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THE ELASTIC BEHAVIOR OF TWO TYPES OF EMBANKMENT DAMS UNDER SEISMIC LOADING CONSIDERING DAM-RESERVOIR INTERACTION EFFECTS

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Abstract

The dynamic interaction between dam and reservoir during earthquakes represents a challenging topic that stimulated many researchers over the years trying to clarify its influence on the seismic response of the dams. In this work, a series of dynamic elastic analyses was carried out on two types of embankment dams by using a finite difference software which allowed for modeling the presence of the reservoir with two different approaches. The influence of hydrodynamic effects was assessed in terms of differences in the computed response at the dam crest and evaluating the influence of the vertical component of acceleration input motion.

1. Introduction

The influence of the reservoir on the seismic response of the dams is a topic that captured the attention of several researchers over the years, starting from the pioneering work by Westergaard (1933), until to the improvements by Chopra et al. (1980) and more recent studies as, for instance that by Løkke & Chopra (2019). Indeed, most of the literature studies focused on gravity and arch dams, for which the impact of the hydrodynamic effects has demonstrated to be critical. On the other hand, numerical results obtained modeling with simple elastic models the influence of the reservoir on the seismic response of embankment dams (e.g., Hall & Chopra, 1980) suggested that the presence of the reservoir does not change drastically the response of the dam in terms of accelerations at the crest. Nevertheless, more recently some authors predicted non-negligible deformations due to hydrodynamic effects in the upstream shell by using a simple numerical approach to capture the interaction between dam and reservoir (Kontoe et al. 2019, Pelecanos et al. 2020). Other authors (Kartal & Bayraktar 2013, Xu et al. 2016) also remarked the importance of considering the hydrodynamic effects and their detrimental influence on the concrete slabs of Concrete-Face Rockfill Dams (CFRD), especially when the vertical component of input motion is not negligible.
In this study, the dam- reservoir dynamic interaction was studied with reference to two different embankment dams located in a seismically active area in the surroundings of the Mendoza Urban Area (Argentina). Linear elastic analyses were carried out by adopting two different approaches to model the reservoir; the results are hereafter synthesized in terms of computed acceleration at the crest and related Arias intensity, with the aim of highlighting the influence of the geometry and overall deformability of the embankment on the hydrodynamic response.

2. Numerical models

The numerical analyses were carried out on the zoned Carrizal dam and on the Concrete-Faced Rockfill Potrerillos dam using the Finite Difference software FLAC 8 (Itasca 2017). The dam bodies and their foundation soil were modeled as elastic, while two different approaches were adopted to account for the reservoir: (i) the Dam-Reservoir Interaction (DRI) approach, in which the water body was modelled as a "degenerated case" of a solid (ICOLD 1986); (ii) the Boundary Stresses (BS) approach, in which the reservoir was modeled as hydrostatic loads acting over the upstream slope of the dam, thus neglecting the hydrodynamic action.

El Carrizal dam is a 46 m high, and 2114 m long zoned earth dam built in 1970 over a sandstone bedrock across the Tunuyan River in a shallow alluvial valley. Its cross section is composed of an inclined silt core, surrounded by sand filters and gravel shells with 2.5H:1.0V and 2H:1.0V slopes, for the upstream and downstream faces respectively. Recently, due the loss of useful volume by sediment accumulation in the reservoir, the level of the spillway located at the left margin was elevated 1.5 m, leading to a new minimum freeboard of 3 m under the dam crest.

Potrerillos dam is a 120m high CFRD with 395 m length at the crest, constructed in 2000 over a deep alluvial valley with maximum depth between 50-70 m, across the Mendoza River. The embankment has a downstream slope of 1.8H:1.0V and of 1.5H:1.0V along the upstream face, this latter covered by a concrete slab connected to a cut-off wall in the alluvium as impervious barriers. The body material is composed by coarse gravelly soil taken from the alluvial deposits located near to the dam site, with drains constructed with clean classified material from the same source.

