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Seismic Analysis of an Instrumented Earth Dam in Terms of the Variability of the Response Design Spectra

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ABSTRACT

This study evaluates the seismic performance of an instrumented earth dam in terms of the variability of different design spectra commonly used as part of the practice of seismic design of earth dams. The study consists of four stages. The first stage considers the calibration of the dynamic properties for the dam based on the recorded events in the installed accelerometers. The second stage considers the seismic demand quantification at the dam site. The third stage considers the generation of design earthquakes which are compatible with the design spectra previously defined, different approaches are used for this purpose. In the last stage the seismic response of the earth dam and its variability is evaluated for the previously generated design earthquakes. For this purpose, finite difference methods and constitutive models widely used in practice (e.g UBCHYST model (Byrne, 2010)), implemented in the software FLAC (Itasca, 2011) were considered.

Introduction

In Peru there are a large number of earth dams which are used for hydraulic and mining purposes but only some of them have been instrumented with accelerometers to register the seismic events that will occur. This study takes advantage of the information obtained from an earth dam which was instrumented in 2004 with two accelerometers, one located in an inspection tunnel at bedrock level, and the other in the crest. This disposition allows analysis of the propagation of seismic waves over the dam body, in order to account for its dynamic properties.

The earth dam is located in the Junín province of Peru, approximately 170 kilometers east of Lima. It is used for water regulation, is 567 m in length and 56 m in height, with upstream and downstream slopes of 2.5H: 1V and 1.72H: 1V, respectively. The dam site is located in a complex, geologically active region east of a major plate boundary where numerous damaging historical earthquakes have occurred. Thus evaluation of its seismic performance is a critical issue. Peru, as with most of western South America, is situated along the western edge of the convergent plate boundary between the South America plate in the east and Nazca plate to the west. The eastern edge of the oceanic Nazca plate in this region is marked by the deep Peru-Chile Trench (PCT) offshore. The western edge of the continental South America plate is marked by broad, high mountains of the Western and Eastern Cordillera of Peru, and the numerous folds and faults that mark the eastern boundary of the Andes Range.

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Instrumentation and Recorded Events

Two accelerometers were installed in the dam, one of them in an inspection tunnel at bedrock level and the other one in the crest. The installed accelerometers are shown in the Figure. 1. During the seismic monitoring between 2004 and 2012, a total of 6 representative events were recorded in both accelerometers. The characteristics of the recorded events are summarized by Macedo (2012). The events have magnitudes between 4.0 and 6.0 Mw with epicenters located in the near and far field (the main recorded events correspond to the February 16, 2005 Mw 5.4 and March, 29 2008 Mw 5.6 seismic events)

Figure 1. Accelerometers installed in the dam. Left: Accelerometer installed at the crest dam. Right: Accelerometer installed at the bedrock level.

Dynamic Calibration of the Dam

The critical section of the dam is chosen for the calibration. Most of the dam body comprises moraine material classified as silty clayey gravel. Figure 2 shows the cross section of the earth dam and its foundation. A foundation depth of 75 m depth is considered for modelling, and about 252 m between left and right boundaries to the toe of the upstream and downstream of dam body. The ratio of crest length to height of the dam is such that 2-D analysis is sufficient for analysis of the propagation of the seismic signals recorded in the bedrock accelerometer over the dam body. Therefore the dam section is discretized into a plane strain model. Figure 2 shows the finite element mesh of the model (another finite difference mesh was prepared to be used on FLAC). Based on Kuhlemeyer and Lysmer´s study (1973), for accurate representation of wave transmission through the model, the maximum dimension for each elements in the finite element model and zones in FLAC is considered to be less than one-tenth of the earthquake wavelength. The properties of the foundation materials were defined by the review of geotechnical studies made before the dam construction. These studies involved boreholes and seismic refraction lines complemented with geotechnical laboratory tests. The available data indicates the presence of thin surficial alluvial deposits, lacustrine deposits (which can be classified as low compressibility clays) and fluviolacustrine deposits over bedrock foundation (riolites). According to the boreholes, the lacustrine materials are deeper in the upstream zone compared with the downstream zone. The majority of the embankment body comprises moraine materials (the shells) and an impervious core. The physical properties for dam and the foundation materials are summarized in the Table 1.

