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Nonlinear seismic response of earth dams due to dam-reservoir interaction

Réponse sismique non linéaire des barrages en terre due à l'interaction barrage-réservoir

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ABSTRACT: Field data show that the seismic response of a dam with a full reservoir is different from a dam with an empty reservoir. This is due to“dam-reservoir interaction” (DRI), which is related to the asynchronous vibration of the dam and reservoir domains. It was for long considered that DRI effects are important for concrete dams and insignificant for earth dams. This was based on findings considering mainly dam crest accelerations, which for earth dams were indeed found to be insensitive to DRI. However, other aspects of the response of earth dams, such as the deformation characteristics, should also be considered to fully characterise the seismic dam response. Therefore for a more complete study of the DRI effects on the seismic response of earth dams one should also consider the induced seismic shear stresses and strains, along with the magnitude of reservoir hydrodynamic pressures. This study considers a well-documented case study, the La Villita earth dam in Mexico, for which relevant field measurements are available allowing the development of a well-calibrated numerical model. A series of static and dynamic nonlinear finite element analyses are performed which consider the impact of the reservoir domain on the dam response. It is shown that although earth dam crest accelerations are indeed insensitive to DRI, the actual dynamic soil behaviour can be severely affected, developing large values of seismic shear stresses and strains within the dam body. This study highlights the importance of accurately considering DRI when assessing the seismic performance of earth dams.

RÉSUMÉ: L'interaction barrage-réservoir n'est pas considérée comme importante pour les barrages en terre. Cependant, cela est dû aux recherches se concentrant sur les accélérations à la crête du barrage. Cette étude examine plus en profondeur le problème lié au stress et à la déformation du sol dus aux séismes.

Keywords: earth dam; earthquake, dynamic analysis, finite elements, dam-reservoir interaction

1 INTRODUCTION

The seismic response of dams with a full reservoir is known to be different to that of dams with an empty reservoir. This is due to dynamic dam-reservoir interaction (DRI), in which the dynamic response of the dam affects the response of the reservoir and vice versa.

DRI and hydrodynamic pressures are usually considered by discretising the reservoir domain in different ways, including boundary elements (Antes & Von-Estorff, 1987), solid finite elements (Zienkiewicz et al., 1986; Dakoulas & Gazetas, 2008; Pelecanos et al., 2013) or fluid elements (Kucukarslan et al., 2005). Relevant reservoir boundary conditions exist

(Sommerfeld, 1949; Sharan, 1985; Higdon, 1991) which may truncate the infinite reservoir domain efficiently.

Although DRI may have a significant effect on the seismic response of concrete dams (Chopra, 1968), it has been for long considered as insignificant for earth dams (Hall & Chopra, 1982a; Pelecanos et al., 2016). Hall & Chopra (1982b) showed that crest accelerations of elastic earth dams are practically insensitive to DRI and therefore the reservoir does not need to be modelled. Subsequently, it has been assumed that DRI effects are not important for earth dams.

However, most of the previous studies of DRI considered mainly crest accelerations of elastic earth dams and therefore did not examine in detail the developed stresses and strains within the dam body. This paper examines the DRI effects in an earth dam and considers nonlinear material behaviour. Nonlinear dynamic time-history finite element (FE) analyses are performed with and without the reservoir domain. Both dam accelerations and internal stress-strain response are considered and therefore this work provides a more in-depth investigation of DRI for earth dams.

2 LA VILLITA EARTH DAM

La Villita is a 60m high zoned earth dam in Mexico with a crest about 420m long, founded on a 70m thick alluvium layer.

