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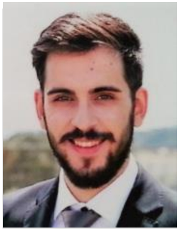
SEISMIC ANALYSIS OF CABRIL DAM. MEASURED RESPONSE AND COMPARISON WITH NUMERICAL RESULTS FROM CODE_ASTER AND DAMDYSSA



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ABSTRACT

This paper presents a study on the seismic response of the 132 m high Cabril arch dam, for an earthquake measured in-situ with the installed Seismic and Structural Health Monitoring system (in operation since 2008). The measured acceleration time histories are compared with results from finite element analysis in various positions in the dam body, using the seismic accelerations recorded at the dam-rock interface as inputs. The numerical simulations are conducted using two programs: i) *DamDySSA4.0*, a 3D finite element program develop in LNEC for dynamic analysis of arch dams – the dam-reservoir-foundation system is simulated based on a coupled model, using a formulation in displacements and pressures, considering the substructure method to simulate the foundation; and ii) *Code_Aster*, a finite element program developed in EDF – dam-water interaction is considered based on the potential fluid approach and the mass of the foundation is taken into account with absorption of the waves radiating from the dam by viscous-spring boundaries around the foundation. The investigation is focused on the required damping ratios, in the dam and foundation, to fit the computed results to the measured response, which is a key aspect to consider in arch dam seismic analysis.

Keywords: Cabril arch dam, Seismic monitoring, FE seismic analysis, Damping, Substructure foundation method, Energy dissipating foundation.

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1. INTRODUCTION

Large concrete dams are civil engineering structures of great importance for the management of water resources, by contributing decisively to water supply, energy production, irrigation and flood control, especially in recent times because of climate change. These dams are associated with a high potential risk [1], and according to the International Commission on Large Dams (ICOLD) it is fundamental to assess their structural safety for static and dynamic loads, particularly for dams located in seismic regions. With that aim, systems for Seismic and Structural Health Monitoring (SSHM) have been installed in new large dams, to evaluate their performance since the first filling of the reservoir, and for older dams, built several decades ago, with possible deterioration problems [2,3].

Regarding the numerical modelling of the dynamic behaviour of dam-reservoir-foundation systems, it is common the use of formulations based on the Finite Element Method [4]. For simulating the reservoir and dam-water interaction, there is the classic added water mass model, formulated in displacements, which use Westergaard's solution [5] and proportional Rayleigh damping. However, these present some limitations and require the use of an added mass reduction factor for dynamic analysis [6,7]. Alternatively, there are the coupled models with non-proportional damping, formulated in displacements and pressures [8,9] or velocity potentials [10], which enable to consider the dynamic dam-water motion coupling and the propagation of pressure waves in water (radiation damping).

For the foundation modelling, several methods can be used. The simplest is the massless approach [11], which considers foundation flexibly but does not account for dam-foundation interaction, with uniform seismic inputs at the foundation boundaries. Then, the substructure method [12] simulate the foundation as an elastic substructure, considering stiffness and damping components at the dam-rock interface, and uniform seismic inputs uniformly distributed at the dam base. In alternative, the foundation can be partially modelled with viscous spring boundaries [13,14] to considering dam-foundation interaction and radiation damping in the rock mass, while the seismic input is introduced as compression and shear waves, vertically propagating from the base of the foundation (ground motion spatial variation) [15,16].

Currently, the safety control of dams tends to be supported by SSHM systems, to measure the dynamic response of dams over time, under ambient/operational vibrations and during seismic events, and sophisticated FE models, to simulate the dynamic behaviour of the dam-reservoir-foundation system (Fig. 1). For seismic response analysis, the combined use of measured response and numerical results can provide high value data for studying the behaviour of arch dams [2,3,14,17-21], under low, medium or high intensity earthquakes, based on the acceleration records in the dam body, along the dam-rock interface, and possibly in the free-field. This enables further investigations to be conducted regarding important questions in this field, including dam-reservoir interaction, water level effects, foundation behaviour, seismic input modelling and damping under seismic ground motion. Additionally, quality seismic monitoring data can be useful to calibrate/validate and improve the developed numerical models or help in the development of new ones.

To contribute for knowledge in this field, a study on the seismic response of Cabril arch dam is presented, by comparing acceleration records and results from FE analysis. Therefore, two different models that consider dam-reservoir interaction are used to simulate the dynamic behaviour of the dam-reservoir-foundation system, namely with energy dissipating foundation (*Code_Aster)* and substructure foundation method (*DamDySSA).* The required damping ratios in the dam and foundation to fit the computed results to the acceleration records is investigated.

