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Numerical simulation of seismic response of earth dams

Analyse numérique de la réponse sismique des barrages en terre

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ABSTRACT: The paper aims at evaluating the capabilities and limitations of some numerical tools for estimating the seismic response of earth dams. In particular, the recorded acceleration time histories and permanent displacements are compared against those predicted by using a 2D FEM code (Quake/W). Acceleration time histories and displacements were recorded during centrifuge tests of reduced scale model of an earth-core rockfill dam (ECRD). Such tests were carried out by researchers at KAIST (Korea Advanced Institute of Science & Technology) and results were recently published. This paper summarizes the essential aspects of these experiments for the sake of clarity.

RÉSUMÉ: L'article est finalisé à étudier potentialités et limites des méthodes numériques pour évaluer la réponse sismique des barrages en terre. En particulier, mesures expérimentales des histories temporelles en accélération et désplacements sont compares avec celles indiquées selon la méthode FEM. Les histories temporelle en accélération et désplacements out été registrées pendant les tests en centrifuges utilisant modéles de digues en terre. Ces textes out été développés par les chercheurs des KAIST (Coree) et le résultats ont été déja publiés. L'article présente seulement les aspects essentielle de cette essais.

Keywords: Seismic response; earth dams; centrifuge tests; 2D FEM analysis

1 INTRODUCTION

Most of Italian earth dams are located in seismic areas of moderate to high seismicity. Moreover, they were built tens of years ago according to technical codes and regulations which actually appear partially if not completely outdated.

Therefore, their global as well as local stability should be assessed according to recent EU codes (EC7-1 2005, EC8-1 2005) or national codes and recommendations (NTC 2008) to guarantee the safety of urban areas in the downstream site adjacent to reservoirs.

Several studies were recently carried out to define more reliable methodologies for the assessment of the ultimate and serviceability limit states of existing earth dams (Albano et al. 2012, Banti 2018, Elia et al. 2011, Pelecanos et al. 2016, Seco e Pinto and Simao 2010, Sica and Pagano 2009).

The scope of the paper is to use as benchmark the recorded acceleration and displacement time histories of a centrifuge test to assess the capabilities and limitations of 2D FEM analysis (Quake/W, Krahn 2004).

The centrifuge test was carried out on a reduced scale model of an ECRD at KAIST University (Park et al. 2016).

The main goal was to identify the most relevant influential factors and discuss the most relevant features of commonly used constitutive models.

2 CENTRIFUGE TEST

In the technical literature there are few centrifuge model tests concerning the behaviour of dams under seismic conditions (Ng et al. 2004, Sharp and Adalier 2006, Peiris et al. 2008). On the other hand there is a lack of usable data regarding the seismic behaviour of real dams.

In the present study, one centrifuge test (Park et al. 2016) was used as benchmark.

The test was carried out by means of the facilities of the Korea Construction Engineering Development (KOCED) at the Geotechnical Centrifuge Testing Center of KAIST. Table 1 summarizes the scaling factors (model vs. prototype) that were considered.

Table 1. Scaling Factors for different variables in Centrifuge Modelling (Bilotta and Taylor 2005)

Variable	**Scaling Factor (Model vs. Prototype)**
Length	N^{-1}
Acceleration	N
Density	1
Stresses	1
Strains	1
Deformations	1
Displacements	N^{-1}
Permeability	1
Hydraulic gradient	N
Loading frequency	N
Time (inertial effects)	N^{-1}
Time (seepage, consolidation, spread)	N^{-2}

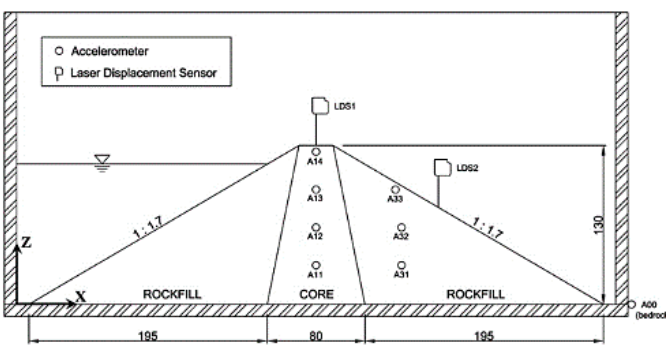

Figure 1. Layout of model ECRD dam and its instrumentation (Kim et al. 2011)