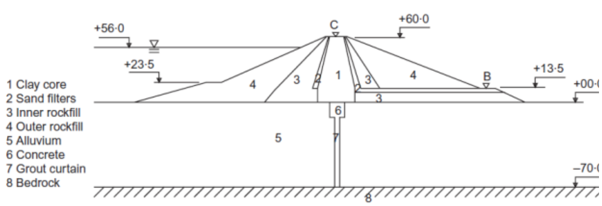


Figure 1. Geometry of La Villita dam

The dam cross-section (Figure 1) is composed of a central clay core of very low permeability, with sand filters and rockfill shells. Alluvial deposits beneath the clay core were grouted below the dam, while there is also a concrete cut-off wall to control seepage through the alluvium below the dam.

A summary of known material properties is given in Table 1. According to Elgamal (1992), the maximum shear stiffness, G_{max}, for all the materials in the dam embankment varies and is about 140-260 MPa from top to bottom, whereas the foundation alluvium layer has a constant value of around 200 MPa.

Table 1. Summary of known material properties.

Material	**Mass density ρ [kg/m^3]**	**Poisson ratio, ν []**	**Cohesion, c [kPa]**	**Shearing angle, φ [°]**	**Dilation angle, ψ [°]**
Clay core	2000	0.49	5	25	0
Sand filters	2180	0.33	0	35	0
Inner Rockfill	2080	0.33	5	45	0
Outer rockfill	2080	0.33	5	45	0
Alluvium	2080	0.33	5	25	17.5

The dam was built in 1967 and operated safely until a major seismic event in 1975. It experienced six major seismic events during the period between 1975 and 1985 (Table 2), which resulted in some minor permanent deformations. The earthquake motions were recorded by three accelerometers installed on the dam, at the crest (shown as C in Figure 1), the berm in the downstream side of the dam (shown as B in Figure 1) and at the right rock bank.

According to Elgamal (1992) only EQ2 and EQ5 are useful for numerical analysis. Also, the acceleration records from the rock abutment can be used as the input “bedrock” accelerations in a numerical analysis (see Pelecanos et al., 2015) for more details about the instrumentation). The seismic response of the dam was investigated by previous researchers, who were mainly interested in dynamic dam behaviour (Elgamal, 1992; Pelecanos, 2013; Pelecanos et al., 2015; 2018), permanent displacements (Elgamal et al., 1990; Succarieh et al., 1993; Gazetas & Uddin, 1994; Uddin, 1997) and dam-canyon interaction (Papalou & Bielak, 2001; 2004).

Table 2. Significant earthquake events for La Villita dam.

No	Date	Ms	Epic. Dist. [km]	Max. Rock accel. [g]	Max. Crest accel. [g]
EQ1	11/10/1975	4.5	52	0.07	0.36
EQ2	15/11/1975	5.9	10	0.04	0.21
EQ3	14/3/1979	7.6	121	0.02	0.40
EQ4	25/10/1981	7.3	31	0.09	0.43
EQ5	19/9/1985	8.1	58	0.12	0.76
EQ6	21/9/1985	7.5	61	0.04	0.21

3 FINITE ELEMENT MODEL

To study the seismic response of earth dams, dynamic FE analysis is usually employed, whereas the simpler pseudo-static FE analysis can be used only for the assessement of dam slope stability (Kontoe et al., 2013). Therefore, two-dimensional (2D) plane-strain static and dynamic-in-the-time-domain coupled-consolidation FE analyses, employing the Imperial College Finite Element Program (ICFEP) (Potts & Zdravkovic, 1999; 2001; Kontoe et al., 2008), were performed. The FE mesh is shown in Figure 2. The full stress history of the dam prior to the earthquake events (including layered embankment construction, reservoir impoundment and consolidation) is modelled to establish a realistic starting point for the subsequent time-domain dynamic analyses. More details about the static analysis of La Villita dam and its verification can be found by Pelecanos et al. (2015).