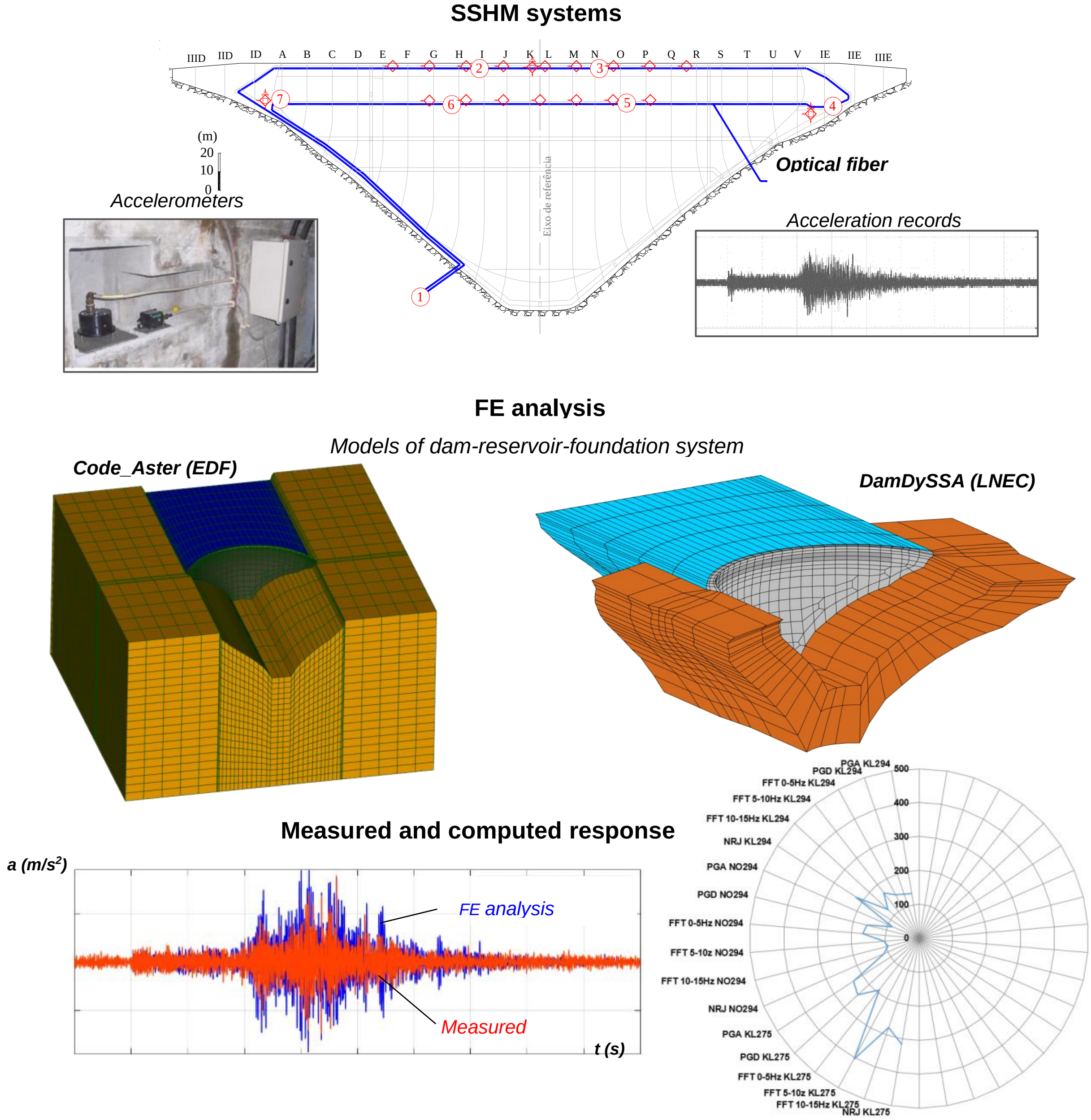


Fig. 1 – Safety control for large concrete dams. SSHM systems with FE models.

2. CABRIL DAM AND THE SSHM SYSTEM

Cabril dam (Fig. 2), the highest dam in Portugal, has been in operation since 1954 on the Zêzere river. It is a 132 m high double curvature arch dam, founded on a granite mass rock foundation of good quality. The crest is at el. 297 m and has a 290 m long arch. The dam has a maximum width of 20 m at the base, in the central cantilever, and a minimum of 4.5 m at el. 290 m, 7 m below the crest, which has a greater width. A horizontal cracking phenomenon was detected at the upper part of the structure, around el. 280-290 m, during the first filling of the reservoir, and concrete internal swelling phenomena were detected in the late 90's. Nevertheless, recent health monitoring studies enabled to conclude that structural behaviour is normal [2,3]. The water level usually ranges from a minimum at el. 265 m to the maximum storage level at el. 295 m. A reinforced concrete intake tower, with the same height of the dam, was built near the upstream face, and it is connected to the central cantilever at the crest level via a concrete walkway, with a joint in the contact surface.

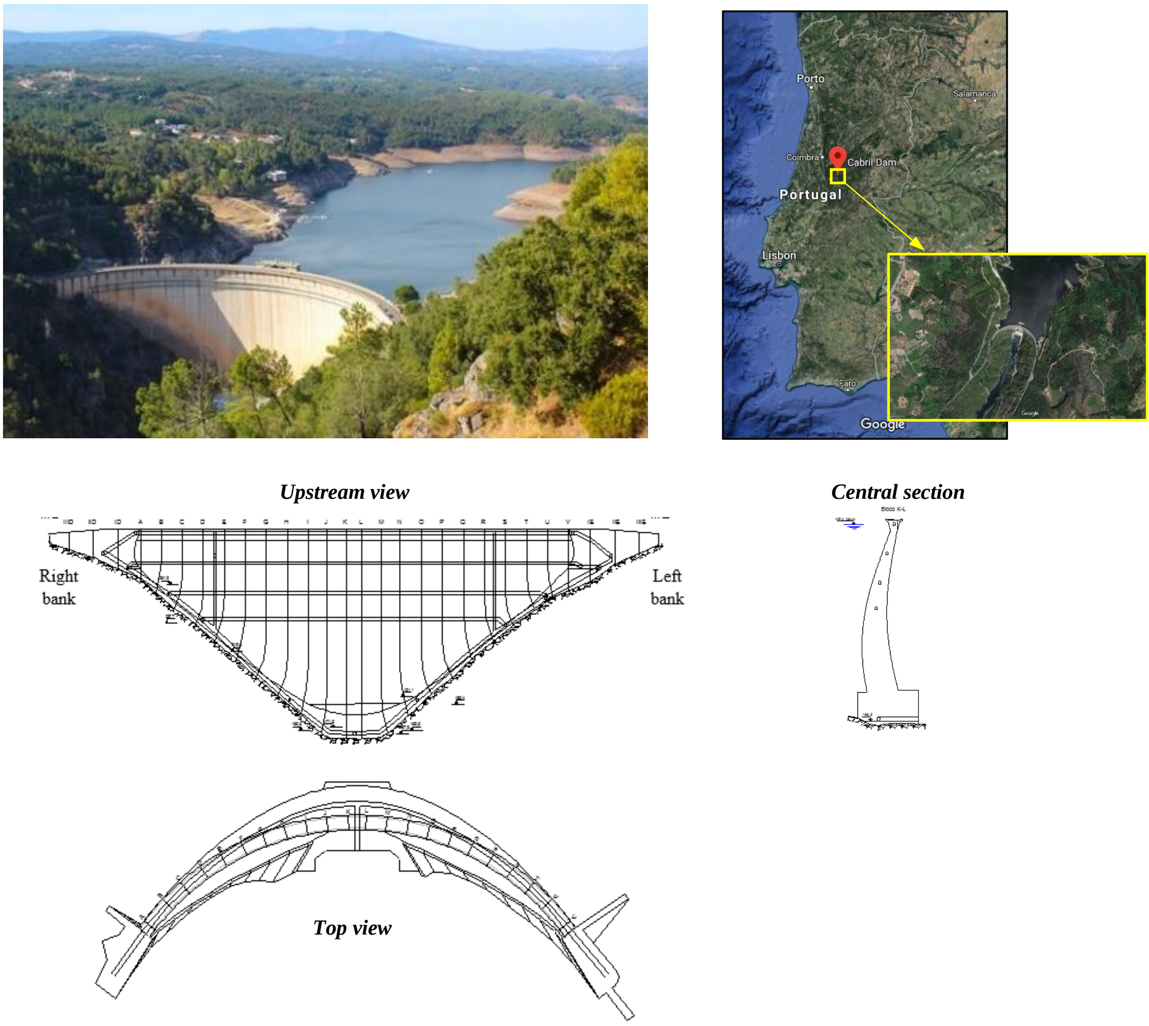
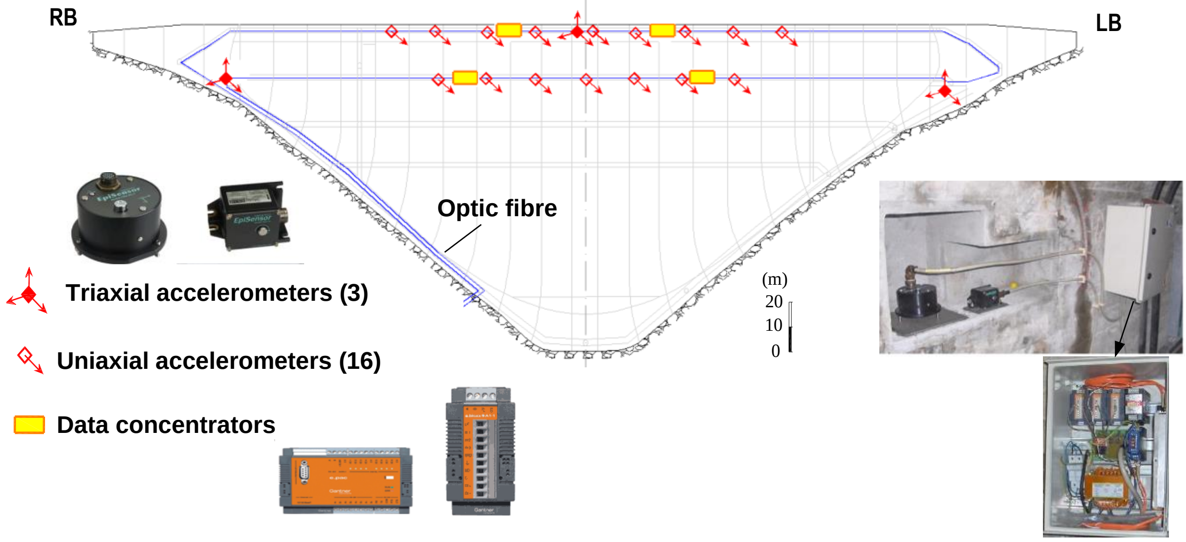


