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# CALIBRATION OF A DYNAMIC MODEL FOR YURACMAYO EARTH DAM

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## ABSTRACT

In this paper the calibration of a dynamic model for Yuracmayo earth dam, is presented. The dam was instrumented with two accelerometers, located at bedrock level, and in the crest. The calibration was made comparing the analytical response spectra obtained in the crest by the propagation of the recorded events in the bedrock accelerometer (using a 2D numerical model for the dam), with the real response spectra from seismic signals recorded at the crest accelerometer.

For the calibration, different kind of models were proposed, taking into account the boundary conditions and variation of maximum shear modulus. The two larger events recorded and two models to represent the soil behaviour, (the equivalent linear model and a non-linear model), were used. As a result of the calibration it is concluded that the calibrated model represents well the dynamic behaviour of the Dam, especially if a non linear model is considered

Keywords: Shear Modulus, response spectra, equivalent linear model, non-linear model.

## INTRODUCTION

Yuracmayo dam is located in the Junin province of Peru, approximately 170 kilometers east of Lima, at approximately latitude 11.84S and longitude 76.15W, the dam is used for water regulation. It has 567 m in length and 56 m in height, with upstream and downstream slopes of 2.5H: 1V and 1.72H: 1V, respectively. In Peru there are a large amount 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. Yuracmayo dam 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 analyzing the propagation of seismic waves over the dam body.

## INSTRUMENTATION AND RECORDED EVENTS

As was mentioned before, 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 accelerometers that were installed are shown in the Fig. 1.

During the seismic monitoring between 2004 and 2009, a total of 6 representative events were recorded.

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The characteristics of the recorded events are summarized in the Table 1. The events have magnitudes between 4 and 7 ML with epicentres located in the near and far field (the main recorded events correspond to the February 16,-2005 and March, 29-2008 seismic events).


(a) (b)

**Figure 1. Accelerometers installed in the dam (a) Accelerometer installed at the crest dam. (b) Accelerometer installed at the bedrock level**

**Table 1. Seismic events recorded during monitoring period**

| Date | Time(GMT) | Latitude(S) | Longitude(W) | Deep (Km) | Magnitude (ML) |
|---|---|---|---|---|---|
| April 2, 2004 | 11:55 | 12.98 | 77.13 | 37 | 4.5 |
| April 4, 2004 | 19:52 | 12.23 | 76.40 | 74 | 4.0 |
| February 16, 2005 | 22:12 | 11.30 | 76.32 | 121 | 5.2 |
| March 2, 2005 | 08:48 | 11.83 | 76.15 | 132 | 5.0 |
| April 18, 2005 | 19:53 | 12.61 | 76.70 | 57 | 4.1 |
| March 29, 2008 | 07:51 | 12.25 | 77.25 | 51 | 5.3 |

## MATERIALS AND MESH

The critical section of Yuracmayo dam is chosen for the calibration; most of dam body is constituted by moraine material classified as silty clayey gravel. Fig. 2 shows the cross section of the earth dam and its foundation. The upstream and downstream slopes are 2.5H: 1V and 1.72H: 1V, respectively. 75 m depth of the foundation is modelled, also about 252 m distance is considered between left and right boundaries to the toe of the upstream and downstream of dam body.

Ratio of crest length to height of the dam is such a way that 2-D analysis is enough for analyze the propagation of the seismic signals recorded in the bedrock accelerometer over the dam body. Therefore the dam section is discretized into a plan strain finite element model. Fig. 2 shows the prepared mesh of the model. Based on kuhlemeyer and Lysmer´s study (1973), for accurate representation of wave transmission through the model, maximum dimension for each element is considered to be less than one-tenth of the earthquake wavelength.

The properties of the foundation materials were defined by the revision of the geotechnical studies made before the dam construction, these studies involved boreholes and seismic refraction lines complemented with soil mechanics essays. 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 embankment body is majority constituted by moraine materials conforming the shells and an impervious core. The physical properties for dam and the foundation materials are summarized in the Table 2.

