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Seismic response of earth dams in narrow canyons

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ABSTRACT: It is nowadays well appreciated that dams built in narrow canyons exhibit a stiffer response than those in wide canyons, due to the confined geometry of the canyon banks. The numerical modelling of dams in wide canyons is usually considered as computationally less expensive than those in narrow canyons. This is because the former can be idealised by a two-dimensional plane-strain model, while the latter requires a full three-dimensional analysis to appropriately consider the stiffening effect of the narrow canyon geometry. This paper presents a computationally-efficient way to consider the stiffening effect of a narrow canyon in a two-dimensional analysis by using an appropriately increased material stiffness.

1 INTRODUCTION

The seismic safety of earth dams has for long been a fundamental problem of earthquake engineering. The early studies on the seismic response of earth dams adopted the pseudo-static method of analysis (Terzaghi, 1950; Sarma, 1979) in which the seismic load is considered as an equivalent static force. This approach provided an insight into the threshold seismic load that may cause instability of the dam slope. An attempt to estimate the permanent seismically induced dam slope displacements followed by using the sliding block analysis method (Newmark, 1965; Ambraseys & Sarma, 1967), which involved integration of seismic accelerations exceeding the critical acceleration of dam slope instability.

Consideration of the actual transient dynamic response of earth dam structures was later achieved by using the two-dimensional (2D) shear beam method (Ambraseys, 1960, Gazetas, 1981; Dakoulas & Gazetas, 1985) in which the dam is assumed to respond primarily in horizontal shear mode. Subsequent advanced dynamic finite element analyses considered the true three-dimensional (3D) dynamic and nonlinear response of earth dams (Griffiths & Prevost, 1988). Because of the limited available seismic field measurements, most of the seismic analyses of earth dams were not compared to real earthquake records to check their reliability.

Moreover, it was observed that dams in narrow canyons exhibit a stiffer response than dams built in wide canyons and this was based on both theoretical (Ambraseys, 1960) and experimental studies (Gazetas, 1987). Therefore, it was suggested that dams built in narrow canyons are analysed considering their full 3D geometry, as a 2D plane-strain approximation may not be appropriate.

This paper presents a numerical study on the effects of a narrow canyon on the seismic response of earth dams. A well-documented case study is considered and 2D nonlinear dynamic finite element analyses are performed. It is shown that a 2D plane-strain analysis results in a softer dam response than the one inferred from the field measurements, thus suggesting that dams in narrow canyons exhibit a stiffer response than dams in wide canyons.

Also, it is shown that this stiffening effect can be considered in a computationally-efficient way by increasing the material stiffness.

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. 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. La Villita dam is built in a narrow canyon (length over height ratio: L/H=3.2) and therefore narrow canyon stiffening effects are expected to be significant.

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

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) and the berm in the downstream side of the dam (shown as B in Figure 1) and the right rock bank.

According to Elgamal (1992) only EQ2 and EQ5 are useful for numerical analysis, as the remaining records were incomplete. 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).

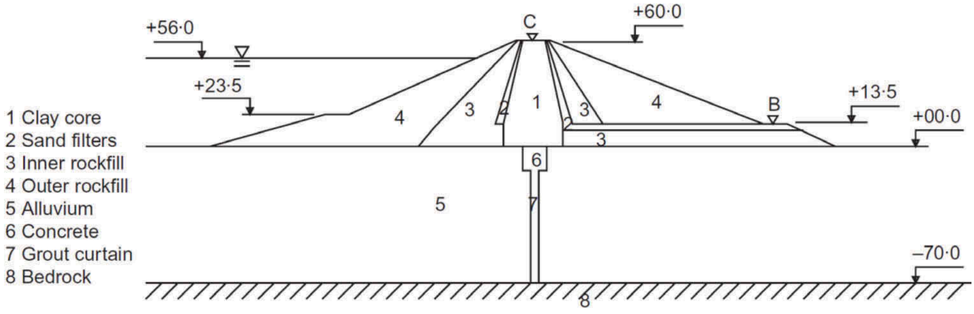


Figure 1. Geometry of La Villita dam

Table 1. Summary of known material properties.

No	Material	Mass density $\rho[kg/m^3]$	Poisson ratio $\nu[]$	Cohesion $c\ [kPa]$	Angle of shearing $\varphi'[deg]$	Angle of dilation $\psi[deg]$
1	Clay core	2000	0.49	5	25	0
2	Sand filters	2180	0.33	0	35	0
3	Inner rockfill	2080	0.33	5	45	0
4	Outer rockfill	2080	0.33	5	45	0
5	Alluvium	2080	0.33	5	35	17.5

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	19/11/1985	8.1	58	0.12	0.76
EQ6	21/11/1985	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 assessment of dam slope stability (Kontoe et al., 2013). Therefore, 2D plane-strain static and dynamic-in-the-time-domain coupled-consolidation FE analyses, employing the Imperial College Finite Element Program (ICFEP) (Potts & Zdravković, 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).

