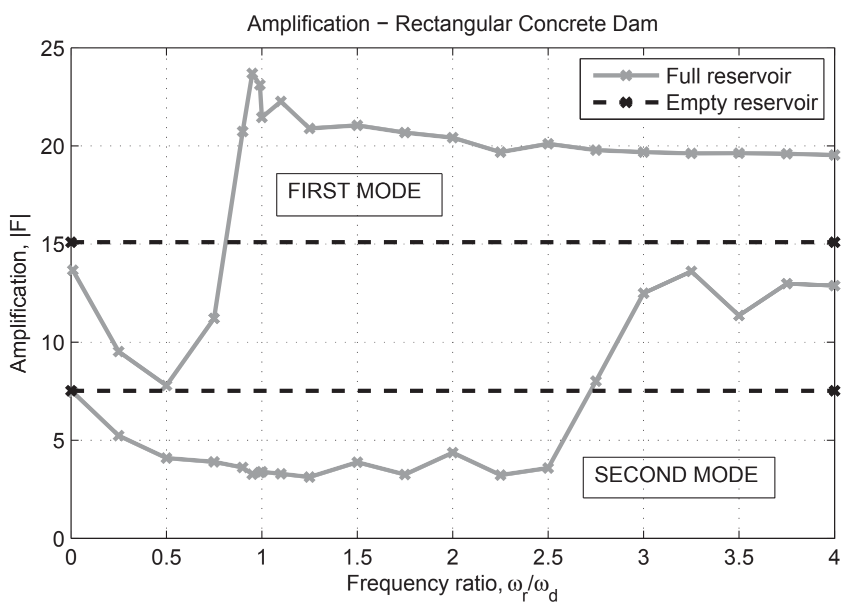

Figure 5: Amplification of the concrete dam with respect to ω_r/ω_d for the first two modes of vibration.

3. Trapezoidal earth dam

The dimensions of the considered dam (see Figure 1) are: H=60m, W=18m, B=180m, L=300m, T=18m, B/H=1/3 and L/H=5 [4].

3.1. Dam with empty reservoir

The dam properties are: E = 468 MPa, ν=0.3 and ρ=2000 kg/m^3 (i.e. giving V_s = 300 m/s). The dashed black line in Figure 6 shows the amplification spectrum. Peak $|F|$ values occur at $\omega/\omega_d = 1$, 2 and 3.9, which correspond to the first three modes of dam vibration. The analytical value of ω_d, based on shear beam (SB) theory [14], is larger (by 21%) than the calculated FE value. This is attributed to the dam bending deformations, considered by the FE analysis, but neglected by the SB theory [1, 15].

3.2. Dam with full reservoir

The dam properties are the same as before, whereas V_s is altered to obtain 22 different values of ω_r/ω_d. Figure 7 shows $|F| - \omega/\omega_d$, for various values of ω_r/ω_d and the dashed line is for the empty reservoir case. The $|F| - \omega/\omega_d$ spectrum follows a similar trend for all ω_r/ω_d: three main peaks for each ω_r/ω_d, which correspond to the first three modes of dam vibration, but there are minor differences for different values of ω_r/ω_d.

Figure 6 shows a comparison of the $|F|$ - ω/ω_d spectrum for a dam with an empty and a full reservoir. The $|F|$ values are very similar for the two cases and their maxima occur for almost identical values of ω/ω_d. Figure 8 shows the value of ω/ω_d for which the maximum $|F|$ occurs against ω_r/ω_d. Generally the maximum $|F|$ occurs very close to the ω/ω_d value of the empty reservoir case for all values of ω_r/ω_d. Finally, Figure 9 shows the maximum $|F|$ with respect to ω_r/ω_d for the first three modes. Again, the amplifications for the full and empty reservoir cases are very similar.

DRI effects are found to be insignificant for earth dams. This is attributed to (a) the sloped upstream face which results in small hydrodynamic pressures [16] and (b) the large inertia of a trapezoidal earth dam which is very large compared to the inertia from the additional mass of the reservoir.