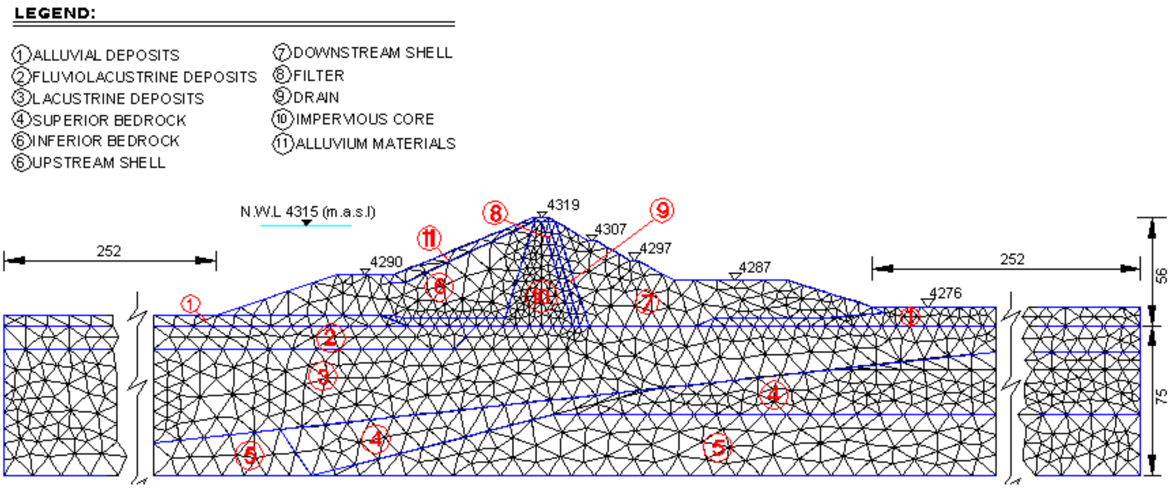



**Figure 2. Dimensions of the model and finite element discretization of Yuracmayo dam.**

**Table 2. Physical properties of the Yuracmayo dam materials**

| Material. | Classification | Density (KN/m3) | Cohesion (kN/m2) | Friction angle (º) | Plasticity index (IP) |
|---|---|---|---|---|---|
| 1 | GW-GC | 21.58 | 0 | 35.00º | 12.10 |
| 2 | GP-GM | 21.58 | 13.70 | 35.00º | 12.50 |
| 3 | CL/CL-ML | 19.62 | 20.60 | 28.00º | 13.00 |
| 4 | Riolite | 22.56 | 114.80 | 37.87º | --- |
| 5 | Riolite | 23.54 | 113.80 | 34.02º | --- |
| 6 | GC-GM | 21.58 | 0 | 40.00º | 6.10 |
| 7 | GC-GM | 21.48 | 0 | 40.00º | 6.70 |
| 8 | SW | 20.60 | 0 | 36.50º | --- |
| 9 | GW , GP | 20.60 | 0 | 36.50º | --- |
| 10 | GC | 21.28 | 0 | 40.00º | 8.30 |
| 11 | GW | 22.36 | 0 | 36.50º | 6.80 |

## PROPOSED MODELS

In order to make the calibration different kind of models were proposed, which took into account the boundary conditions and variation of maximum shear modulus. 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).

$$G_{max} = Af_{(e)}OCR^{k}\left(\frac{p'}{P_{ref}}\right)^{m} \quad (1)$$

where $G_{max}$ is the maximum small-strain shear modulus in MPa, $p'$ is the mean effective stress in KPa, $P_{ref}$ =100 KPa is a reference pressure equal to the atmospheric pressure, OCR is the overconsolidation ratio, $f_{(e)}$ is a function of the void ratio and A, k and m are the correlated parameters.

For the different correlations the shear modulus was evaluated calculating maximum, minimum, and average values for each material. The shear modulus for the rock was kept constant and equal to the values given for the geophysical tests made before the dam construction. Additionally, to determine the dynamic properties for dam body materials, geophysical tests were carried out for this research.

The tests included lines of seismic refraction and multichannel array surface wave analysis (MASW) tests. The results obtained by the different correlations and for the geophysical tests are summarized in the Table 3