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 to capture plasticity. 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 EQ5 (Table 2) which is the most complete record and therefore reliable for use in a FE analysis. Finally, as the effects of dam-reservoir interaction were found to be insignificant for earth dams (Hall & Chopra, 1982; Pelecanos et al., 2013; 2016) the upstream reservoir is not modelled. More details about the numerical model, its parameters, calibration, verification against the recorded data may be found in Pelecanos et al. (2015) and therefore are not repeated here for brevity.

The seismic response of the dam during EQ5 is analysed in 2D plane-strain twice: (a) using the material stiffness (shear modulus, G) provided by Elgamal (1992) who carried out 3D

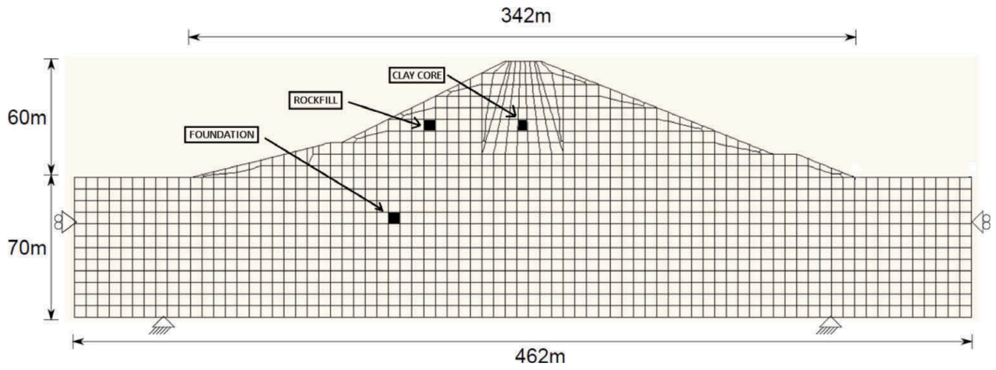


Figure 2. FE mesh of La Villita dam

Table 3. Material stiffness considered in the FE model of La Villita dam.

	Dam	Foundation Alluvium
Case	G [MPa]	G [MPa]
(a) Original	140~260	200
(b) Canyon stiffening	490~910	700

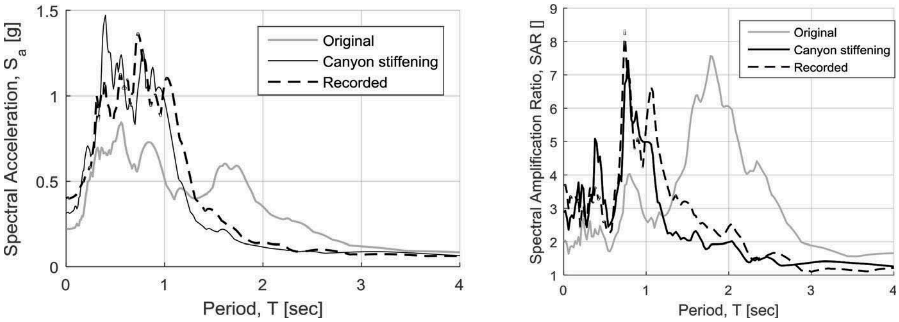


Figure 3. Response spectra (ξ=5%) at the crest of the dam.

seismic analysis of the dam and obtained a very good agreement with the recorded dam crest accelerations, and (b) using an updated (increased) material stiffness (G) to account for the stiffening of the 3D narrow canyon geometry. The adopted values of G for both cases are listed in Table 3 and it may be observed that the latter case considers a G which is 3.5 times larger than the one from Elgamal (1992) and case (a). The updated material stiffness is applied uniformly to the entire FE model, including the dam embankment (clay core and rockfill shells) and the foundation.

Figure 3 shows the response spectra at the crest of the dam during EQ5 and the corresponding spectral amplification ratio, SAR, which is the spectral acceleration values of the response at the crest divided by those of the input motion. This figure includes the predicted spectra following the two analysis cases described earlier (Table 3) and the spectra of the recorded motions. It is shown that the second case (b: Canyon stiffening) with an increased G matches more closely the spectrum of the recorded motion and therefore appears to be more representative of the true dynamic response of the dam. Moreover, it is shown that case (a) with the original values of G results in larger spectral acceleration values for larger periods. This suggests that the modelled dam system in case (a) exhibits a softer response than the observed dam response and additionally, it indicates stronger nonlinearity in the response.