The calibration was performed in terms of the maximum shear modulus and the shear modulus reduction and material damping curves for the different materials in the dam. Different maximum shear modulus and different reduction curves were considered for that purpose. For the variation of the shear modulus the correlations compiled for Benz (2006) were used (For detailed information about the correlations see the page 32 of the reference). For these correlations the evaluation of maximum shear modulus is based on the modified Hardin and Black equation (1978).

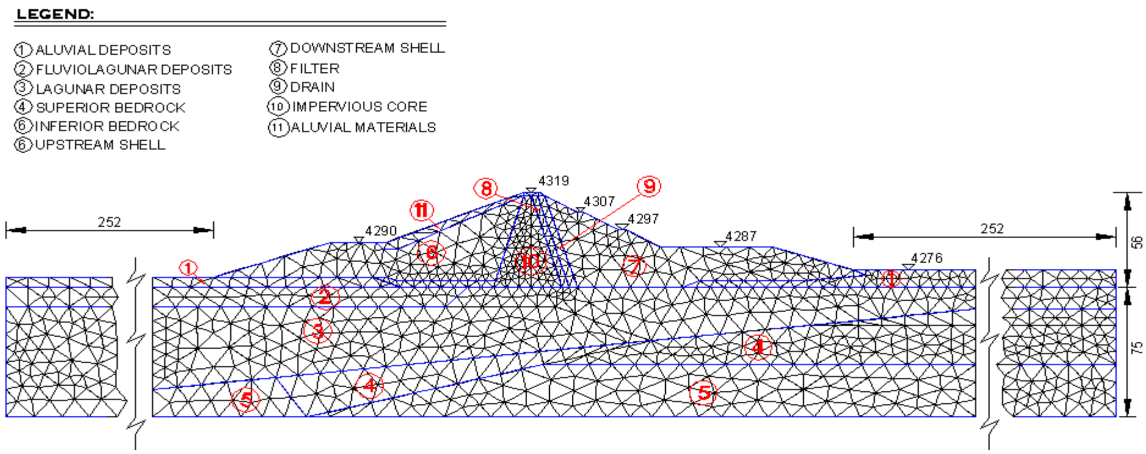


Figure 2. Dimensions of the model and finite element discretization of the earth dam

Table 1. Physical properties of the Yuracmayo dam materials

Material	Clasification	Density (KN/m3)	Cohesion (KN/m2)	Friction Angle (º)	Plasticity Index (IP)
1	GW-GC	21.60	0	35.0	12.00
2	GP-GM	21.60	14	35.0	12.50
3	CL/CL-ML	19.70	21	28.0	13.00
4	Riolites	22.60	115	38.0	---
5	Riolites	23.50	114	34.0	---
6	GC-GM	21.60	0	40.0	6.00
7	GC-GM	21.50	0	40.0	7.00
8	SW	20.60	0	36.5	---
9	GW o GP	20.60	0	36.5	---
10	GC	21.30	0	40.0	8.00
11	GW	22.36	0	36.5	7.00

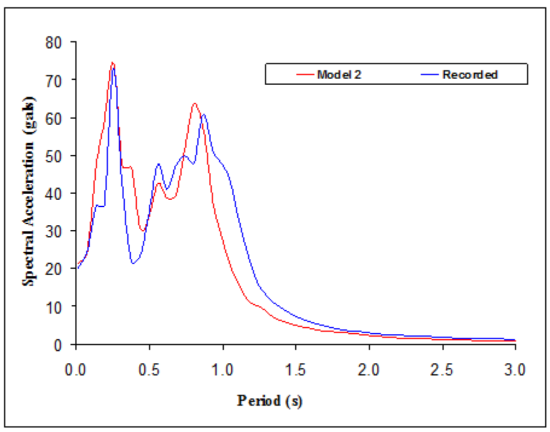
For the different correlations the shear modulus was evaluated calculating maximum, minimum, and average values for each material. Additionally to determine the maximum shear modulus for dam materials, geophysical tests were carried out as part of this study. The tests included seismic refraction lines and multichannel analysis of surface wave analysis (MASW). The results obtained from different correlations and those from the geophysical tests are summarized in the Table 2. For the variation of the shear modulus reduction and material damping, representative curves published in the literature (e.g curves included in the software edushake; Ishibashi and Zhang, 1993, among others) were selected depending of the material characteristics.