**Table 3. Values obtained for the maximum shear modulus (KPa)**

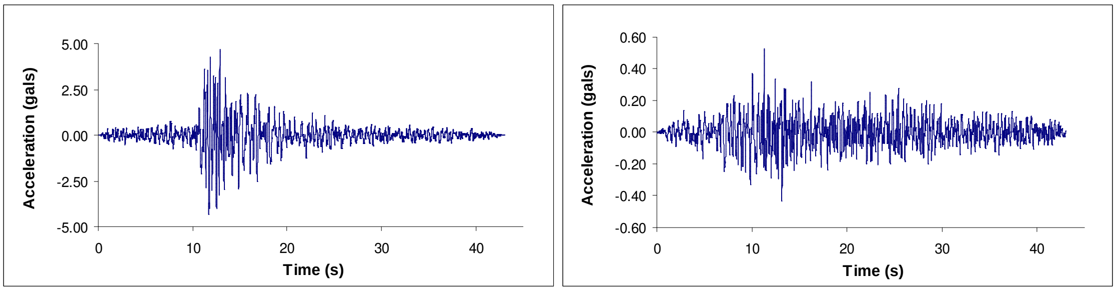
| Material. | Geophysical Tests | Minimun | Average | Maximun |
|---|---|---|---|---|
| 1 | 3.26E+05 | 8.28E+04 | 1.42E+05 | 2.02E+05 |
| 2 | - | 1.18E+05 | 2.10E+05 | 3.05E+05 |
| 3 | 2.96E+05 | 1.63E+05 | 2.34E+05 | 2.97E+05 |
| 4 | 3.30E+06 | - | - | - |
| 5 | 2.54E+06 | - | - | - |
| 6 | 3.56E+05 | 1.01E+05 | 1.74E+05 | 2.43E+05 |
| 7 | 3.54E+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 | 1.26E+05 | 1.88E+05 | 2.70E+05 |
| 11 | 2.95E+05 | 2.45E+04 | 7.83E+04 | 7.84E+04 |

The proposed models are described as follows:

- Model 1, which considers the shear modulus values obtained by the geophysical tests. About boundary conditions, no restrictions are considered for the lateral boundaries, the bottom boundary is considered fixed.
- Model 2, which considers the shear modulus values, obtained by the geophysical tests, but in this case the Lysmer-Kuhlemeyer boundary (Lysmer and Kuhlemeyer, 1969) is used to limit spurious wave reflections at the mesh boundary.
- Model 3, considering the lower values of the shear modulus obtained by the different correlations. The boundary conditions are similar to the conditions of the model 2.
- Model 4, considering the average values of the shear modulus obtained by the different correlations. The boundary conditions are similar to the conditions of the model 2.
- Model 5, considering the higher values of the shear modulus obtained by the different correlations. The boundary conditions are similar to the conditions of the model 2.

## CALIBRATION OF THE MODEL

The recorded bedrock motions of the February 16, 2005 and March 29, 2008 having magnitudes of 5.2 ML and 5.3 ML respectively were used for the calibration. The time–histories of these events are shown in the Fig. 3.




(a) (b)

**Figure 3. Seismic events used in the calibration a) Recorded acceleration time-history, March 29, 2008 b) Recorded acceleration time-history, February 16, 2005**

For the calibration two different models were considered, the equivalent linear model and the nonlinear model in terms of effective stresses both incorporated into the software Geoestudio 2007. These two models are following explained.

## Equivalent linear method

The equivalent-linear method (Seed and Idriss 1970) take into account the modulus and damping degradation curves with shear strain. Modulus and damping values are computed from these degradation curves by an iterative algorithm. At each iteration the effective strain is determined updating the modulus and damping values. This is done until a convergence limit is reached between the effective strains at two consecutive iterations

Degradation of secant shear modulus and increase of damping ratio with increasing shear strain for the rock, filter and drain materials are based on the studies of Seed and Idriss (1970) and Seed et al. (1986). For the rest materials these curves were evaluated taking into account the relations proposed by Ishibashi and Shang (1993). The degradations curves for the different materials are shown in Fig. 4.

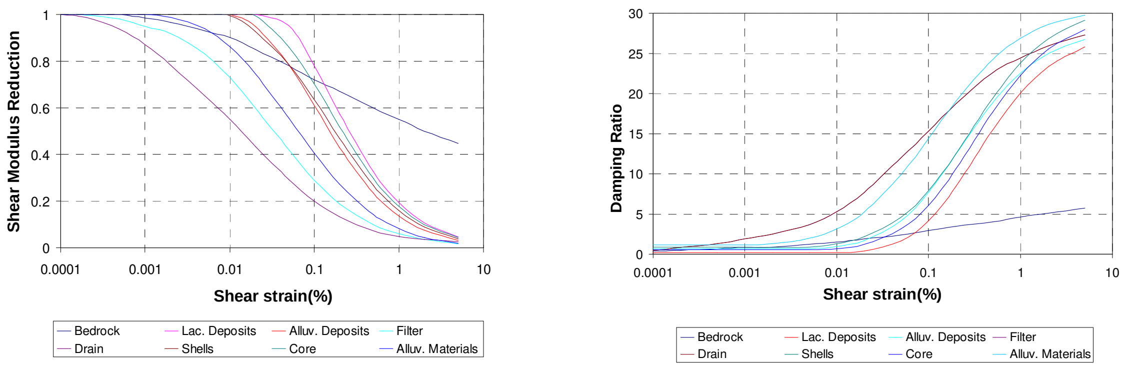



**Figure 4. Degradation curves considered for the Yuracmayo dam materials a) Shear modulus reduction curves b) Damping ratio curves.**