Fig. 2 – Cabril arch dam (132 m high). Upstream view, central cantilever and top view.

In Portugal, the SSHM of large concrete dams started in 2008 with the installation of a pioneer system for continuously monitoring the dynamic behaviour of Cabril dam over time, under ambient/operational vibrations, and to measure the response during seismic events [2] (Fig. 3).

Seismic and Structural Health Monitoring system in Cabril dam



Software developed in LNEC for monitoring data analysis

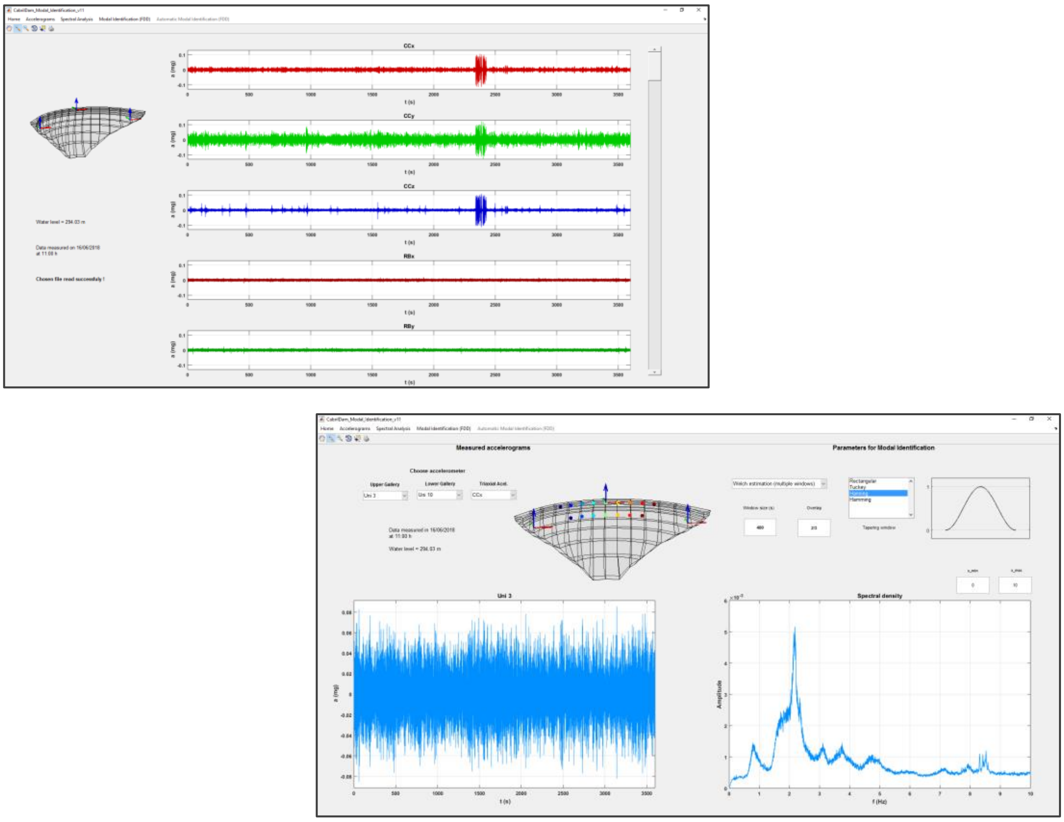


Fig. 3 – Cabril dam. SSHM monitoring system. Hardware components and developed software.

The monitoring scheme was developed in the scope of a research program supported by the Portuguese Foundation for Science and Technology (FCT) and by Energias de Portugal (EDP). The aim was to implement a system with high dynamic range, capable of accurately measuring the dam's response in normal operation conditions and during low/medium or high intensity earthquakes. Therefore, it was designed for continuously recording accelerations at the upper part of the dam body and at the dam-rock interface, using 16 uniaxial (EpiSensor ES-U2) and 3 triaxial (EpiSensor ES-T) force balance accelerometers from Kinemetrics Inc (www.kmi.com): 25 accelerograms are recorded and stored every hour (in 24 bit), at a sampling rate of 1000 Hz. The uniaxial sensors, to measure vibrations in the radial direction with a full-scale recording range of ± 0.25g, are located at the upper part of the dam in two galleries, above and below the cracked zone. Regarding the triaxial sensors, with a recording range of ± 1g, one is positioned in the upper gallery, central cantilever, while the other two are in the gallery close to the foundation, in both banks. All accelerometers are connected to a modular system composed by acquisition/digitalization units, which are controlled by 4 data concentrators that receive the data records. This data is sent through a local optical fibre network to a server in the offices at the dam's power station.