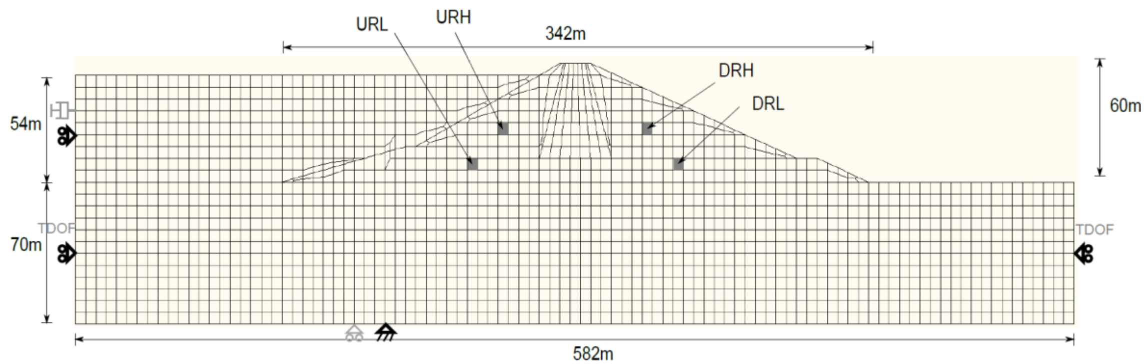


Figure 2. FE mesh of dam and reservoir

The constitutive model employed is a cyclic nonlinear elastic (CNL) model (Taborda et al 2010), which uses a logarithmic function to describe the backbone curve of soil's monotonic response (Puzrin & Burland, 2000), coupled with a Mohr-Coulomb yield criterion. The logarithmic relation dictates the degradation of shear stiffness, G, and the increase of damping, ξ, with cyclic shear strain, γ and it is able to reproduce hysteretic cyclic soil behavior. Due to the lack of experimental data, the CNL model is calibrated on empirical relations. The curves of Vucetic & Dobry (1991), Seed et al. (1986) and Rollins et al. (1998) were used for the clay core, sand filters and rockfill-alluvium materials respectively.

The analyses presented in this paper are based on the records from EQ2 and EQ5 (Table 2) which, according to Elgamal (1992) are the most complete records and therefore reliable for use in a FE analysis.

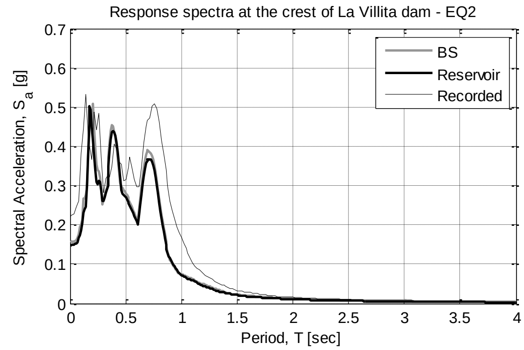
In order to examine the effects of DRI, two approaches are followed to simulate the seismic reservoir hydrodynamic pressures. In the first approach, the hydrodynamic pressures are ignored and therefore a constant hydrostatic variation of the water pressure is applied along the upstream slope of the dam as a boundary stress (BS).

In the second approach, the reservoir domain is discretised with linear elastic (bulk and shear moduli are $K_w = 2.2\ 10^6$ kPa and $G_w = 100$ kPa respectively) displacement-based finite elements (Pelecanos et al., 2013). In addition, interface elements (shear and normal stiffnesses are $K_S = 1\ kN/m^3$ and $K_N = 10^8\ kN/m^3$ respectively) are placed along the interface between the reservoir and the dam and between the reservoir and the foundation alluvium. The truncated boundary is modelled with the Standard Viscous BC (Lysmer & Kuhlemeyer, 1969), i.e. a series of dashpots placed normal to the boundary. More details about the performance of this BC in DRI problems may be found in Pelecanos et al., (2013).

