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Crosshole Seismic Tomography to Assess Rock Mass Foundation of Dams - Alto Ceira II Dam Case Study

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Summary

Crosshole seismic tomography is a widespread geophysical method to estimate the elastic properties of materials in the crosshole section, for a variety of applications, including engineering site characterisation and foundation treatment evaluation.

This method was applied to Alto Ceira II dam in three phases: Phases 1 and 2 – before and after rock mass foundation treatment, and Phase 3 – after the reservoir first filling. The resulting time-lapse seismic tomographies allowed assessing the schist and greywacke rock mass foundation treatment, and the influence of the reservoir filling.

This study demonstrated that the method can be used as a management tool to evaluate the rock mass behaviour along the dam's construction phase and during its working lifetime.

Introduction

Crosshole seismic tomography is a geophysical method that can provide a high-resolution imaging of the subsurface, in terms of seismic P-wave velocity (V_P). Consequently, this technique is especially adequate to characterize, zone and delineate weak areas on rock mass foundations of structures, such as bridges (Butchibabu, et al. 2017, Mota, 2017), dams (Mota et al. 2015, Coelho et al. 2018, Mota et al. 2018) among others (Coelho et al. 2004, Oliveira and Coelho 2004, Lehmann 2007).

Seismic wave velocity variation with time of rock masses are due to external actions applied to it, such as rock blasting or grout injections. Seismic velocity depends mainly on porosity, joint density and water content, with an inverse relation that is velocity decreases as porosity increases, for example. Barton (2007) states that porosity, joint density and uniaxial stress play an important role on seismic wave velocity increase or decrease.

Since seismic wave velocity is related with the quality and strength of the rock mass it can be used to evaluate, for example, the effectiveness of foundation treatment, which usually decreases the porosity of the medium, if time-lapse seismic tomographies are carried out before and after the treatment (Coelho et al. 2018 and Mota 2017). The rock mass consolidation treatment generally consists in grout injection to fill joints that are open or filled with soft erodible materials (previously removed before the injection). V_P tomographic zoning of rock mass dam foundation can also be used to calibrate its mechanical parameters used in the finite element model that supports the analysis and interpretation of dam-foundation behaviour during the first filling of the reservoir (Mota et al. 2018).

Here Alto Ceira II dam (central Portugal) case study is presented. This is a 41 m high concrete arch dam, with a total crest length of about 133 m. In its schist and greywacke rock mass foundation 8 boreholes were specifically drilled for seismic crosshole tests, allowing obtaining a V_P crosshole seismic tomography of the entire foundation along its reference line. In order to have a tomographic time-lapse evaluation of the rock mass foundation, seismic tests and corresponding tomographies were carried out before - Phase 1 (Mota 2012) and after - Phase 2 (Mota 2013) the dam's foundation global treatment (consolidation and grout curtain), and also after the first reservoir filling - Phase 3 (Mota 2014).

Material and methods

In the crosshole seismic tomography here presented, P-wave velocity (V_P) distribution is reconstructed from a multitude of travel time ray paths, corresponding to several crosshole seismic measures as illustrated in Figure 1, assuming a purely bidimensional wave propagation on the crosshole section. So, for each seismic source activation along the source borehole, there is a multi--channel seismic record from the receivers array along the receiver borehole.