Specific software has been developed in LNEC to analyse data collected with continuous SSHM systems. This software includes modules for automatic modal identification, using frequency domain methods, and automatic earthquake detection, based on maxima and pattern analysis, enabling daily emails with data summaries and seismic alert emails to be sent to owners and/or engineers responsible for safety control. The obtained experimental results have been of great value to study the measured dynamic response of Cabril dam and to conduct comparative studies with results from FE analysis [2,3].

3. USED SOFTWARE FOR FE ANALYSIS: *DamDySSA AND CODE_ASTER*

3.1. *DamDySSA*

First, the seismic simulations were carried out using *DamDySSA4.0,* a 3D FE program developed in LNEC for dynamic analysis of arch dams (Fig. 6). The dynamic behaviour of the dam-reservoir-foundation system is simulated using a coupled formulation in displacements (solid domain) and pressures (fluid domain), considering the dynamic dam-reservoir interaction, the pressure waves propagation in water and the free surface condition [4,8]. The substructure method [12] is used to compute the foundation block as an elastic, massless substructure, and hence the seismic input is applied at the dam base and is uniformly distributed. Therefore, the dynamic analysis is performed only for the dam-reservoir system. Rayleigh damping is calculated element by element in the solid domain, while radiation damping due to propagation of pressures waves in water is simulated in the reservoir.

The dynamic response of the coupled system with generalized damping under seismic forces is calculated using a new time-stepping procedure for numerical integration, based on the Newmark method. For seismic analysis under low/medium intensity earthquakes, as intended in this study, linear-elastic behaviour is considered for concrete and joints (vertical contraction joints, dam-rock interface and existing cracks).

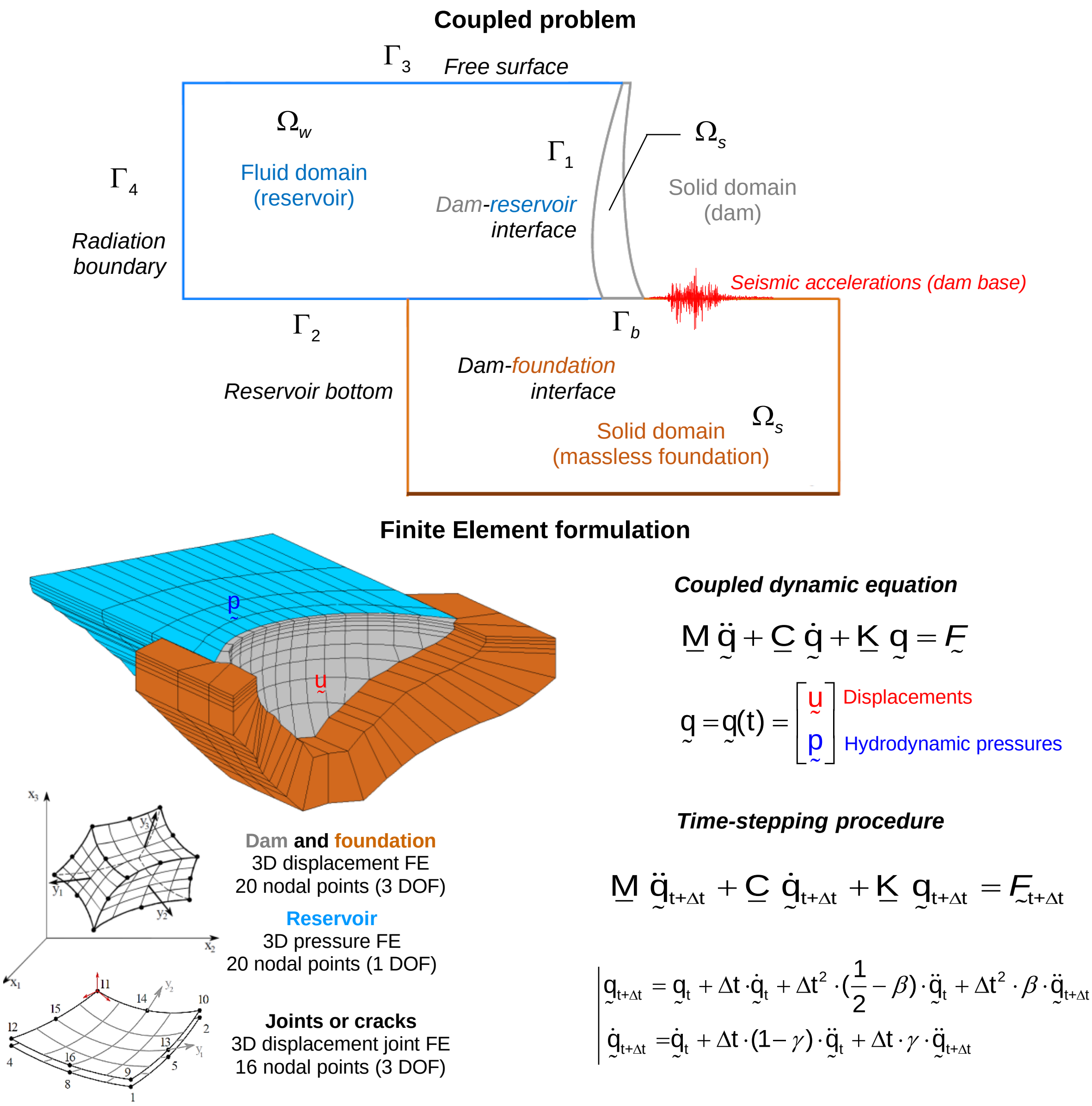


Fig. 4 – *DamDySSA*. Coupled problem, FE formulation and 3DFE mesh.

In this work, the 3D FE model of the dam-reservoir-foundation system presented in Fig.7, which has been previously calibrated/validated based on experimental data [2,3], is used. The dam concrete and the foundation rock are isotropic materials, considering Young's modulus E = 25 GPa and Poisson's ratio v = 0.2. For dynamic analysis, the relation E_{dyn} = 1.3 × E is assumed. The water is an inviscid and compressible fluid with a fluid velocity c_w = 1440 m/s. The reservoir level is chosen as input in the data file. A Rayleigh law with α = 2 and β = 0.006

is used for all dam elements, resulting in a damping ratio of about 10% around frequency band from 2 to 3 Hz (first vibration modes). In the foundation, a damping matrix proportional to the stiffness matrix is computed, to get around 20% in the same frequencies. These high values were required to fit computed and measured seismic response.