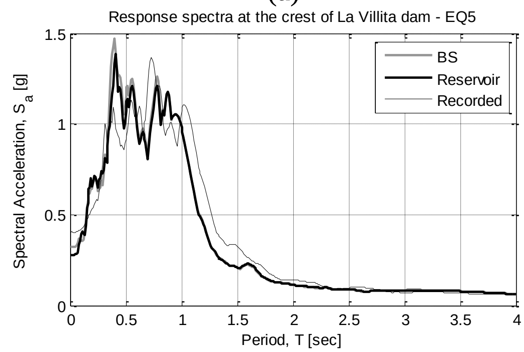
More details about the numerical model, its parameters, calibration, verification against the recorded data may be found by Pelecanos et al. (2015) and therefore are not repeated here for brevity.

4 COMPUTATIONAL RESULTS

Figure 3 shows the response spectra at the crest of the dam for both EQ2 and EQ5. The figure includes the response spectra of the recorded accelerations during the seismic events and those for the two modelled cases. “BS” refers to the case of Boundary Stresses (i.e. ignoring the hydrodynamic pressures, and applying only a hydrostatic boundary stress), whereas “Reservoir” refers to the case of discretising and modelling the reservoir domain (and thus considering hydrodynamic pressures) according to Pelecanos et al. (2013). It is shown that for both earthquakes, the difference between the “BS” and “Reservoir” cases is minor and therefore it is accepted that DRI does not have a major contribution on the crest accelerations of earth dams. This figure also shows that there is a very good agreement between the recorded and predicted (from the FE analysis) seismic response of the dam and thus it confirms the validity of the adopted numerical model and computational procedure.



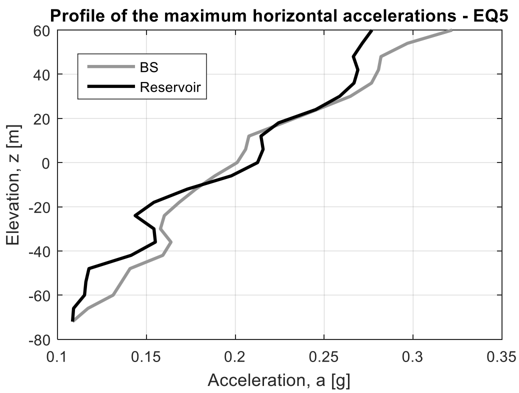
(a)



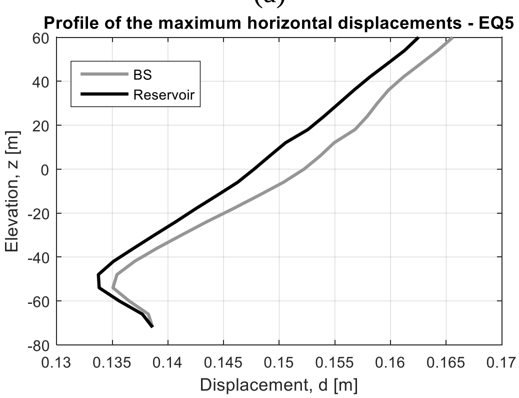
(b)

Figure 3. Response spectra at the crest of the dam during (a) EQ2 and (b) EQ5.

Moreover, Figure 4 shows the vertical profiles of maximum horizontal accelerations and displacements within the clay core of the dam during EQ5, for both cases considered. It is shown that there are some minor differences between the two cases, “BS” and “Reservoir”. In particular, it is shown that the case of “Reservoir” appears to yield slightly smaller values of both horizontal acceleration and displacement. This is believed to be due to the presence of the reservoir, which in the absence of any resonance (where dynamic amplification would be expected), it may “damp” the dynamic response of the dam, because the two domains, dam and reservoir, may be vibrating out of phase. However, in general, the response is very similar for the two modelling cases, “BS” and “Reservoir”, since the differences are generally less than 10%. Therefore it is recognised that both accelerations and displacements appear to be insensitive to DRI for the examined earth dam.