4. Conclusions

This note investigates the effects of DRI on the dynamic behaviour of both thin concrete and large trapezoidal earth dams. The main conclusions of this study may be summarised as follows:

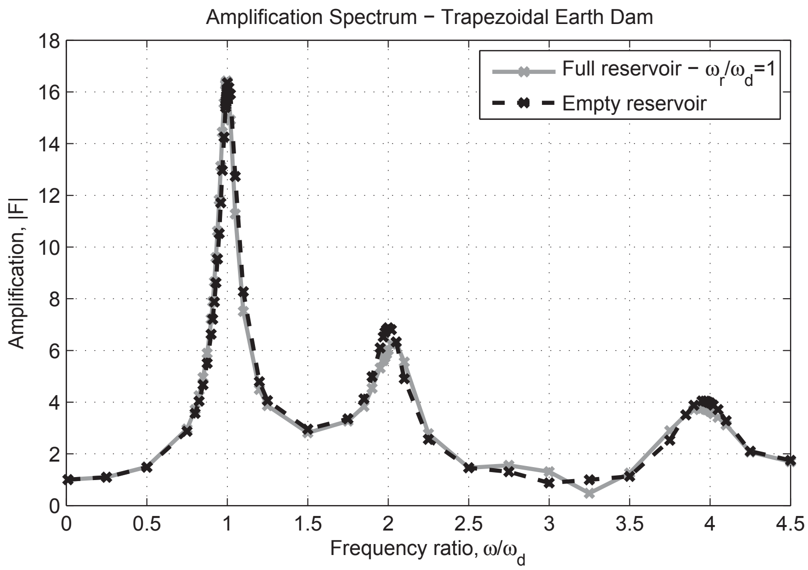

Figure 6: Amplification spectra of the earth dam with full and empty reservoir.

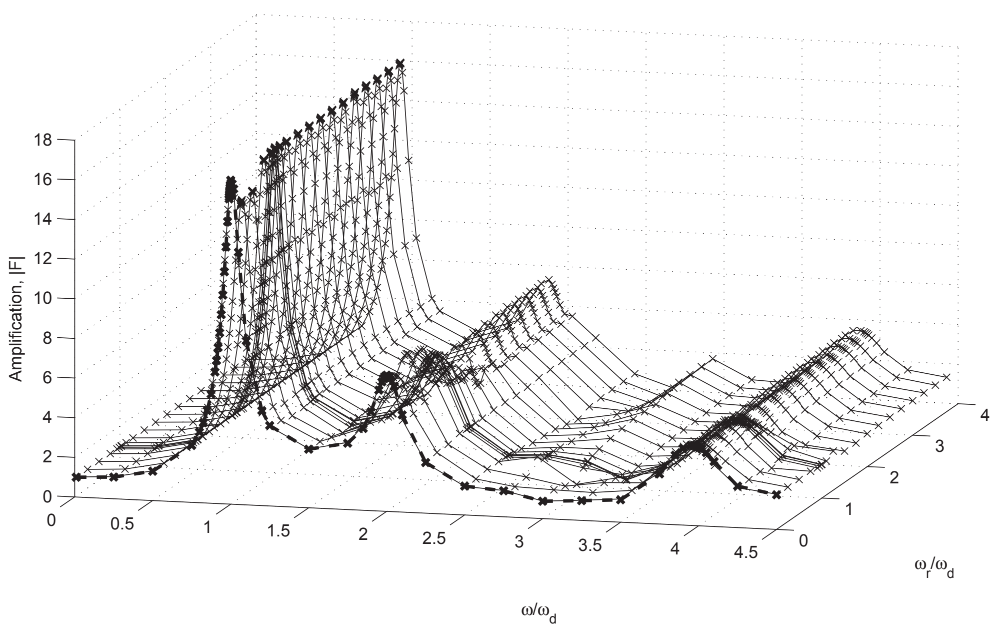

Figure 7: Amplification at the crest of the earth dam against ω/ω_d and ω_r/ω_d.