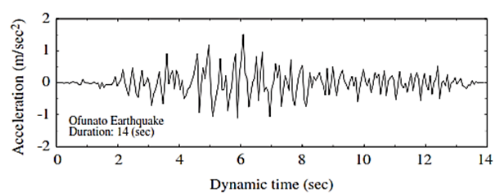

Figure 2. Ofunato Earthquake (Kim et al. 2011)

Figure 1 shows the characteristic cross section of the ECRD model and of the instrumentation. A scaling ratio (N) of 40 (referring to the centrifuge acceleration of 40g) was selected. The ECRD model was 130 mm high, simulating 5.2 m high in prototype scale. As in Korea, ECRDs are mostly constructed on top of bedrock, the dam model was realized directly on the base-plate of a soil container. Anyway, this condition in not that typical of dams constructued in alluvial valleys. In order to simulate the friction between the bedrock and the dam body, sand paper was glued onto the base-plate and the model dams were constructed on it. The side walls of the container were covered with grease to minimize side friction, in order to guarantee plane strain condition. The dam model was constructed in four layers. Each layer was compacted to 95% of the optimum density by using a hand compactor with an approximate compaction energy of 750 kNm/m. A thin membrane was placed on the upstream slopes of the ECRD. The membrane was also glued onto the bottom and sides of rigid container to prevent water from penetrating into the dam body and allowing water to be contained in the upsteam side. Therefore, the filled water imposed a water load on the upstream slope during the earthquake simulation. The upstream reservoir was filled up to 90% of the dam height. Accelerometers were embedded in the model embankment as arrays at the center and downstream of the dam to investigate the amplification of the earthquake acceleration. Laser sensors and a high-speed camera were also mounted to measure the vertical settlement and horizontal displacement, respectively. A series of staged tests were performed on the dam models with real earthquake (Ofunato Earthquake, Figure 2) whose horizontal acceleration was scaled from about 0.065 to 0.35g (Table 2).

Table 2. Bedrock accelerations used in the centrifuge tests. Starred bold writings are the selected accelerations used in the numerical analysis (Kim et al. 2011)

Test numbers	ECRD Bedrock acceleration (g)
001(*)	**0.065**
002	0.082
003	0.087
004	0.098
005(*)	**0.116**
006	0.145
007(*)	**0.221**
008(*)	**0.348**

As for the materials, the following equations represent the shear wave velocity profile for rockfill and core, respectively:

$$V_s = 109.0 \cdot \sigma_c^{0.24} \quad (1)$$

$$V_s = 41.8 \cdot \sigma_c^{0.39} \quad (2)$$

The velocity is in m/s while the confining pressure (σ_c) is in kPa.
The strength parameters and soil unit weight are reported in Table 3. Table 4 reports the characterization of bedrock.

The grain size distribution curves of prototype and model are shown in Figure 3.

3 CENTRIFUGE TEST RESULTS

Results were expressed in terms of horizontal acceleration time histories and frequency contents, measured along the center line of the core and in the downstream shell. During the staged tests, settlements were continuously measured by laser displacement sensors. The residual settlement amounts were obtained after each test. The cumulative settlements at the crest are shown in Figure 4.

Table 3. Parameters of the model materials (Kim et al. 2011)

Parameters	ECRD rockfill	ECRD core
γ_d [g/cm^3] (dry density)	2.02	1.92
w [%] (water content)	4.0	9.0
γ_t [g/cm^3] (total density)	2.10	2.10
c [kPa] (cohesion)	2.0	64.0
φ [deg] (angle of friction)	40.0	33.0

Table 4. Foundation parameters used in the numerical analysis of the dam

Foundation Parameters	Value
γ [kN/m^3] (unit weight)	27
c [kPa] (cohesion)	0.0
φ [deg] (angle of friction)	45.0
V_s [m/s] (shear wave velocity)	3103.7
υ [-] (poisson's ratio)	0.2
D_{max} [%] (max damping)	1.0