(a)

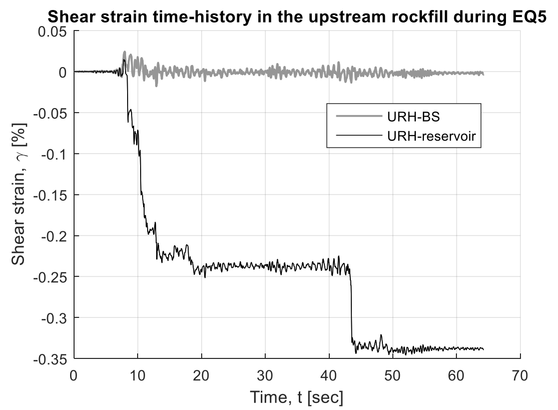


(b)

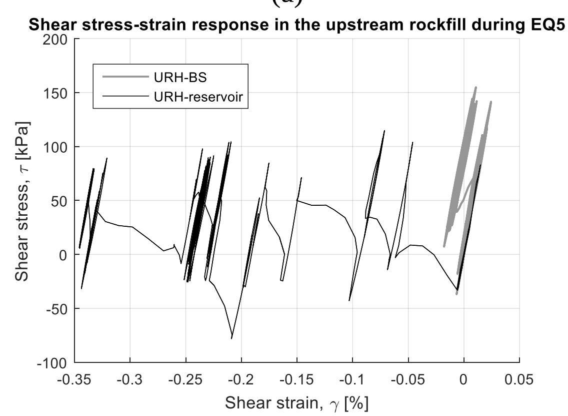
Figure 4. Profiles of maximum values of (a) acceleration and (b) displacement within the core during EQ5.

Finally, Figure 5 concentrates on the dynamic soil behaviour within the dam, in the upstream rockfill. In particular, it shows the time histories of shear strains and the loops of shear stress-strain response in the upstream rockfill (element URH in Figure 2). In contrast to the previous observations, it may be observed here that there are significant differences between the two modelling cases of “BS” and “Reservoir”.

More specifically, it is shown that for the latter case of “Reservoir” modelling (i.e. when DRI is considered, through the discretisation of the reservoir domain) substantial values of soil shear strain may develop within the dam body. This is shown in both plots, of shear strain time-history and stress-strain loops. It is believed that vibrations of the reservoir induced considerable values of hydrodynamic pressures on the upstream face of the dam and therefore the rockfill experiences large stresses and strains, which can be very large compared to those without the upstream reservoir domain.



(a)



(b)

Figure 5. Strain and stress response in the upstream rockfill (a) strain time-history and (b) stress-strain loops.

It is therefore shown that although the overall dam accelerations and displacements are indeed insensitive to DRI, the internal soil stresses and strains may not be and, instead, significant values of strains may develop which could threaten the structural integrity of the dam. Consequently, this suggests that DRI should not be ignored in earth dams, but instead considered appropriately by modelling the reservoir domain and considering the induced hydrodynamic pressures. More details about other significant effects of DRI on the nonlinear response of earth dams, in terms of hydrodynamic pressures and hysteretic response may be found in Pelecanos et al. (2018).

5 CONCLUSIONS

This paper presents a numerical study on the seismic response of dams considering dam-reservoir interaction (DRI). The La Villita earth dam in Mexico is analysed under two scenarios: (a) considering only the hydrostatic water pressures (neglecting hydrodynamic effects) and (b) considering DRI by modelling the reservoir hydrodynamic pressures and thus discretising the upstream reservoir domain.

The study shows that the dam crest accelerations and displacements are insensitive to DRI, which is in agreement with earlier observations from the literature for earth dams. However, major differences exist when one examines the stresses and strains developed within the dam body, especially in the upstream rockfill.

It is therefore recommended that DRI is not ignored for earth dams. Instead it is suggested that the reservoir domain is modelled appropriately to allow rigorous prediction of the hydrodynamic pressures. Ignoring the contribution of the reservoir domain may result in unsafe underprediction of strains within an earth dam.

6 ACKNOWLEDGEMENTS

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