Table 2. Values obtained for the maximum shear modulus (kPa)

Material	Geophysical essays	Minimun Range Correlations	Average Range Correlations	Maximun Range Correlations
1	3.26E+05	8.28E+04	1.42E+05	2.00E+05
2	---	1.18E+05	2.10E+05	3.05E+05
3	2.96E+05	1.63E+05	2.34E+05	2.97E+05
4	3.30E+06	---	---	---
5	2.54E+06	---	---	---
6	3.56 E+05	1.01E+05	1.74E+05	2.43E+05
7	3.54 E+05	1.01E+05	1.74E+05	2.43E+05
8	---	1.26E+05	1.88E+05	2.70E+05
9	---	1.26E+05	1.88E+05	2.70E+05
10	4.75E+05	1.88E+05	2.70E+05	2.70E+05
11	2.95E+05	2.45E+04	7.83 E+04	7.84E+04

Final Calibration

Additionally to the considerations for the variability in maximum shear modulus, and shear reduction and material damping curves, two different models were considered; the equivalent linear model (Seed and Idriss 1970) available in the software Quake Geoestudio (2011) and a fully nonlinear model in terms of total stresses, UBCHYST (Byrne, 2010) available in the software FLAC (Itasca, 2011) as a user defined model, please see the references for details in the models. Also different boundary conditions (e.g transmitting vs. non transmitting boundaries, free boundaries options in FLAC, etc.) were considered. The calibration was performed for the recorded bedrock motions of the February 16, 2005 and March 29, 2008.



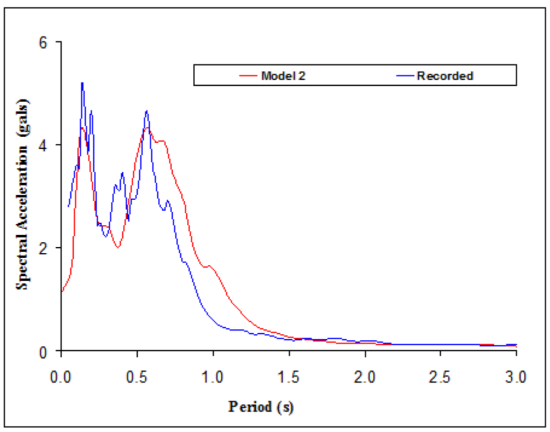


Figure 3. Results obtained for the calibration using the nonlinear model Left) Seismic event from March 29, 2008. Right) Seismic event from February 16, 2005.

The final results of the calibration are shown in Figure 3 (the figure shows the comparison between the real recoded spectra and the analytically calculated spectra). The nonlinear model allowed a better calibration compared with the equivalent linear model, so only these results are shown.

Based on the sensitivity analyses the best results in terms of the calibration were obtained considering the maximum shear modulus obtained from the geophysical test (see values in Table 2) and the shear modulus reduction and material damping curves shown in Figure 4, most of these curves correspond to the curves proposed by Ishibashi and Zhang (1993).