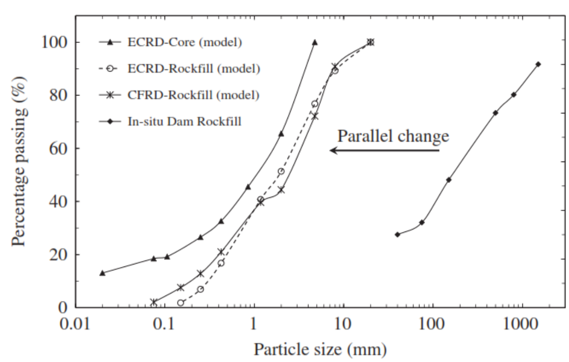

Figure 3. Particle size distribution curves for the prototype and model materials (Kim et al. 2011)

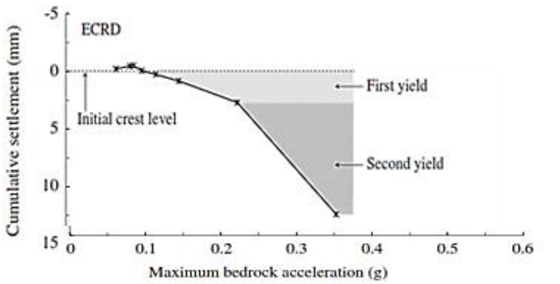

Figure 4. Cumulative settlements with increasing maximum bedrock accelerations (Kim et al. 2011)

The test output is summarized in Table 5 and Figures 5 and 6.

Table 5. Summary of the centrifuge test (40g) results in the prototype scale (Kim et al. 2011)

Test	**ECRD**		
	Bedrock acceleration (g)	**Amplification ratio**	**Crest Settlement (mm)**
001(*)	**0.065**	**2.0**	**-0.22**
002	0.082	2.16	-0.25
003	0.087	1.77	-0.02
004	0.098	2.0	0.42
005(*)	**0.116**	**1.29**	**0.33**
006	0.145	1.57	0.56
007(*)	**0.221**	**1.75**	**1.88**
008(*)	**0.348**	**1.84**	**9.72**

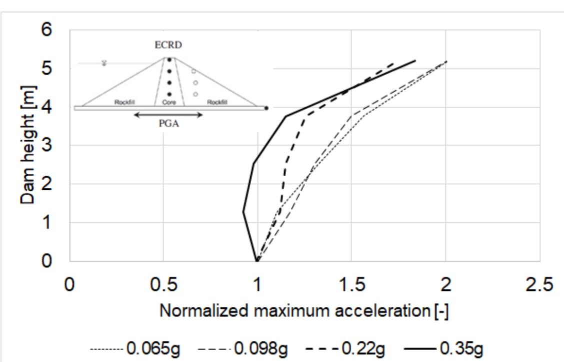

Figure 5. Normalized acceleration distributions at the center for the centrifuge tests (prototype scale) (adapted from Kim et al. 2011)

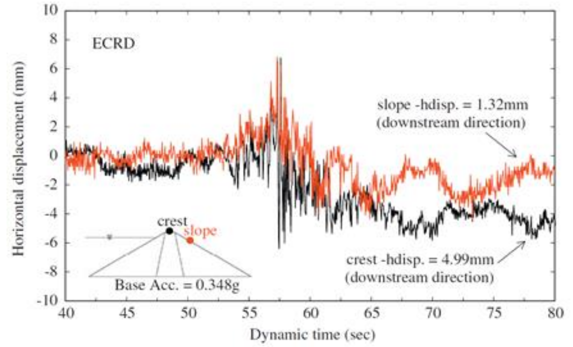

Figure 6. Horizontal displacements by image-processing technique for PGA=0.35g (Kim et al. 2011)

4 NUMERICAL ANALYSES

The Quake/W FEM software (Krahn 2004) was used to numerically simulate the centrifuge test results. The software enables one to perform 2D dynamic finite element analysis by considering both linear equivalent (LE) and true nonlinear (NL) constitutive models. Nonlinear analysis was carried out in the time domain. Model parameters can be summarized as follows:

1) LE model (Yokota et al. 1981):

$$G/G_0\,(\gamma) = 1/\left(1 + \alpha \cdot \gamma^{\beta}\right) \tag{3}$$

$$D(\gamma) = D_{max} \cdot exp(\lambda \cdot G/G_0) \tag{4}$$

α, β, λ and D_{max} are model parameters reported in Table 6 for rockfill and core materials.