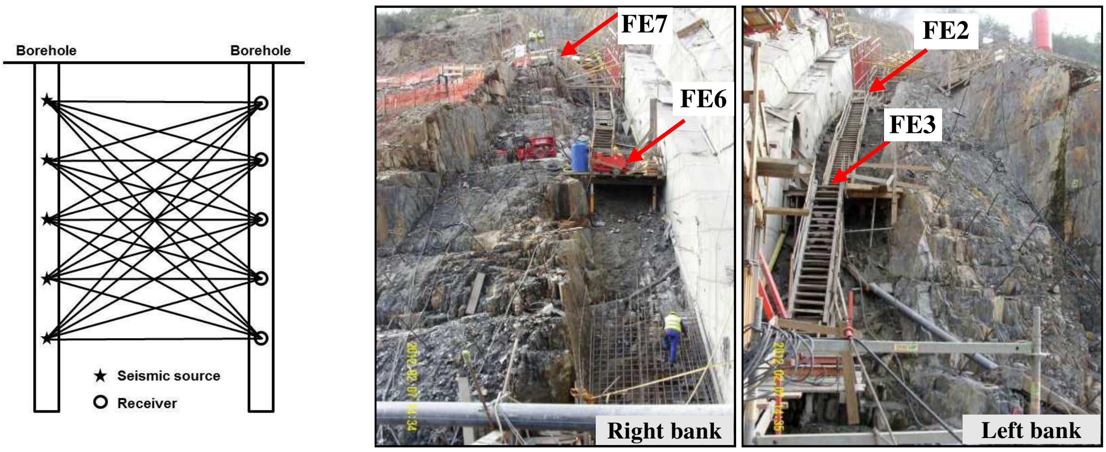

***Figure 1:** Left - Data acquisition layout for crosshole seismic tomography. Right – work development at Alto Ceira II dam foundation during Phase 1, with identification of 4 borehole locations.*

All P-wave measured travel times are jointly inverted into a V_P matrix assigned to a cells grid which discretizes the area crossed by seismic ray paths. The inversion is performed by a SIRT (Simultaneous Iterative Reconstruction Technique) type algorithm (Pessoa, 1990, Lehmann 2007) that assumes straight ray paths (direct waves), constant velocity for each grid cell and isotropic materials. It starts with an initial velocity matrix for which straight ray theoretical travel times and the corresponding differences between these and the measured travel times are computed. These time differences, also called residual times, are the key to improve the velocity model in the consecutive iterations until the desired accuracy is achieved.

In Alto Ceira II dam's foundation, crosshole seismic tomography tests were carried out for 7 adjacent sections defined by the already mentioned 8 vertical boreholes along the foundation reference line (see Figure 2). These boreholes have lengths between 16.8 and 31 m and they are apart each other of about 15 m.

Test boreholes were steel cased, sealed at the bottom and filled with water, in order to carry out the seismic crosshole tests. Electrical detonation caps were used as seismic sources each meter, and, as receivers, two multi-channel cables, having 24 hydrophones moulded in with 2 m spacing. Data acquisition was in general performed simultaneously in two adjacent sections, with source in the centre borehole and each hydrophones cable on the lateral ones. In order to reach a mesh of 1 m x 1 m of source and receiver, after a first series of detonations with one meter spacing, the cables were raised one meter and a second series of detonations was performed each meter.

During Phase 1 only a small part of the drainage gallery floor was built and construction work was on progress (see Figure 1) causing some noise on the records. Between Phases 1 and 2 borehole FE8 position was shifted which caused a slightly different tomographic profile (see Figure 2).

Results

All 7 crosshole sections were jointly processed and inverted for a unique tomographic planned profile. This profile was discretized with 1 m side square cells grid used for the tomographic inversion.

In the colour scale used for the tomographic images present on Figure 2 the red colour was attributed to the lowest velocity values in order to highlight the massif zones which probably have relative lower mechanical quality than the remain rock mass. The main geological discontinuities identified during geological-geotechnical survey (EDP 2011) were depicted over the tomographic images. It can be seen that the areas where more discontinuities occur, mainly on left and right banks, are those that present the lowest seismic wave velocity.

Time-lapse seismic tomography between Phase 2 and Phase 1 allowed verifying a Vp increase on the lowest velocity zones, as expected, confirming the effectiveness of the rock mass foundation treatment. Time-lapse seismic tomography between Phase 3 and Phase 2, regarding the influence of the reservoir first filing, allowed identifying only small variations on seismic wave velocity ($-10\% < \Delta Vp < +10\%$) which indicates that no significant rock mass degradation occurred on the consequence of the first filling.