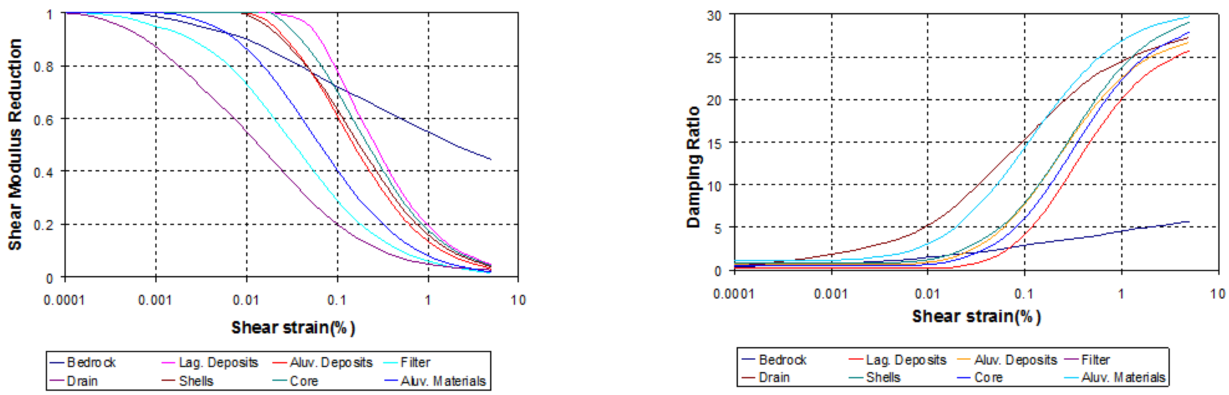


Figure 4. Degradation curves for the dam materials. Left: Shear modulus reduction curves. Right: Damping material curves.

Quantification of Seismic Demand and Design Ground Motions

In order to quantify the seismic demand a site- specific seismic hazard study was carried out using the software EZ-FRISK (Risk Engineering, 2012). Both deterministic and probabilistic approaches were employed to develop site-specific ground motion parameters, using seismic sources defined for a radius of about 500 km from the project site. Different ground motion equation predictions (GMPE) were considered to account for the epistemic uncertainty. The different GMPE used and weighted factors were based on the recommendations of Arango (2010). Details of the site specific hazard analysis (sources characterization, activity rates, geometry of the sources, magnitude PDF´s, considered GMPE´s, weighting factors, deagregation results, etc) are given in Macedo et al, (2012). Figure 5 shows the results of the hazard by sources along with the mean total hazard (only as an example, results for PGA). Figure 6 shows the different response spectra from the site specific seismic hazard analysis. The response spectra corresponding to the Peruvian Code (E030 Seismic code) and the one based on the IBC (2009) code are included only as reference for comparison purposes.

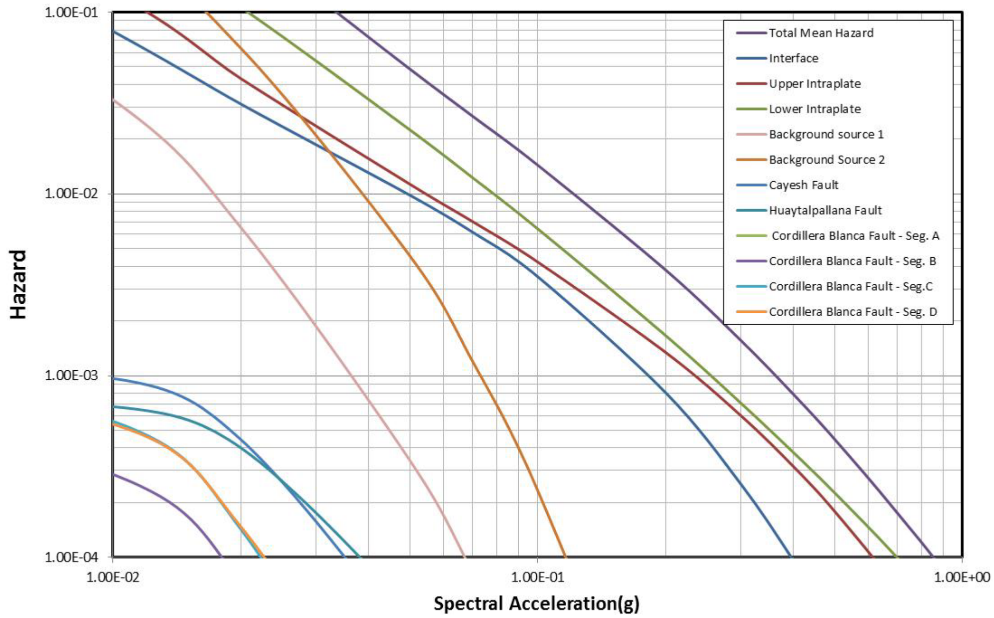


Figure 5. Seismic Hazard calculation results for PGA by source along with the total mean hazard.