Table 6. Parameters adopted in the numerical analyses

Dam materials	**Parameters**			
	α	**β**	**λ**	**D_{max} (%)**
Rockfill	98	1.0	-2.1	25
Core	70	1.0	-2.4	18

2) NL model (hyperbolic stress-strain curve)

The hyperbolic backbone curve, associated Masing criteria and Mohr-Coulomb strength envelope completely define the stress-strain relationships (Krahn 2004). In the nonlinear model the damping is related to the shear modulus G as follows:

$$D(\gamma) = D_{max} \cdot (1 - G/G_0) \quad (5)$$

The constitutive model assumes a Rayleigh type damping in addition to the hysterestic one expressed by the Equation 5. The model and the relative meshing are shown in Figure 7. The embankment consists of the core and the shells, resting on the rigid foundation. Local boundaries were placed far enough to minimize wave reflection effects. These limits were fixed after a parametric analysis of the study case.
The size of the mesh was determined by the criterion considering the maximum frequency and the minimum shear wave velocity to avoid numerical distorsion of the propagating ground motion and to obtain an accurate computation of the model response. The seismic input (Ofunato Earthquake) was applied at the base of the model with PGAs ranging from 0.065g up to 0.35g (see Table 2). In practice the same accelerograms as for the centrifuge test but with PGAs increased by the scale factor N = 40. Initial stress generation, by applying the own-weigth of the materials, was carried out before the dynamic analysis. For such a purpose, the Poisson's ratio (υ) was assumed equal to 0.25, 0.3 and 0.4 for the foundation, the shell and the core material, respectively. As the upstream slope is impermeable, seepage analysis was not performed. The static and dynamic (Zangar 1952) reservoir water pressure was applied during static and dynamic analysis. Recent advanced studies (Pelecanos et al. 2016) show that pore pressure build-up in the core during seismic action could be neglected.

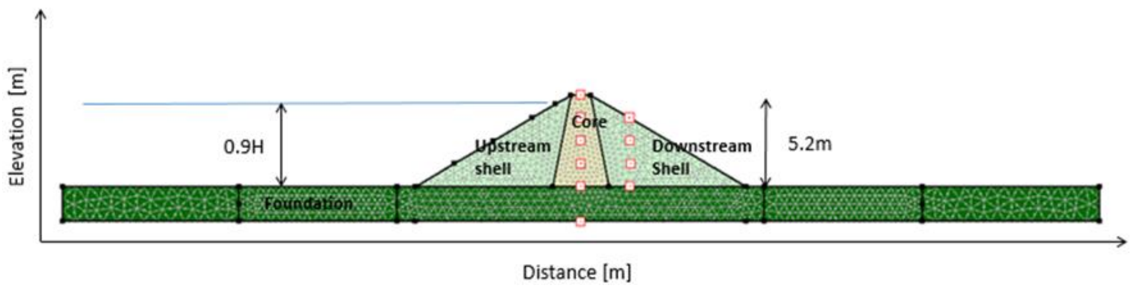

Figure 7. 2D Finite Element Mesh of the ECRD (Banti 2018)

5 COMPARISONS BETWEEN NUMERICAL AND CENTRIFUGE TEST RESULTS

The comparison between the experimental results and numerical predictions was expressed in terms of maximum acceleration distribution in the core and in the downstream shell.

Moreover, Fourier Spectrum of acceleration was evaluated at dam crest (Point A), for four tests (PGA=0.065g, 0.11g, 0.22g and 0.35g).

Computed acceleration amplitudes match quite well the experimental results in the range between 0 and 5 Hz, which represents the dominant frequency range of the input motion. The best fitting is for moderate seismic motions, while discrepancies increase for higher PGAs. On the whole, the form of the spectra (peak spectral frequencies) is correctly predicted by the numerical methods but the computed amplitudes underestimate the measured ones.