Details about the geometry of the main sections and elastic properties for soil and foundation materials were taken from previous studies carried out on the two dams (Barchiesi et al. 2006, Barchiesi & Corazza, 2015; De Cicco et al., 2015). Sketches of the two dam sections are reported in Figs. 1 and 2, while Tables 1 and 2 summarize the mechanical properties adopted in the analyses. In the same table, the mechanical properties used to model the water reservoir are also reported, as suggested by Verrucci et al. (2017). The level of water of the reservoir was adopted as the maximum operative level in both cases.

The procedure followed to model the reservoir was that proposed by Pelecanos et al. (2013), that includes the presence of interface elements characterized by a null shear stiffness, K_S, and a high axial stiffness (K_N=10^5 MPa/m), that guarantee the relative shear movement between the water mass and the dam, while allowing for the transfer of pressure stresses. The horizontal extension of the reservoir was set as 4 times the dam height, as suggested by Pelecanos (2013) for flexible embankment dams. In addition, aiming to avoid the reflection of the waves at the boundary of the reservoir, absorbing "Quiet boundaries" were adopted and defined following the criteria by Lysmer & Kuhlemeyer (1969). The lateral boundaries of the foundation soil deposit were modeled by the "Free-Field" conditions, that reproduce the response of a one-dimensional soil column with the same properties as the last vertical soil column in the model, while at the bottom a "Compliant base" option was adopted. The mesh was discretized consistently to the Kuhlemeyer & Lysmer (1972) criterion, by considering 1/8 of the wavelength and a maximum frequency f_{max} = 20 Hz.

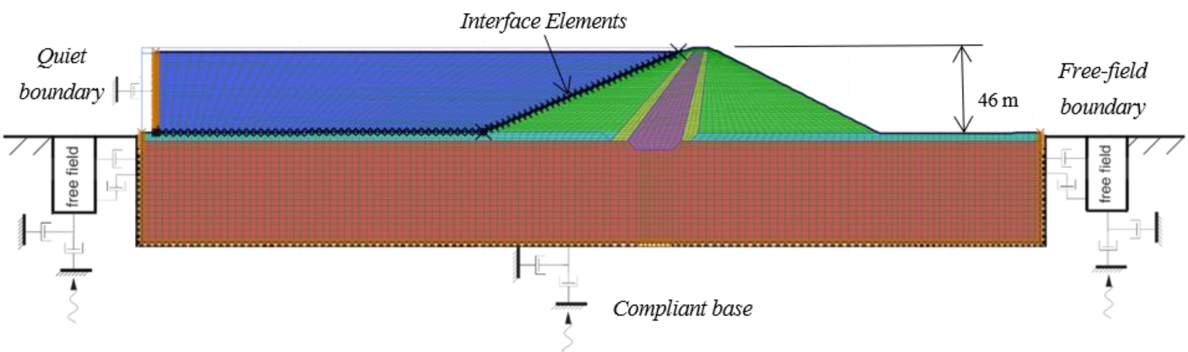

Fig. 1. Geometry and boundary conditions of El Carrizal Dam model

Material	Density	Bulk modulus	Shear modulus	Shear wave velocity	Pressure wave velocity
	[kg/m^3]	[MPa]	[MPa]	[m/s]	[m/s]
Water	1000	2200	1.00E-05	0	1480
Gravel shell	2100	1020	340	400	840
Silt core	1800	747	160	300	730
Sand filter	1900	900	220	340	790
Alluvial material	2000	750	250	350	740
Bedrock	2500	5420	2500	1000	1870