This is attributed to the fact that in case (a) the dam was analysed in 2D plane-strain conditions and therefore ignored the stiffening effect of the narrow canyon. Case b (canyon stiffening), although is still based on a 2D plane-strain analysis, it considered an updated value of G which was 3.5 times larger than the one reported by Elgamal (1992), indirectly accounting for the geometric stiffness of the 3D narrow canyon geometry.

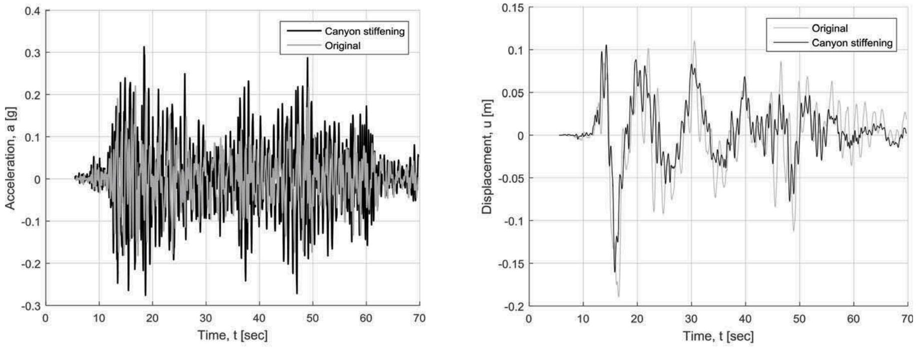
According to Dakoulas & Gazetas (1987) the ratio of fundamental period of vibration of a dam built in a narrow canyon, T_n, over that of a dam built in a wide canyon, T_w, for L/H=3.2 should be: $T_n/T_w = 0.6 \sim 0.75$. In case (b), the updated shear modulus is taken as G*=3.5G, which suggests that the updated value of the fundamental period of vibration, T^* should be $T^* = 0.54T$ (using Equation 1 for the fundamental period of vibration of the dam, according to Ambraseys (1960)), which is close to the suggestions of Dakoulas & Gazetas (1987). This observation confirms that the calculated stiffening of the narrow canyon is in agreement with earlier analytical work from the literature.

$$T = 2.613\, H / V_s \tag{1}$$

Moreover, Figure 4 shows the time-histories of horizontal acceleration and displacement at the crest of the dam during EQ5 for the two modelling cases considered. It is shown that the predicted accelerations in the latter case of canyon stiffening are consistently and considerably larger than those from the original case that ignored the stiffening of the narrow canyon. However, it is shown that, in contrast, the predicted displacements are comparable and that the original case predicts a slightly larger value of the maximum absolute value of displacement.

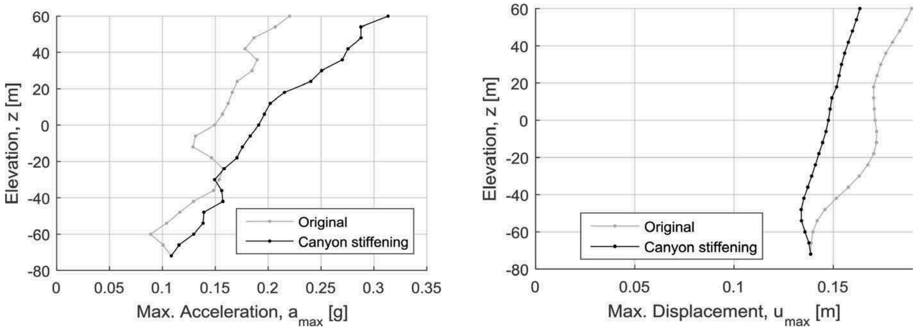
The latter observation is confirmed in Figure 5, where the profiles of the maximum horizontal accelerations and displacements are plotted with the elevation. These are the envelopes of the maximum values along the height of the dam and not a single time snapshot. Again, it is observed that larger values of acceleration and smaller displacements are predicted for the case that considers that stiffening effect of the narrow canyon. This was perhaps expected in this case, as a stiffer dam-foundation system may result in smaller overall displacements. It should also be acknowledged however, that a dam in a narrow canyon could potentially experience larger displacements as a result of topographic amplification which is not explicitly considered herein.