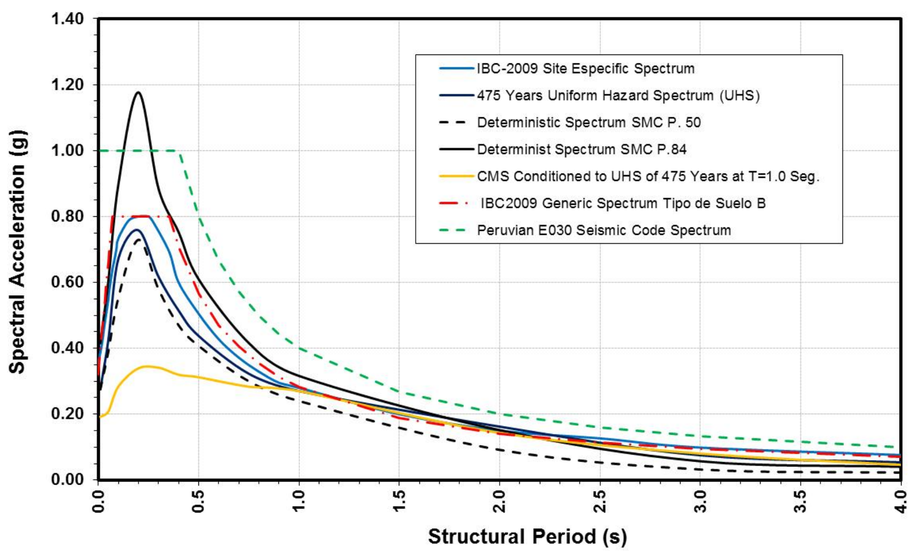


Figure 6. Response spectra defined based on the site specific seismic hazard analysis.

The design ground motions were based on the response spectra previously defined, and three methodologies were considered **1)** Spectral Matching (Attik, L.A. and Abrahamson N. A. ,2009) **2)** The methodology proposed at the University of Texas Austin (Kottke, A. y Rathje, E.,2009) and **3)** The methodology proposed at Stanford University (Jayaram, N., Lin, T., y Baker, J. W., 2011). Methodology 1 was applied to all defined spectra (with exception of the Generic IBC2009 spectrum and the deterministic P.50 spectrum). Recorded ground motions with representative properties of all the spectra in an overall sense were considered. The recorded records considered were Lima, 1974 (October 3, Parque de la Reserva Station), Moquegua, 2001 (June 23, Cesar Vizcarra Station), Tarapacá, 2005 (June 13, Iquique IDIEM Station) and the Maule, 2010 (February 27, Hualañe station) earthquake. For application of methodologies 2 and 3 a database for subduction earthquakes from Peru and Chile with about 200 events was created (in this case only the deterministic P.50 spectrum was considered since it allows the application of the methodologies for a median value). Figure 7 shows one example of the application of the methodology 2.