Table 1. Elastic properties of El Carrizal Dam model

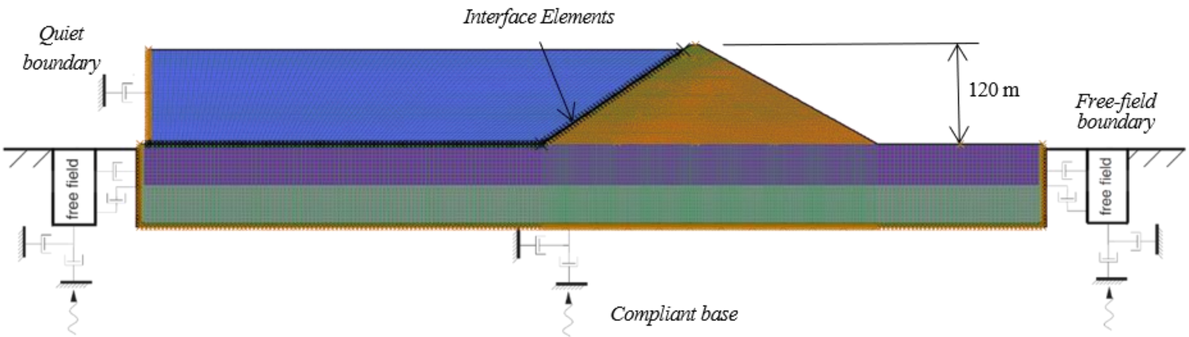

Fig. 2. Geometry and boundary conditions of Potrerillos Dam model

Material	Density	Bulk modulus	Shear modulus	Shear Wave velocity	Pressure Wave velocity
	[kg/m^3]	[MPa]	[MPa]	[m/s]	[m/s]
Water	1000	2200	1.00E-05	0	1480
Dam Body	2300	735	420	430	750
Alluvial material	2000	2520	1300	810	1460
Bedrock	2600	11200	8420	1800	2940

Table 2. Elastic properties of Potrerillos Dam model

A set of Ricker wavelet accelerograms was used to reproduce input motions with variable mean frequencies and peak ground acceleration, *PGA*, as high as 0.65 g, close to the value expected in the region where the dams are located (Mingorance & Barbagelata, 2022). The adopted frequencies respectively correspond to: i) the natural frequency of the embankment, as estimated by empirical equations (Gazetas, 1987); ii) the natural frequency of the embankment, as numerically evaluated from the model response in the frequency domain; iii) the natural frequency of the reservoir, assumed as $f_m = V_{pw}/4H_R$ by considering the pressure wave velocity of the water, V_{pw}, and the height of the reservoir, H_R; iv) a frequency higher than the previous ones. A first set of analyses was carried out by applying the acceleration input motion as horizontal shear stress-time history at the base nodes following the compliant base option in FLAC; a second series was then performed by also considering a simultaneous vertical acceleration component, with an amplitude equal to 50% of the corresponding horizontal time history. It is worth to note that the characteristic frequencies are not the same for the two dams, as shown in Fig. 3.

(a) (b)

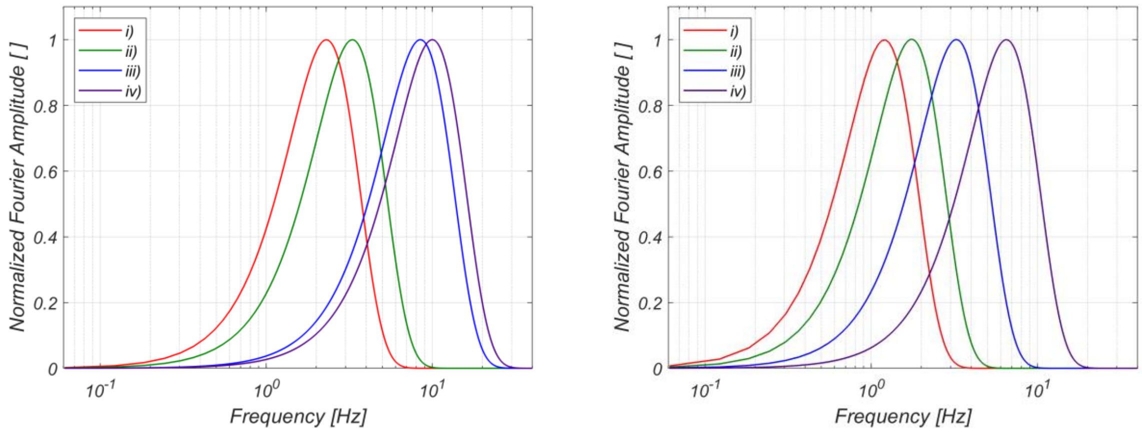

Fig 3. Fourier spectra of the wavelet input motions adopted for El Carrizal (a) and Potrerillos (b) models

3. Results

Due to space constraints, the results obtained applying the input motion (ii characterized by the main frequency close to the natural frequency of the system will be presented hereafter. The results are synthesized in terms of acceleration at the crest of the dam and Arias Intensity (I_a) in the form of Husid plot, as expressed by:

$$I_a = \frac{\pi}{2 \cdot g} \int_0^t a(t)^2 \, dt \qquad (1)$$

On the same Husid plot, the significant duration, $D_{5\text{-}95}$, defined as the time interval between the development of 5% and 95% of the Arias Intensity, is also indicated. The results for El Carrizal earth zoned dam and Potrerillos CFRD computed just considering the horizontal acceleration component of the input are shown in Fig. 4a and in Fig.5a, respectively. Fig. 4b and Fig. 5b report those obtained on both dams also accounting for the vertical component of the acceleration.