## Non-Linear Model In Terms of Effective Stresses

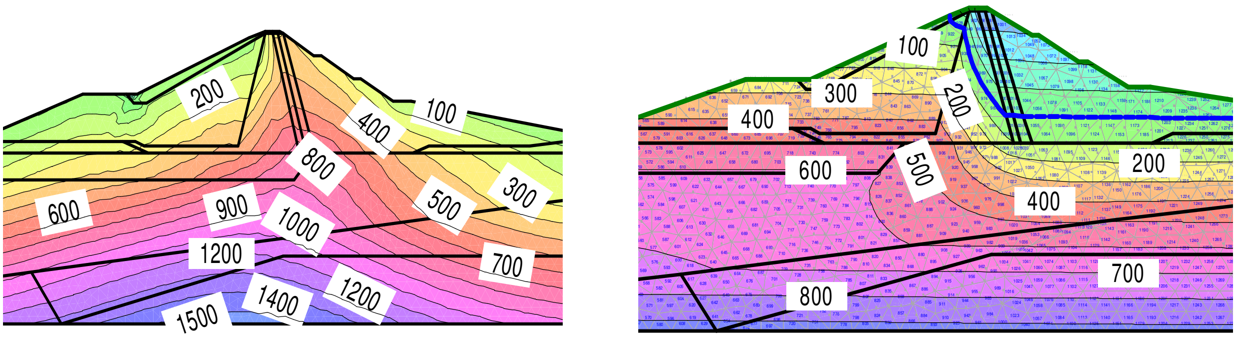
This model considers the fact that the stress-strain relationship of soils, particularly granular soil, can be approximated by a hyperbolic curve .The curve can be defined by two parameters which are the slope at zero strain and the asymptotes at large strains. In terms of soil properties the initial slope of the curve is the small strain shear modulus Gmax; and the horizontal asymptote for large strains is the shear strength of the soil.

When the hyperbolic curve is drawn for both negative and positive shear stresses and strains, the hyperbolic curve in cyclic nonlinear models is referred to as the backbone. One key component for the model is that when there is a stress reversal, the shape of the unloading curve is the same as the backbone curve except the origin moves to the point of the stress reversal. In addition the curves follow what are known as Masing rules (Masing, 1926).The model is expressed in terms of effective stresses, it inherently incorporates the hysteretic nature of damping and the strain-dependence of the shear modulus and damping ratio (Kramer, 1996).

**Analysis and Results**
To start the analysis the initial in-situ static stresses and distribution of pore pressures for the dam were defined, the results obtained are shown in the Fig. 5.

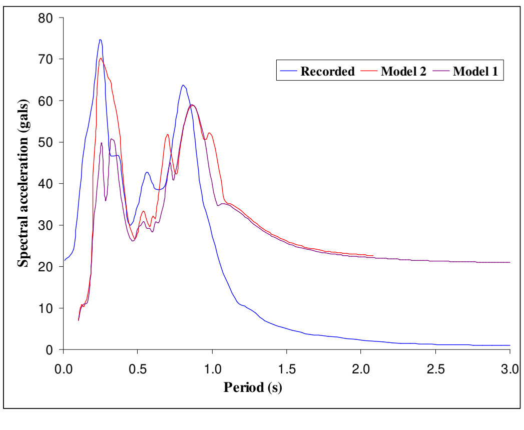
The calibration was made in two stages, first, the equivalent linear model was used, the results obtained using the proposed models for the seismic event from March 29, 2008 are shown in the Fig. 6. As a result of these analyses, the model 2 was chosen as the most representative. An additional equivalent linear analysis was made considering the seismic event from February 16, 2005. The results obtained are shown in Fig. 7 again the model 2 was choose as the most representative.