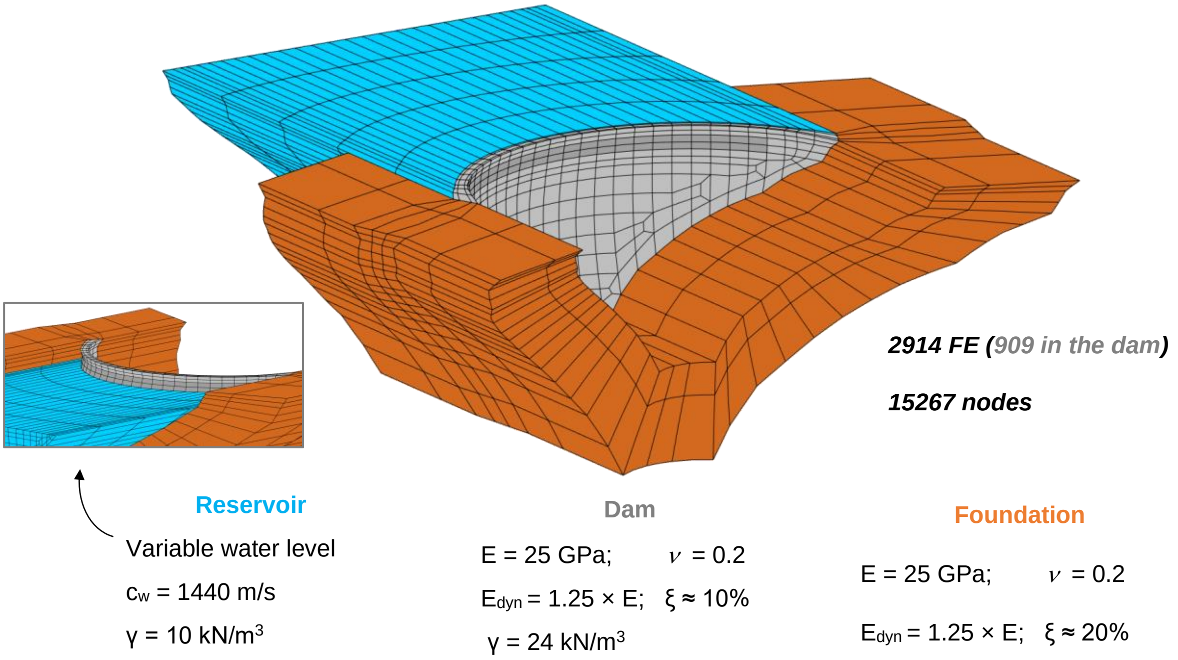


Fig. 5 – *DamDySSA*. 3DFE model of dam-reservoir-foundation system and material properties used for FE analysis of Cabril dam.

3.2. *Code_Aster*

In order to provide another source of comparison, additional analyses are performed with the open-source software *Code_Aster* (www.code_aster.org), developed by EDF. Similar analyses have been carried out to compare computed and recorded dam's response under earthquake [14,17].

In *Code_Aster*, a viscous spring boundary model around the foundation is implemented as proposed and well described in [14,17] and briefly summarized in Fig. 5. It is employed to absorb the wave energy radiating away from the dam and the foundation. In this method, earthquake input is introduced as compression and shear waves, vertically propagating from the bottom to the top of the foundation. The mass of the foundation is considered. Side boundaries should not be neglected using free-field column providing the propagation of the wave in an unbounded foundation. Fluid-structure interaction is similar to what has been described previously with fluid elements for *DamDySSA*, with radiation boundary at the end the channel and fluid-structure interaction between the dam and the reservoir. In addition, fluid-structure interaction is also considered between the reservoir and the foundation.

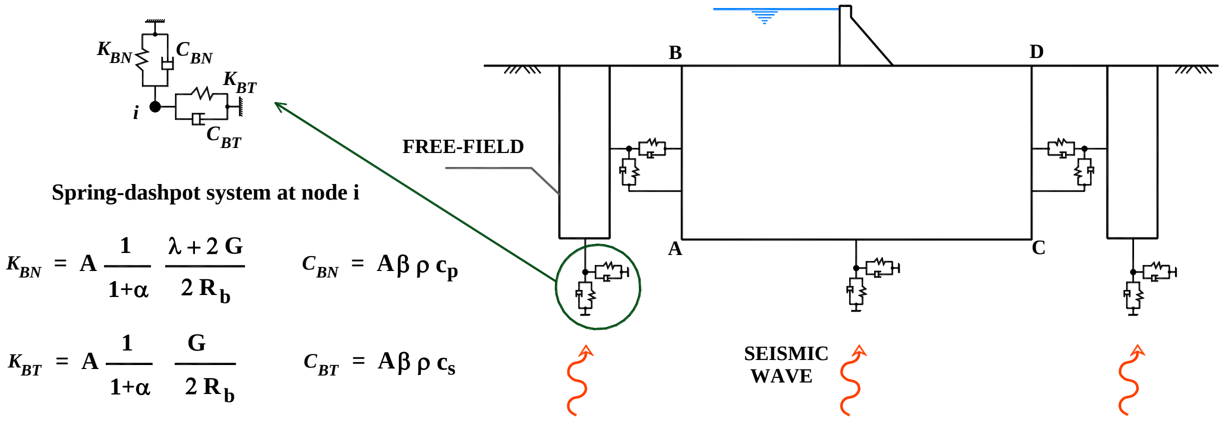


Fig. 6 – *Code_Aster.* Viscous spring boundaries model for the foundation.

In order to use this method, a new mesh of the foundation is realized (Fig. 6), while the mesh of the dam itself remains as described in the previous chapter for the model used in *DamDySSA*. Concerning the dam and foundation material properties, the same values presented in the previous chapter are considered (see Fig. 5). There is no damping in the foundation except the radiative damping due to the absorbing boundaries. A Rayleigh damping is considered for concrete with α = 0.0036 and β = 5.57. Such values provide 20% of damping at the natural frequency and 15 Hz, but a lower value for intermediate frequencies (15% between 4 and 9 Hz). Such high values of damping, needed to roughly reproduce the dam's response, are not usual (usually values between 1-3% are considered for concrete).