(a) (b)

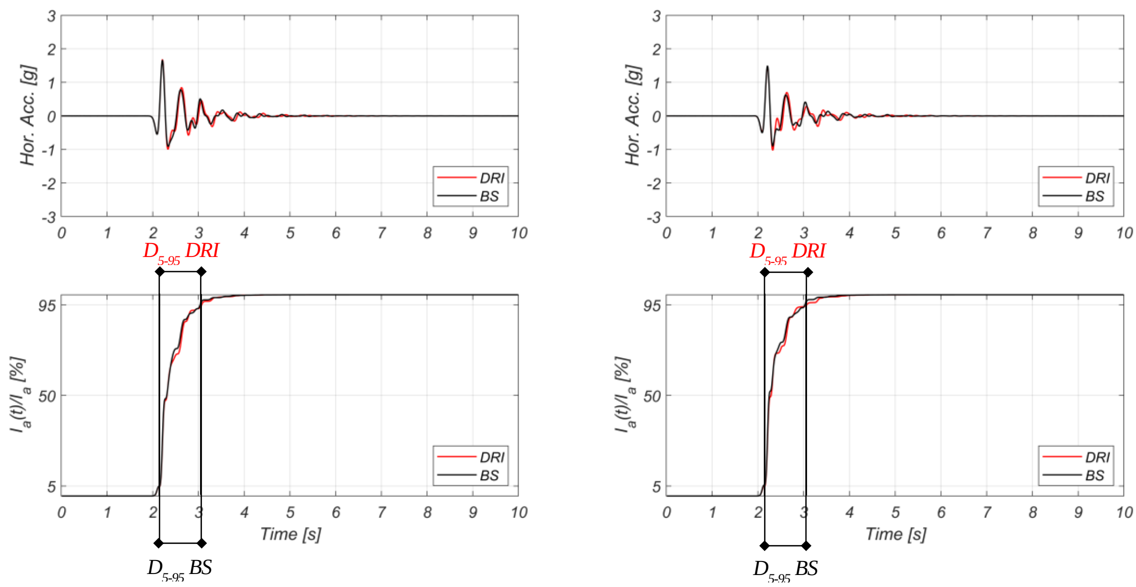

Fig. 4. El Carrizal dam: acceleration at the crest, Husid plot and significant duration computed applying only the horizontal acceleration component (a) and horizontal plus vertical acceleration components (b) of the input motion.