Conclusions

In summary, this case study illustrates that time-lapse seismic tomography proves to be a valid complementary tool to evaluate the improvement of rock mass mechanical properties after its treatment. Moreover it provides a continuous image of the rock mass dam foundation in opposition to discrete measurements obtained from other methods.

This method may also be considered as a management tool to monitor the rock mass behaviour along the dam's working lifetime. Their results can additionally be used to calibrate the mechanical parameters for the modelling of the dam's structural behaviour.

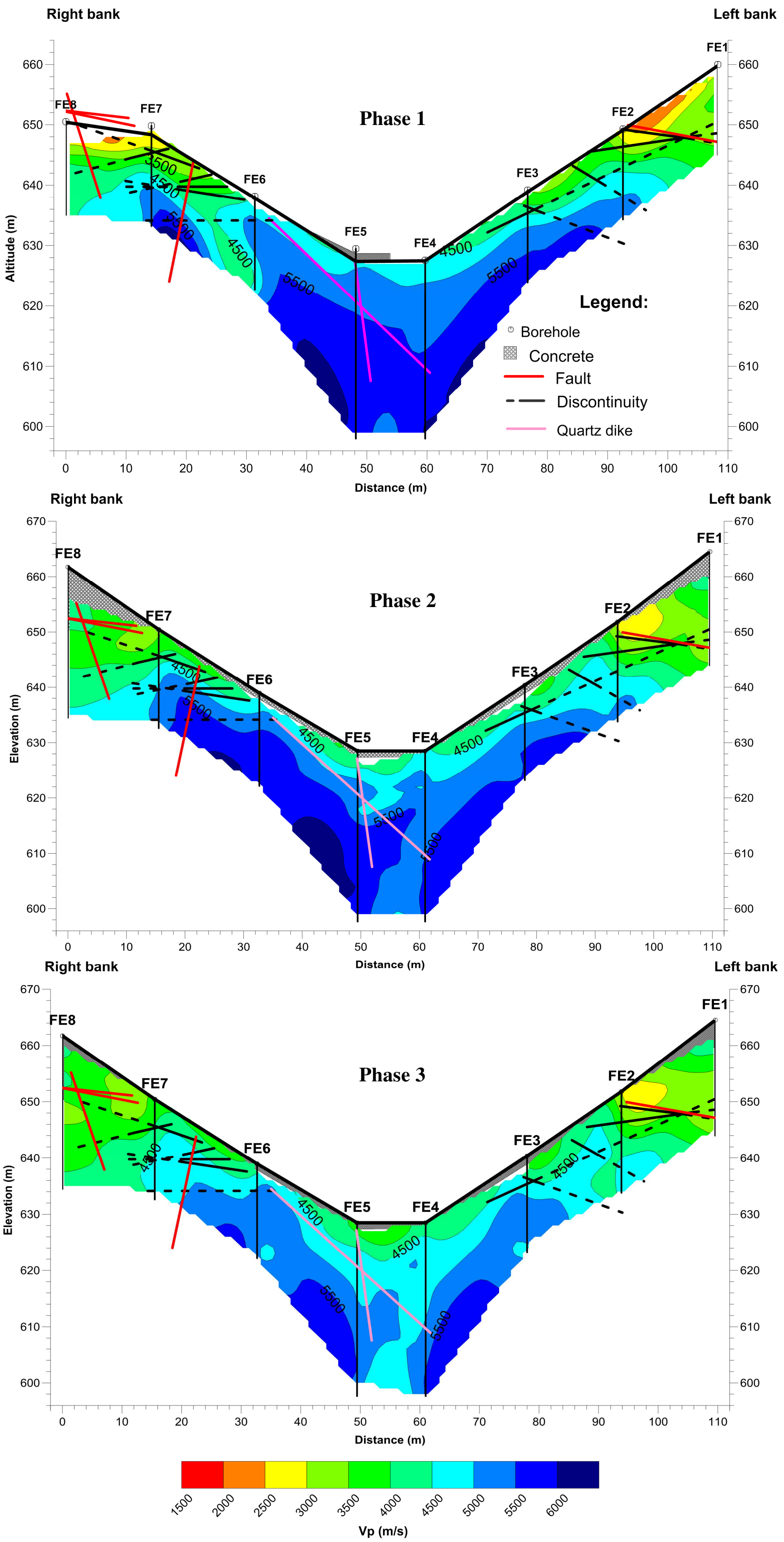

Figure 2: *Seismic tomographies obtained in each Phase (adapted from Mota 2012, 2013 and 2014).*

Acknowledgements

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References

Barton, N. [2007] *Rock Quality, Seismic Velocity, Attenuation and Anisotropy*. Taylor & Francis/Balkema.

Butchibabu, B., Sandeep, N., Sivaram, Y.V., Jha, P.C. and Khan, P.K. [2017] Bridge pier foundation evaluation using cross-hole seismic tomographic imaging, *Journal of Applied Geoph.*, **144**, 104-114.

Coelho, M.J., Salgado, F.M. and Fialho-Rodrigues, L. [2004] The role of crosshole seismic tomography for site characterization and grout injection evaluation on Carmo convent foundations, *ISC'2, 2nd Int. Conf. on Site Charact.,* Viana da Fonseca and Mayne (eds.), Porto, Vol. 1, 443-449.

Coelho, M.J., Mota, R., Morgado, A. and Neves, J. [2018] Time-lapse crosshole seismic tomography for characterisation and treatment evaluation of the Ribeiradio dam rock mass foundation, Submitted to *NUMGE 2018 - 9th European Conf. on Numerical Methods in Geotechnical Engineering*, Porto.

EDP [2011] Geological-geotechnical profile through the reference line (PRT201102911.pdf file).