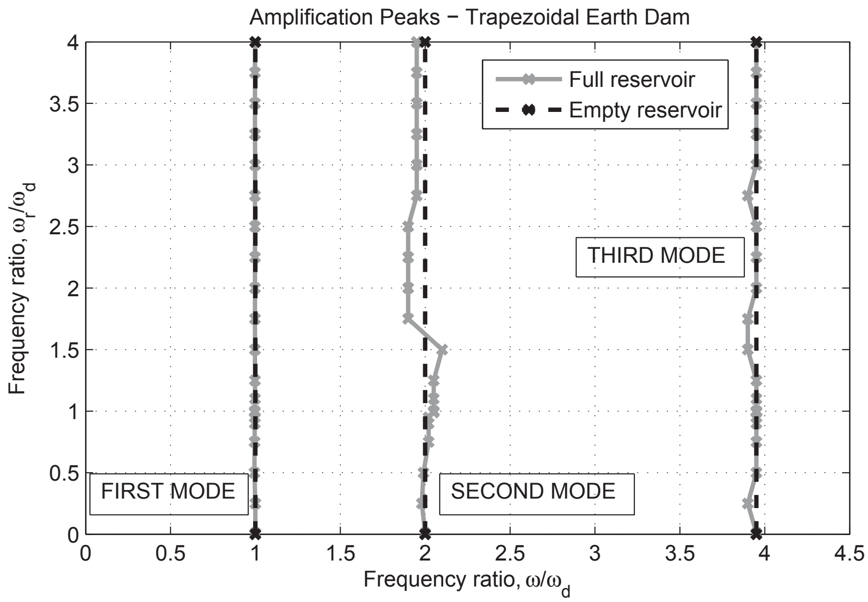

Figure 8: Amplification peaks of the earth dam with full and empty reservoir.

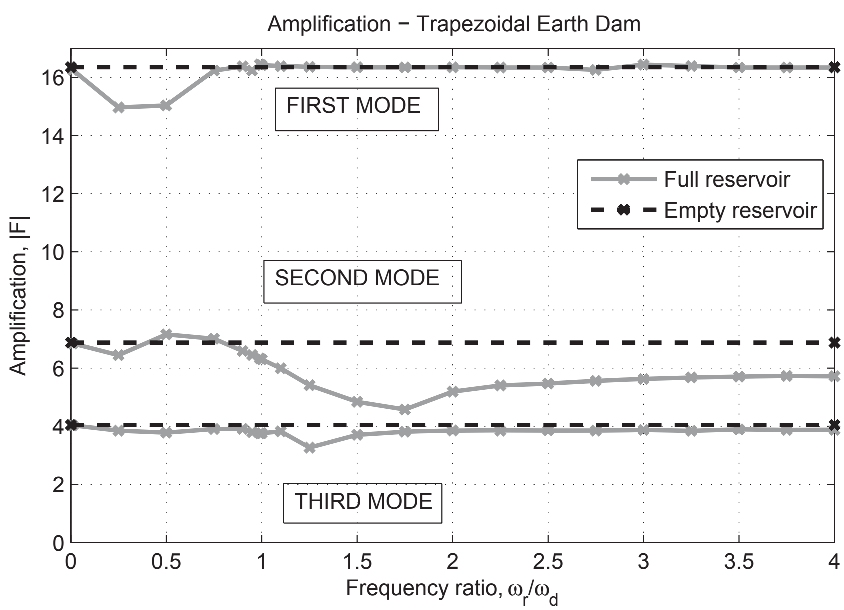

Figure 9: Amplification of the earth dam with respect to ω_r/ω_d for the three first modes of vibration.

- DRI effects are more pronounced for thin rectangular concrete dams than large trapezoidal earth dams and they affect both T_d and $|F|$.

- The reservoir "softens" the response of the dam, resulting in a larger T_d. This is due to the "added mass" of the reservoir.

- The $|F|$ for a full reservoir can be either higher or lower than for an empty reservoir depending on the relative magnitude of ω, ω_d and ω_r.

- The $|F|$ is larger when there is resonance between any two of the load, dam or reservoir and the maximum occurs for $\omega \approx \omega_d \approx \omega_r$.

- DRI effects are insignificant for large earth dams, due to: (a) the small hydrodynamic pressures on the sloped upstream surface and (b) the comparatively small inertia from the reservoir additional mass.

- The calculated FE values for T_d are larger than the analytical ones as the latter do not consider both bending and shear deformations.

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