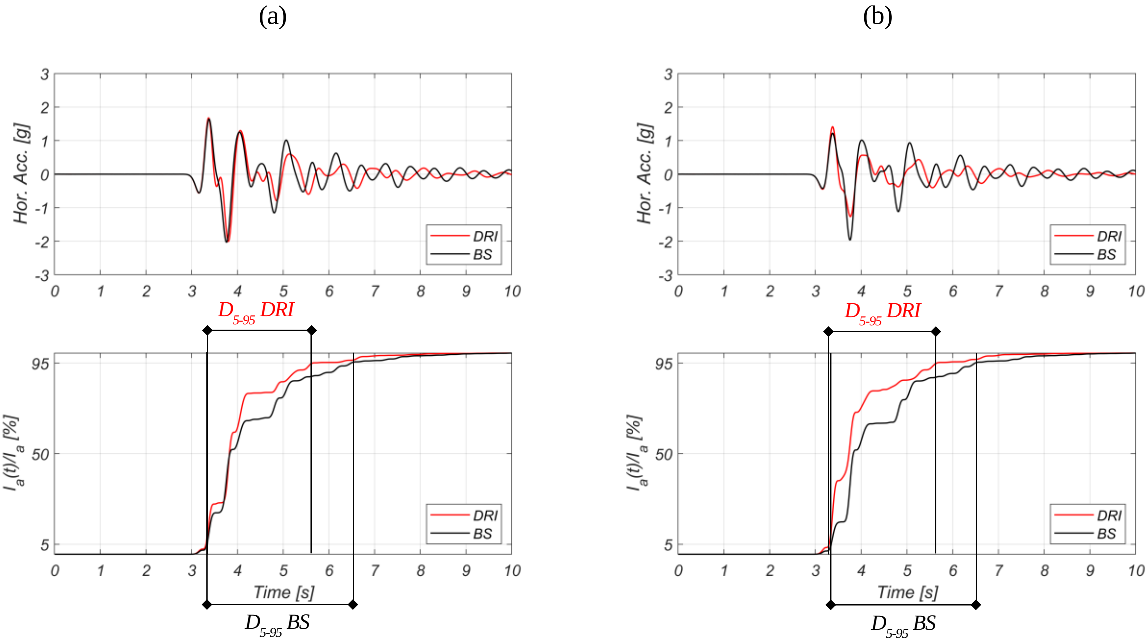

Fig. 5. Potrerillos dam: acceleration at the crest, Husid plot and significant duration computed applying only the horizontal acceleration component (a) and horizontal plus vertical acceleration components (b) of the input motion.

No significant differences can be observed in the response of El Carrizal dam (Fig. 4a-b) highlighting that in this case the hydrodynamic effect can be considered as negligible, even when the vertical component of the acceleration input motion is taken into account.

This is not the case of Potrerillos dam (Fig. 5a-b): for this dam, a significant influence of the hydrodynamic effect can be observed not only in the shape of the acceleration time history at the crest in the free vibration decay, but also in the considerable differences in the Husid plot computed by DRI and BS approaches. It follows a consequent reduction of the significant duration when the interaction between the reservoir and the embankment is considered.

Whatever the approach adopted (DRI or BS), the vertical component of the input motion tends to reduce the horizontal acceleration at the crest of both dams. In the case of Potrerillos dam, where the influence of the reservoir is noteworthy, the vertical component of the input enhances the interaction effect between dam and reservoir, as shown by Fig 5b.

4. Discussion

The seismic response of El Carrizal dam, computed assuming a simple elastic model, seems not to be affected by the presence of the reservoir, as shown in Fig. 4. Nonetheless, the response of Potrerillos dam, evaluated adopting the DRI approach, shows that even when the maximum acceleration at the crest does not change substantially with respect to that computed by the BS approach, significant differences can be observed in the acceleration time history at the crest, which affect the Husid plot consequently inducing an evident reduction in the significant duration.

This different response can be explained considering that the tallest and sloped dam (Poterillos dam) is more flexible and that its complex interaction with the reservoir, characterized by significantly different dynamic properties, results in a destructive interference, that induces a faster decrease in the acceleration in the free-vibration phase with respect to that computed by BS approach.

Furthermore, the vertical component of input motions introduces a new source of interference, highlighted by the reduction of the maximum horizontal acceleration at the crest with respect to that computed considering only the horizontal component, thus enhancing the effect of the hydrodynamic interaction. This can be explained by considering that, even when only the horizontal component of the input motion is considered, the path of pressure waves in the reservoir is mainly horizontal and the water mass motion has a significant vertical component, due to its lack of shear stiffness and its almost incompressible behavior. The introduction of a vertical acceleration component in the input motion leads to enhance the significance of this phenomenon, thus increasing the DRI effects.

5. Conclusion and Future Works

The above results represent just a preliminary inquiry on the likely influence of the Dam-Reservoir Interaction on the seismic behavior of two different kinds of embankment dams, which will be the subject of future research. By means of simplified input signals and linear elastic approach, it could be inferred that the influence of the DRI on the response at the dam crest is expected as being negligible in the case of the zoned earth dam, but this conclusion cannot be extended to the CFRD dam, where the DRI approach shows evident differences with respect to the BS one.

Future developments are needed by introducing nonlinear soil properties for both dam and foundation materials and using actual seismic records with variable energy content as input motions. In fact, a more thorough evaluation of the DRI effects should require the assessment of dam response in terms of performance-based approaches.

6. References

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