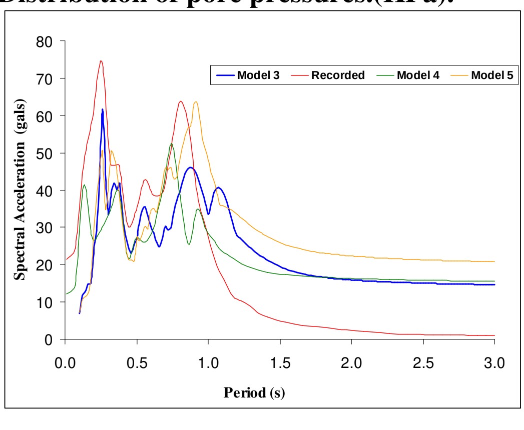
For the next stage the chosen model in the first stage (model 2) was used for the analysis, considering the non linear model for the dam materials. The result obtained for the event from March 29, 2008 is shown in Fig. 8a, and finally Fig. 8b shows the result obtained considering the event from February 16, 2005.




**(a)** **(b)**

**Figure 5. Initial conditions for the analysis. a) Contours of the initial effective static stresses (KPa).b) Distribution of pore pressures.(KPa).**



(a) (b)

**Figure 6. Results obtained for the first stage of the calibration using equivalent linear model (seismic event from March 29, 2008)**

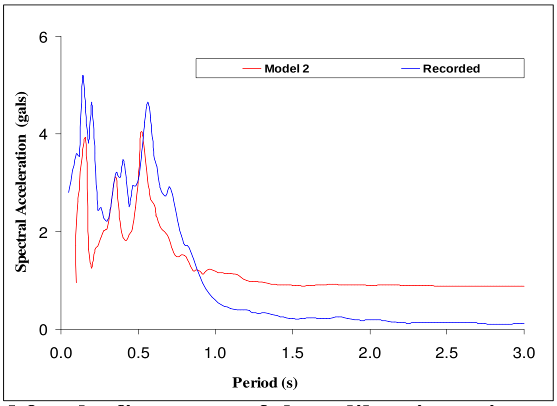
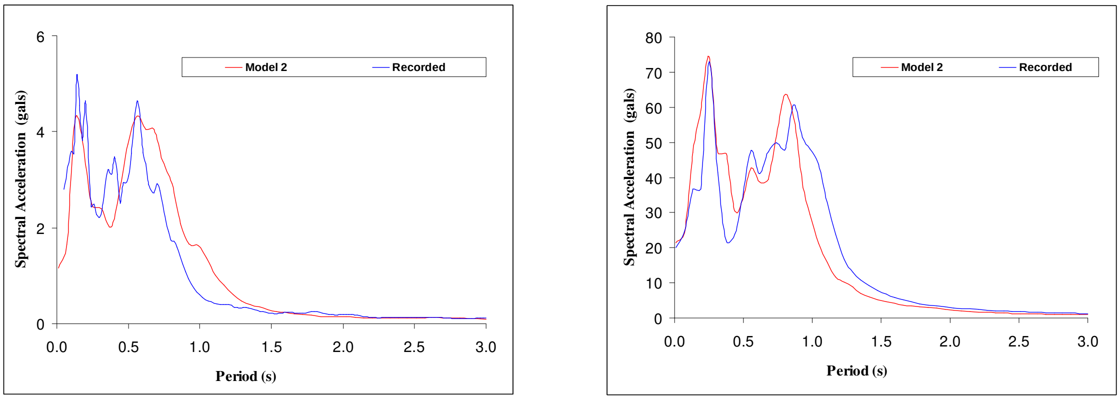



**Figure 7. Results obtained for the first stage of the calibration using equivalent linear model (seismic event from February 16, 2005)**




**(a)** **(b)**

**Figure 8. Results obtained for the second stage of the calibration using the non linear model a) Seismic event from March 29, 2008. b) Seismic event from February 16, 2005.**

## CONCLUSION

This study was focused in the calibration of a dynamic model for Yuracmayo earth dam, using the seismic recorded events in the accelometers that were installed. The response spectra obtained using a linear equivalent model (considering the proposed model 2) showed a good agreement with the real spectra for short periods; however, it shows same larger spectral amplitudes in the large periods range. This behavior could be associated with the excessive degradation caused by the shear modulus reduction curves, which cause amplification in high periods. On the other hand, the response spectra obtained in the second stage, using a non-linear model, showed a good agreement with the real spectra for short and large period ranges. Therefore, it is concluded that the model 2 represents well the dynamic behavior of the Yuracmayo dam for the recorded events, especially if a non linear model is considered.

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