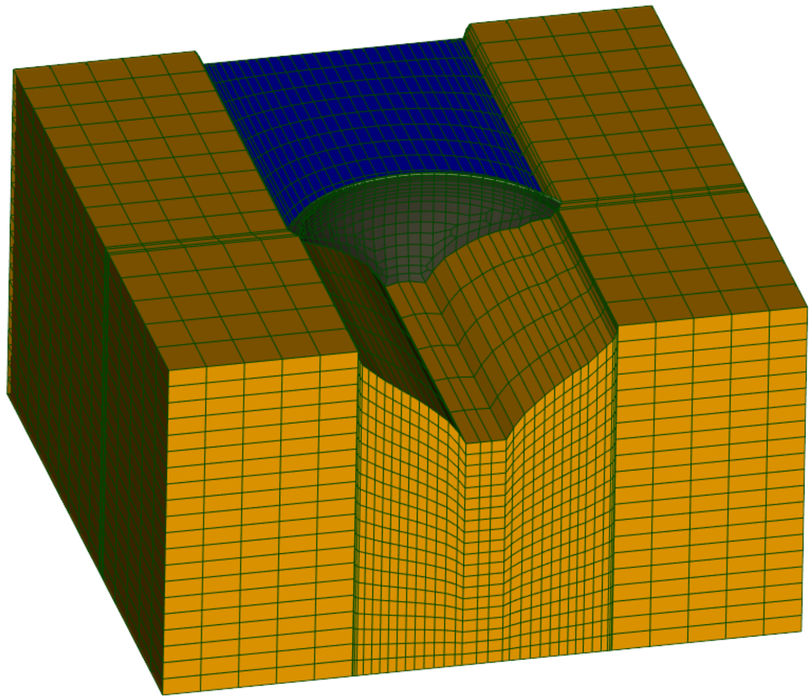


Fig. 7 – *Code_Aster.* Mesh of dam-water-foundation system for analysis of Cabril dam.

4. SEISMIC RESPONSE OF CABRIL

The SSHM system installed in Cabril dam and the respective software have made it possible to automatically record accelerations and detect earthquake events, thus enabling to study the seismic response from measured accelerations in the dam and near the dam-rock interface. This paper presents a comparison between recorded and computed seismic response.

4.1. Recorded seismic event

On September 4, 2018, Cabril dam experienced a M 4.6 earthquake with epicentre at 200 km from the dam, in the Peniche abyssal region. The water level was at el. 281.2 m, 15.8 m below the crest level. The acceleration time histories recorded with the right bank triaxial sensor (RB_{xyz}), near the dam-rock interface, are shown in Fig. 8. The peak accelerations were 2.16 mg (0.0212 m/s^2) in the cross-valley (cv) direction, 1.39 mg (0.0136 m/s^2) in the upstream-downstream (us/ds) direction and 1.23 mg (0,012 m/s^2) in the vertical (vert) direction.

Earthquake (M 4.6) on September 4, 2018

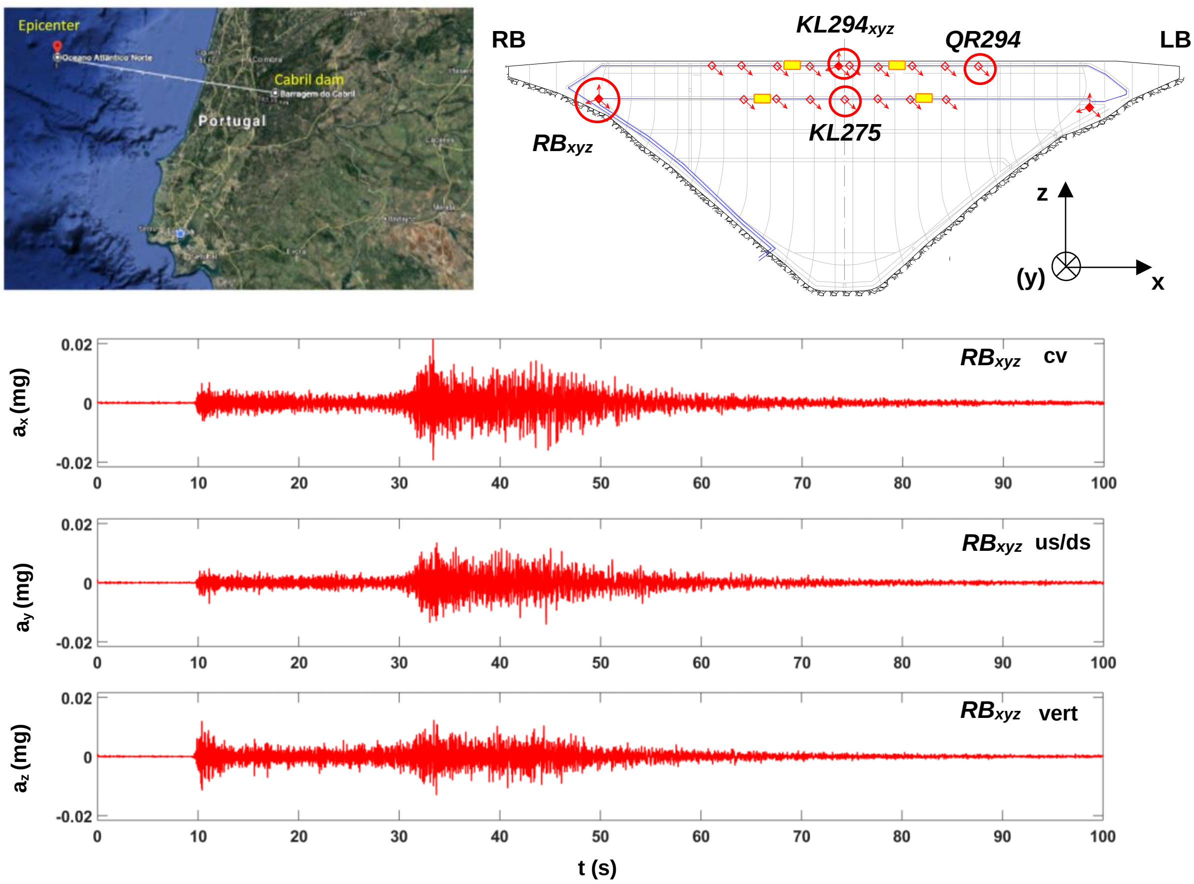


Fig. 8 – Measured earthquake in Cabril dam on September 4, 2018. Seismic acceleration records at the dam-rock interface (RBxyz).

The dam's response was recorded on all accelerometers located on the dam (see Figs. 3 and 8). In this paper, the measured acceleration time series are compared with the results from FE analysis, namely for: i) the triaxial accelerometer RB_{xyz}, in the three directions (cv, us/ds, vert), to evaluate the introduction of the input in the analysis; ii) the triaxial accelerometer $KL294_{xyz}$, located on the central section at the upper gallery, in the three directions (cv, us/ds, vert); iii) the uniaxial accelerometer QR294, located to the left side at the upper gallery, in the radial direction; and iv) the uniaxial accelerometer KL275, located on the central cantilever at the lower gallery, in the upstream-downstream direction.

Regarding the measured response, the peak acceleration, 3.59 mg (0.035 m/s^2), was recorded at the top of the central cantilever with $KL294_{xyz}$, in the upstream-downstream direction. Compared to the peak acceleration near the abutment in this direction (2.16 mg), the amplification ratio is surprisingly low (2.5). The same conclusion can be made in the other directions with amplification ratio of 0.6 in the cross-stream and 1.0 in the vertical directions. For example, in the case of 90m high Monticello arch dam [17], peak acceleration ratio between the crest and the abutment are 3.8, 2.2 and 2.4 respectively in the us/ds, cross-valley and vertical directions for a small earthquake with a peak ground acceleration of approximately 0.01g.