Different considerations could be advocated to explain such differences. Indeed, it is possible to consider the likely stiffening effect due to the centrifuge box sizes. As the L/H ratio of the centrifuge box is equal to 3.61 (i.e. less than 4), the centrifuge model can exhibit a stiffer response than the 2D numerical simulation of an infinitely wide canyon, according to Dakoulas and Gazetas

(1987). As for the NL analysis, it is possible to consider the effect of the Rayleigh type damping (viscous damping). Indeed, at higher vibration modes (higher frequencies) such a mechanism produces a higher dissipation. A more accurate calibration of such dissipation mechanism could be necessary. Figures 8 and 9 compare at four different earthquake levels measured and computed peak accelerations along the dam center line of the core and the rockfill downstream.

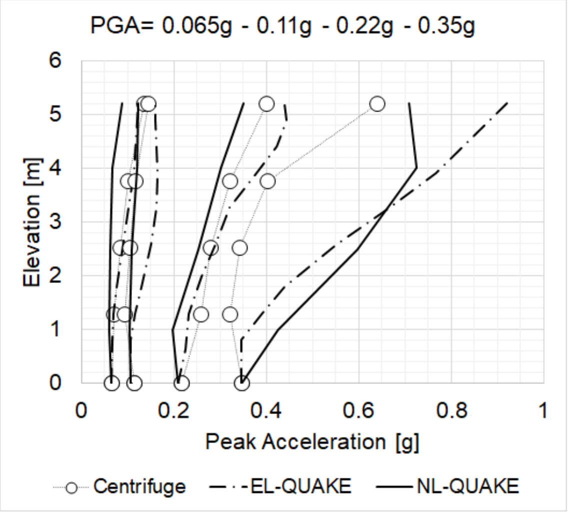

Figure 8. Maximum acceleration distribution in the prototype scale for the numerical analyses and the centrifuge test into the core (Banti 2018)

Those figures show that the numerical analyses of the present study are basically in agreement with those obtained with the centrifuge test. On the whole, numerical and experimental results agree, especially in the case of NL numerical analyses. In particular, the cyclic nonlinear model predicts more accurately the peak acceleration, especially at higher input motion and at crest (Figure 8). Indeed, true NL analyses lead to smaller values of the PGA. This is a consequence of the fact that true NL analyses account for the soil strength which limits motion amplification especially in the most shallower layers (Lo Presti et al. 2006, Angina et al. 2018).

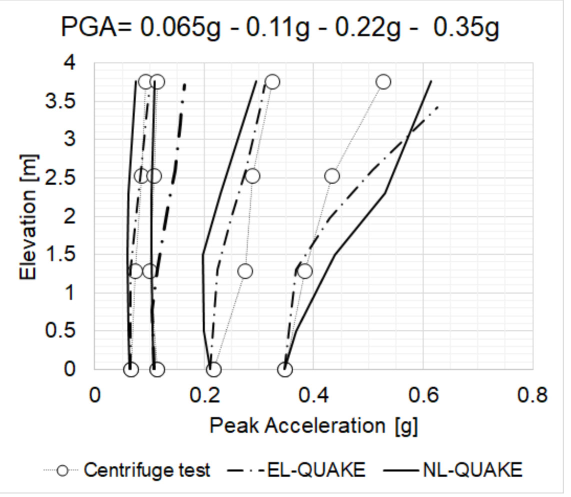

Figure 9. Maximum acceleration distribution in the prototype scale for the numerical analyses and the centrifuge test into the shell (Banti 2018)

Computed and measured permanent displacements were compared for the earthquake scaled at 0.35g. The maximum recorded horizontal displacement was 4.99 mm at crest while the maximum recorded vertical settlement was 9.72 mm. Figure 10 shows the computed and measured time histories of horizontal displacement at crest for the Ofunato Earthquake scaled at 0.35g.