Finally, Figures 6 and 7 show the shear stress-strain loops and shear strain time-histories at selected points within the dam and its foundation, respectively. More specifically, these figures



(a) (b)

Figure 4. Predicted dam crest response: (a) accelerations, and (b) displacements.



(b) (b)

Figure 5. Profiles of (a) maximum acceleration and (b) maximum displacement.

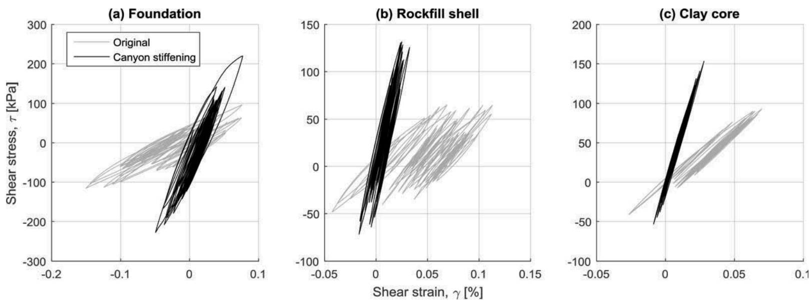


Figure 6. Shear stress-strain loops during the earthquake.

consider three points: in the foundation alluvium, in the upstream rockfill and the dam clay core (elements shown in Figure 2). Figure 6 shows that modelling case (b), which considers the stiffening effect of the narrow canyon, results in larger values of shear stress, but smaller strain compared to case (a) which ignores the canyon stiffening effect. Also, it is observed that the slope of the stress-strain loops is steeper in case (b) due to the higher initial value of G. Figure 7 shows that ignoring the canyon stiffening effect (case (a)) may result in accumulation of larger permanent shear strains with time and overall larger amplitude of these strains.

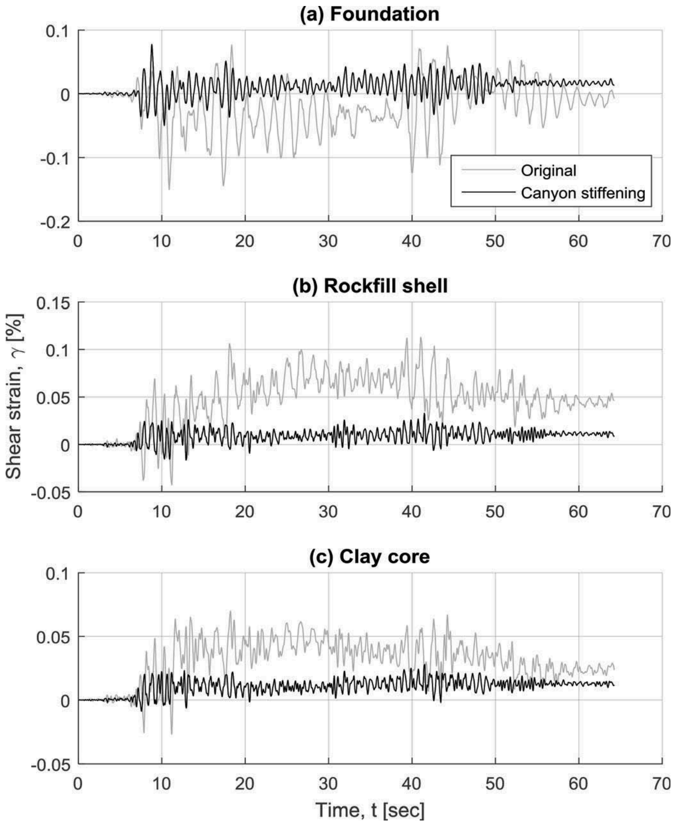


Figure 7. Shear strain time-histories during the earthquake

4 CONCLUSIONS

This paper presents a numerical study related to the seismic response of earth dams. A well-documented case study is considered for which available monitoring data is available and two-dimensional nonlinear static and dynamic finite element analyses are performed. The aim is to examine the effect of the narrow canyon geometry on the dynamic seismic response of earth dams. Two cases are considered: the former ignores the stiffening of narrow canyon geometry and the latter considers this stiffening by using an appropriately increased material stiffness.

The comparison of the response predicted by 2D plane strain analyses with field measurements at the crest of the dam varying the material stiffness implies that dams built in narrow canyons exhibit a stiffer response than dams built in wide canyons. The three-dimensional stiffening effect of a narrow canyon can be considered in a computationally-efficient two-dimensional plane-strain analysis by adopting an appropriately enhanced material stiffness, adopting an increased value of shear modulus, G.

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