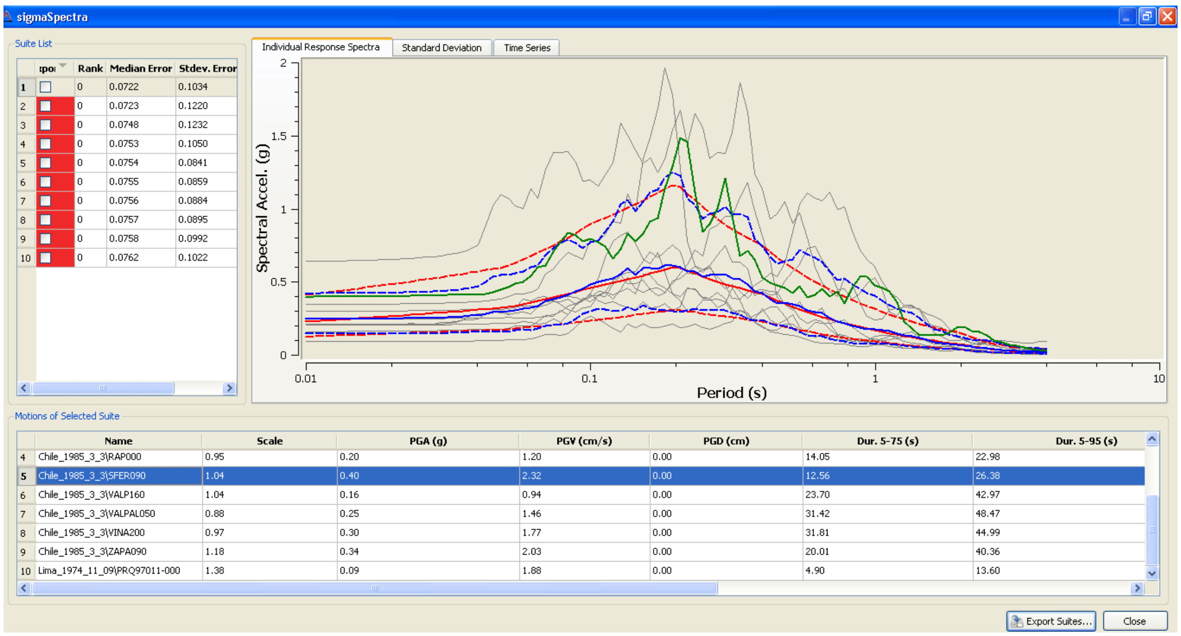


Figure 7. Example of application of methodology 2 (Kottke, A. y Rathje, E.,2009) for design ground motions

Dynamic analyses and Seismic Dam Performance

A vast number of seismic dynamic analysis were performed considering the dynamic and mechanical properties defined during the initial calibration stage and all the range of design ground motions compatible to the response spectra defined based on the site specific seismic hazard analysis.

For the seismic analysis the same calibrated model and constitutive model UBCHYST (Byrne, 2010) considered during the calibration stages was used for compatibility. Figure 8 shows an example of the permanent deformations obtained for ground motions compatible to different response spectra.

As part of the seismic analysis different time histories of displacements were recorded at different points downstream, upstream and in the crest area of the dam. The mean value of the displacements considering all the range of design ground motions and different response spectra for the crest area displacements are shown in Figure 9. This paper, due to space limitation, only shows the mean displacements in the crest since these were found to compromise the stability of the dam and govern the adequate free board for the dam, a critical factor during operation. The numerical simulations did not show formation of failure mechanisms in the dam. The mean displacements considering all the range of response spectra are lesser than 0.80 m which is less than the free board of the dam, as shown in Figure 9. Also notice that the maximum displacement is calculated for the E030 spectrum, however this spectrum was formulated for conventional structures (e.g. buildings) and should not be used for critical structures, like dams, emphasizing the necessity of performing a site specific seismic study to define design ground motions for earth structures, since it could lead to an unnecessary conservative design. Having said that, the maximum demand was obtained for the deterministic P 0.84 spectrum with displacements in the order of 0.60m. The demand based on the UHS with 475 years return period, the deterministic P0.50 spectrum, and the IBC2009 site specific spectrum was found to be in a narrow range (0.35 to 0.40 m), however again the IBC2009 spectrum is defined for conventional structures. Finally the spectrum that caused the lesser demand was the conditional mean spectrum with displacements in the order of 0.30m.