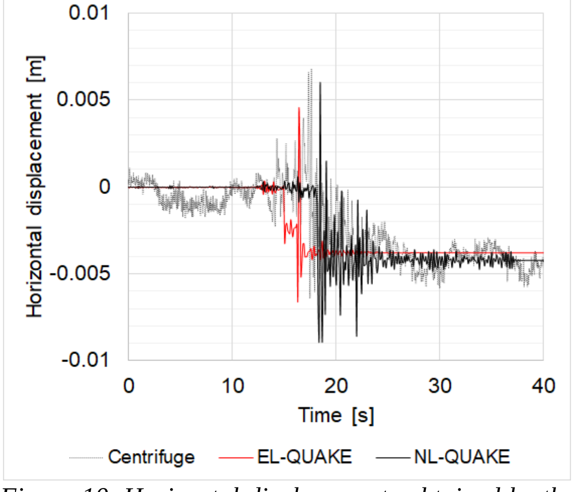

Figure 10. Horizontal displacements obtained by the centrifuge test and the numerical analyses (Banti 2018)

In particular, the results obtained from LE and NL analyses are shown in Figure 10. It may be observed that numerical and experimental results are in good agreement. Figure 10 shows that in both cases, the numerical and the experimental results tend to reach the same stable displacement value. Again, the NL analysis appears more realistic. The numerical analyses can reproduce the beginning of the increase of horizontal displacements.

The displacement increases after about 17 seconds from the beginning of the event for both the experimental and numerical results and reaches the maximum value which remains constant until the end of the time history.

Computed vertical displacement histories are plotted in Figure 11.

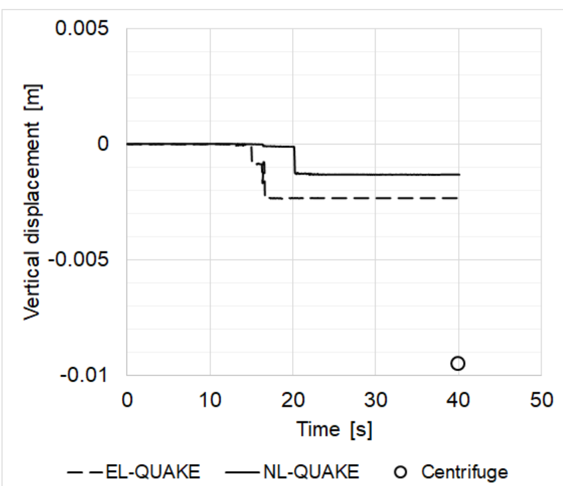

Figure 11. Vertical displacements obtained by centrifuge test and the numerical analyses (Banti 2018)

The measured residual vertical settlement at the end of the centrifuge test (0.35g) is compared to these time histories. The vertical settlement, inferred numerically, at crest ranges in between 1 to 3 mm. These results show that the crest settlements start to increase after about 20 seconds from the beginning of the dynamic event. The vertical predicted displacements at crest show a stable trend: the maximum value remains constant up to the end of the motion. The results in term of vertical settlements was available only for the experiment at 0.35g. The available centrifuge result shows a higher residual settlement value. However, comparing the calculated results with the Swaisgood's trend (Swaisgood 2003) it can be noted a good agreement between the numerical crest settlement ratios (Δ/H, where Δ is the crest settlement and H is the height of the dam) and the collected data (Banti 2018).

6 CONCLUSIONS

In this study, 2D FEM analyses were performed to simulate the seismic response of a prototype ECRD (5.2 m height) and results were compared to a centrifuge model test. A series of staged tests was performed on the numerical model of the dam with real earthquake motion scaled at different peak accelerations. Numerical results, and especially NL analysis results, demonstrate that the acceleration increases continuously from the bedrock to the dam crest and the obtained values are also in agreement with those inferred experimentally. Experimental horizontal displacements induced by dynamic loading tend to reach the same stable value of the numerical results. Again, NL analysis appears more realistic.

The available centrifuge test result shows a higher residual settlement compared to the computed one. The experimental result was obtained by the laser technique, thus experimental results could show higher value due to the accuracy level of its measuring method.

However, numerical settlement at crest shows a good agreemt with the Swaisgood's trend which shows the relationship between the crest settlement ratios and the relative earthquake magnitude.

7 ACKNOWLEDGEMENTS

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