Lehmann, B. [2007] *Seismic traveltime tomography for engineering and exploration applications*, EAGE, Houten.

Mota, R. [2012] Seismic tomography of the New Alto Ceira dam's foundation. Phase 1 (before treatment). (in Portuguese) Report LNEC 81/2012, Lisboa.

Mota, R. [2013] Seismic tomography of the New Alto Ceira dam's foundation. Phase 2 (after treatment). (in Portuguese) Report LNEC 81/2013, Lisboa.

Mota, R. [2014] Seismic tomography of the New Alto Ceira dam's foundation. Phase 3 (after the first filling of the reservoir). (in Portuguese) Report LNEC 276/2014, Lisboa.

Mota, R., Neves, J. and Monteiro dos Santos, F.A. [2015] Geophysical methods applied to the assessment of the geological and geotechnical conditions of dam sites: the case study of Pedrógão dam (Portugal), *Dam World 2015 – Second International Dam World Conference*, Lisbon, Portugal.

Mota, R. [2017] Seismic tomographies at the foundation pillars of the railway bridge over Tua river. Pillars 2, 3 and 4 (after river bed bedrock blasting). (in Portuguese) Report LNEC 21/2017, Lisboa.

Mota, R., Coelho, M.J., Piteira Gomes, J., Batista, A.L., Neves, J., Lima, C. and Silva Matos, D. [2018] Rock mass foundation seismic tomography and its contribution for the modelling of Baixo Sabor dam's structural behaviour, Submitted to *Dam World 2018 – Third International Dam World Conference*, Foz do Iguaçu, Brazil.

Oliveira, M. and Coelho, M.J. [2004] Decomposed rock mass characterization with crosshole seismic tomography at the Heroísmo station site (Porto). *ISC'2, 2nd International Conference on Site Characterization,* A. Viana da Fonseca and P.W. Mayne (eds.), Porto, Vol. 1, 531-538.

Pessoa, J.M.N.C. [1990] *Application of tomographic techniques to crosshole seismic exploration*, (in Portuguese), Monography, Public examination for Assistant Professor, Aveiro, Aveiro University.