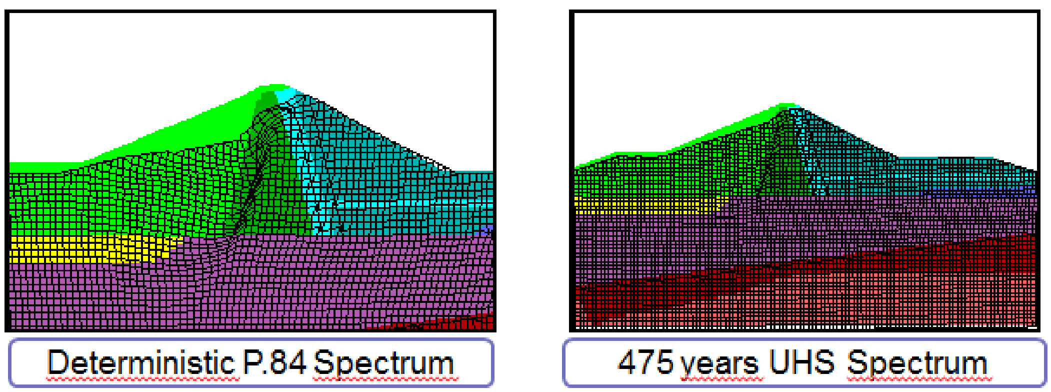


Figure 8. Permanent deformations pattern considering the Maule, 2010 earthquake compatible to the deterministic P.84 spectrum and the 475 years UHS spectrum (methodology 1 applied).

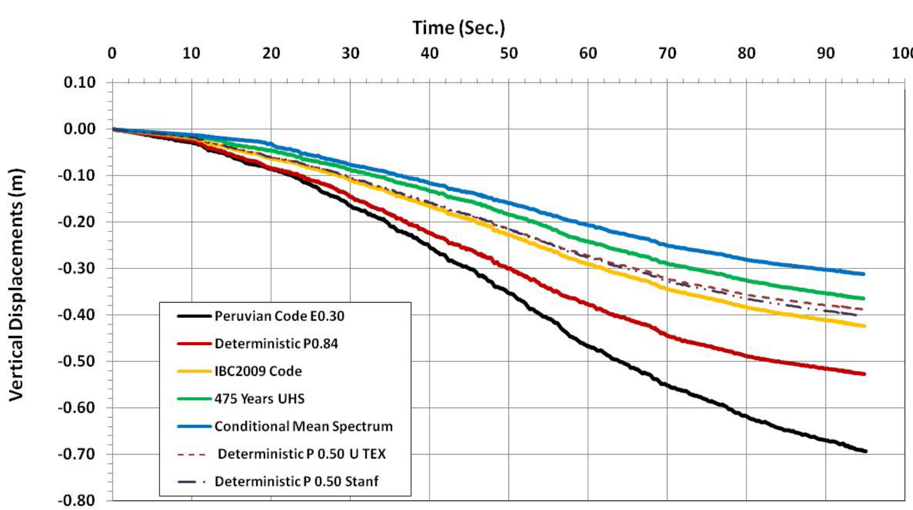


Figure 9. Calculated Mean displacements in the crest area from the dull set of ground motions

Conclusions

This study considered the evaluation of the seismic performance of an instrumented earth dam (by means of accelerometers); the seismic performance was evaluated in terms of the permanent displacements (mean values). For that purpose information from the recorded seismic events was used to characterize the dynamic properties of the dam. Once the dynamic properties for the dam were calibrated, the dam performance was evaluated for a large set of design ground motions, to account for uncertainties. The design ground motions were compatible to the response spectra defined based on a site specific seismic hazard study. Based on the time history analysis, it was found that the critical deformations were associated with the settlements in the crest area. However, it is not expected that these settlements would compromise the free board of the dam after a seismic event or cause instabilities, as no failure mechanisms were observed in general for the upstream or downstream area of the dam. It is highlighted the advantages of perform a site specific seismic analysis to define design ground motions for critical structures, like a dam, since the use of standard code based design spectra (e.g E030 Peruvian code) applicable to standard structures can lead to unnecessary conservative results, when applied to structures for which they are not defined. From the seismic analyses, the design ground motions compatible to the SMC P.84 spectrum imposed the highest demand, the ones compatible to the IBC2009, UHS475 and SMC P.50 imposed similar demands while the ones compatible to the CMS475 imposed the lesser demand. Since the earth dam is considered a critical structure (Macedo, 2012) the SMC P.84 was found as the most appropriate to evaluate the seismic performance of the dam leading to estimated mean vertical settlements in the order of 0.60 m. This loss in free board has to be taken account in establishing the operational management of the reservoir.

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