Such low amplifications ratio between the crest and the abutment raise questions about the particular behaviour of this dam that will need to be investigated in the future. This also explain the need to use high damping value in the analyses to fit the records.

4.2. Measured and computed results

The comparison between the measured response of Cabril dam and the results computed with *DamDySSA* and *Code_Aster* is presented in this chapter. The analysis is focused on several aspects, including the acceleration and displacement time histories and the acceleration spectrum for the accelerometers mentioned above.

The comparison with the FE results obtained with *DamDySSA* is presented in Fig. 9. The FE seismic analysis was carried out considering the model reservoir level at el. 280 m (close to the real water level) and using the seismic accelerograms recorded with RB_{xyz} as inputs, applied at the dam base. As expected, the computed response at the RB_{xyz} location has an excellent agreement with the measured response. Also, the comparative study shows a very reasonable agreement between recorded and computed acceleration time histories for the upstream-downstream component of $KL294_{xyz}$ and for both uniaxial accelerometers QR294 and KL275 (radial direction). However, the cross-valley and vertical components at the top of the central section are still overestimated in the FE analysis, even with damping ratios of 10% in the dam and 20% in the foundation.

Comparison between measured and computed response (*DamDySSA)*

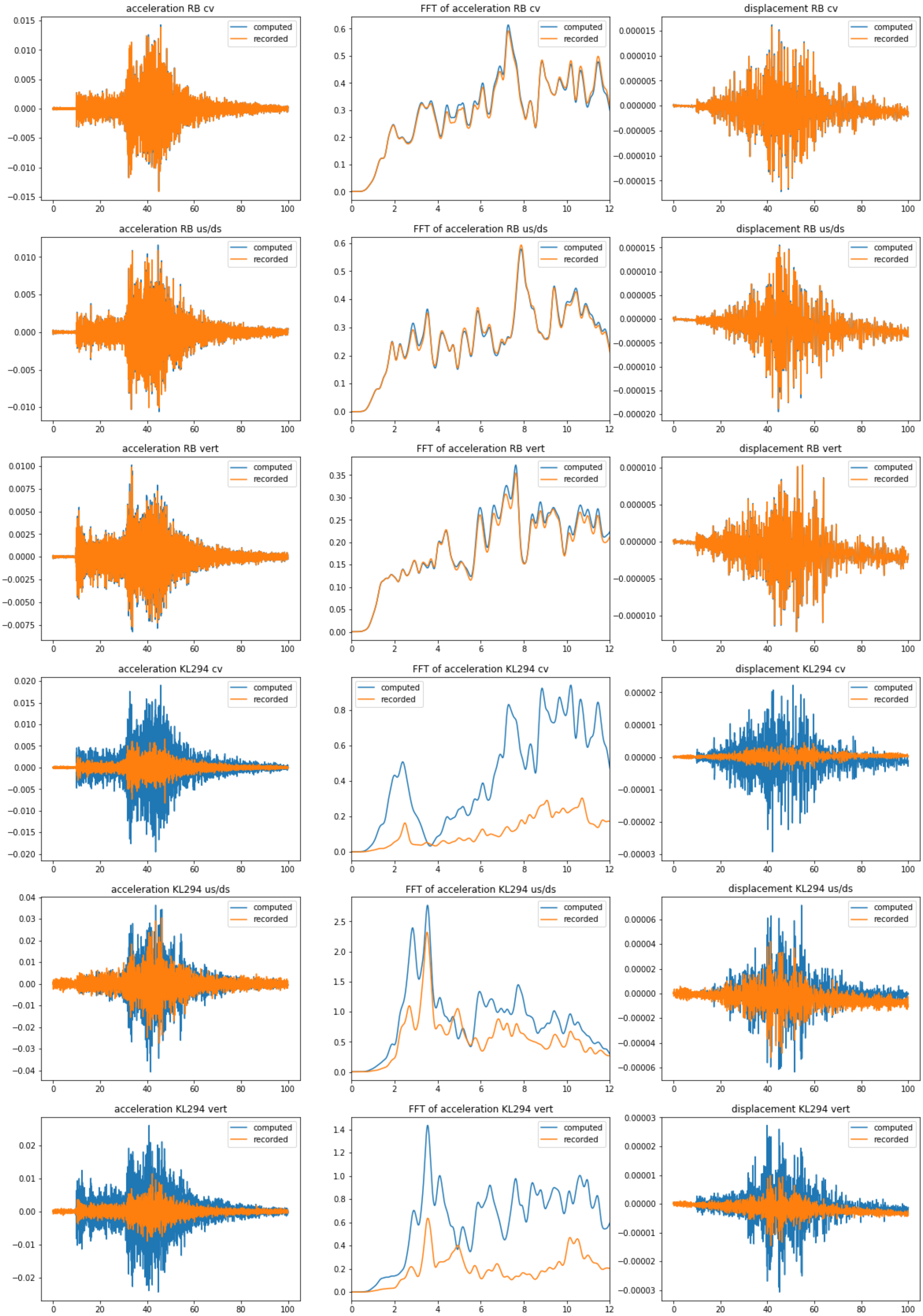


Fig. 9 - Cabril dam. Recorded and computed seismic accelerations (*DamDySSA).*

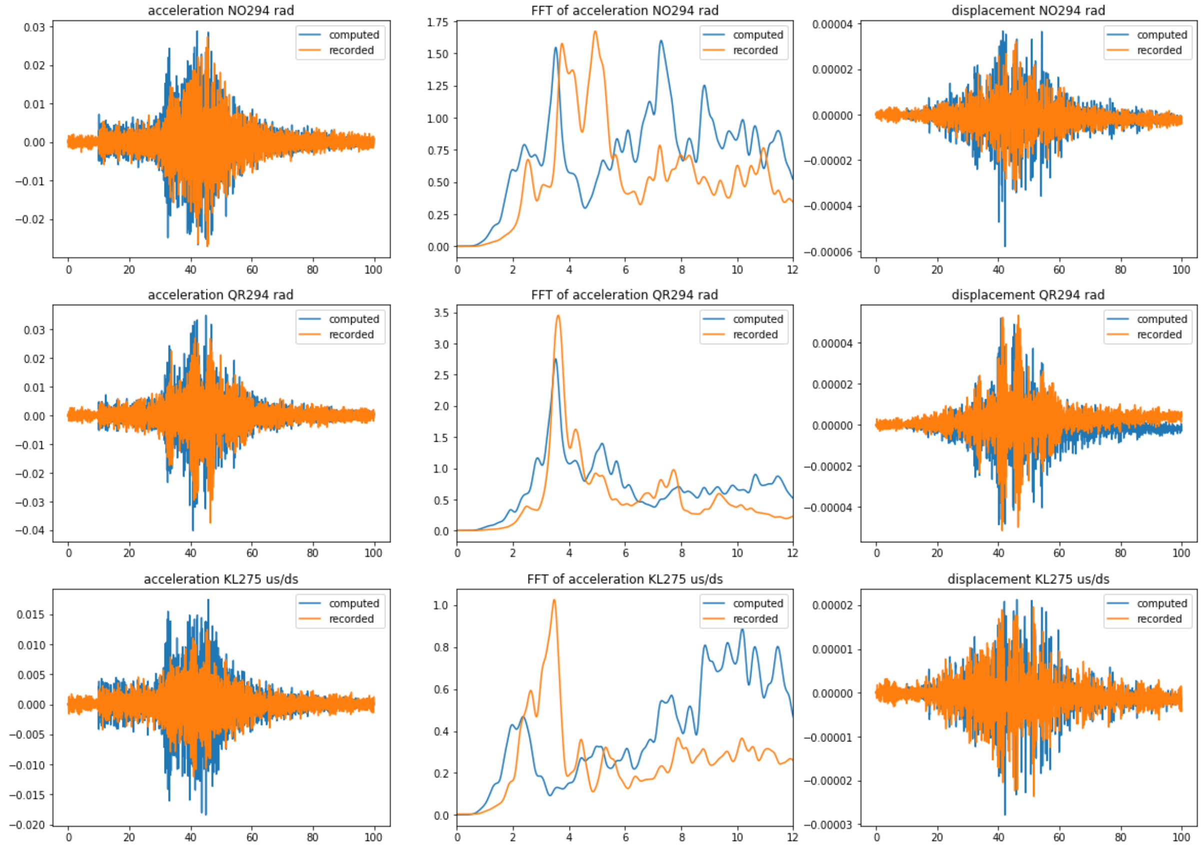


Fig. 9 (cont.) - Cabril dam. Recorded and computed seismic accelerations (*DamDySSA).*

The comparison between the recorded response and the results obtained with *Code_Aster* is presented in Fig. 10. In *Code_Aster*, the seismic input is introduced at the bottom of the foundation, vertically propagating. Therefore, considering that the chosen input (acceleration records from RB_{xyz}) cannot be considered as free-field, there is no surprise that the computed response at RB slightly differs from the recorded one. Even with an overestimated damping in the concrete, the computed response still overestimates measured response at the crest ($KL294_{xyz}$), particularly in the cross-valley and vertical direction.

Although high damping values are required to fit computed and measured response, in comparison with standard ratios used for seismic analysis of large dams, analogous conclusions have been drawn in other studies [3,14,17-20].

Comparison between measured and computed response (*Code_Aster)*

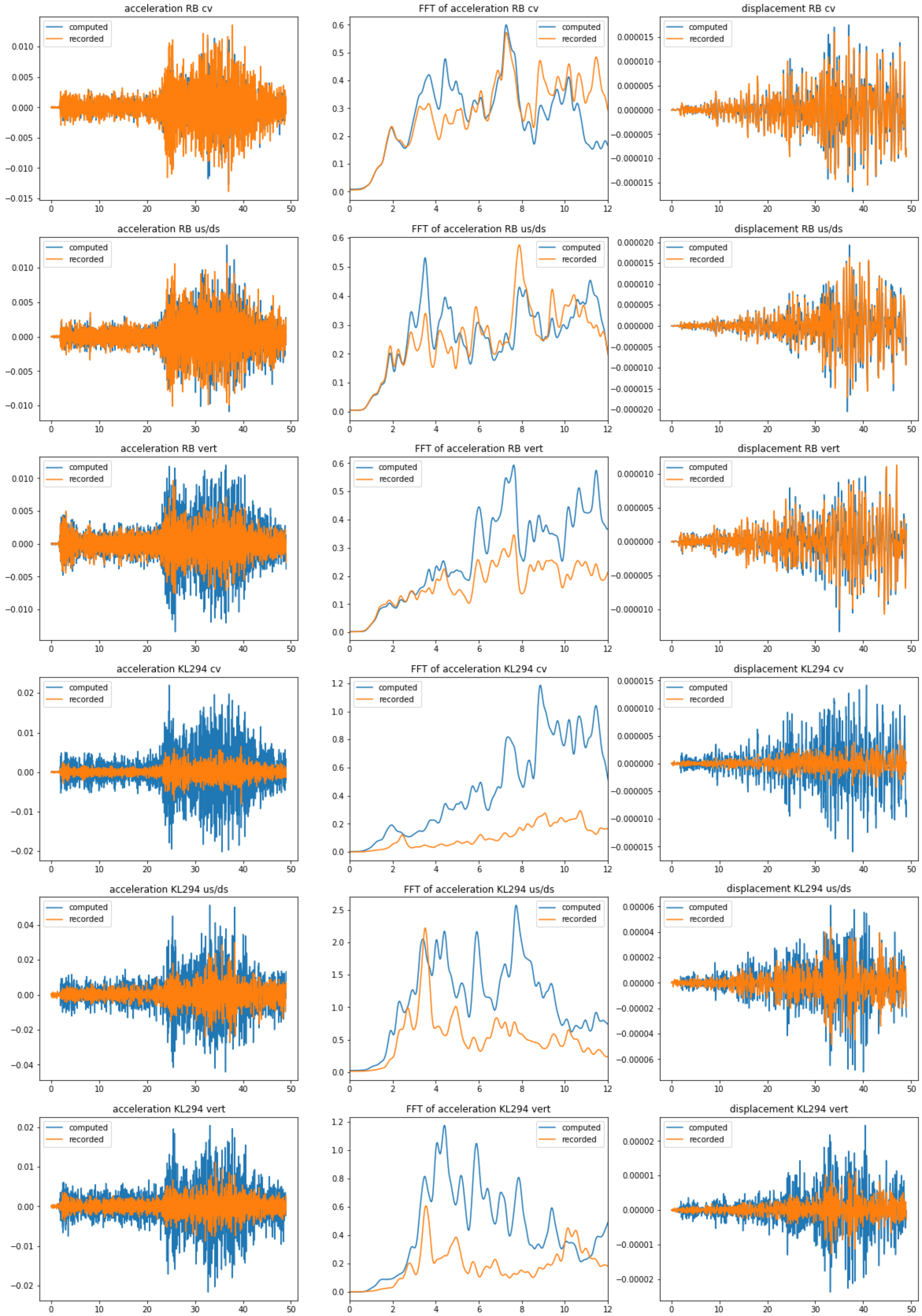


Fig. 10 - Cabril dam. Recorded and computed seismic accelerations (*Code_Aster).*

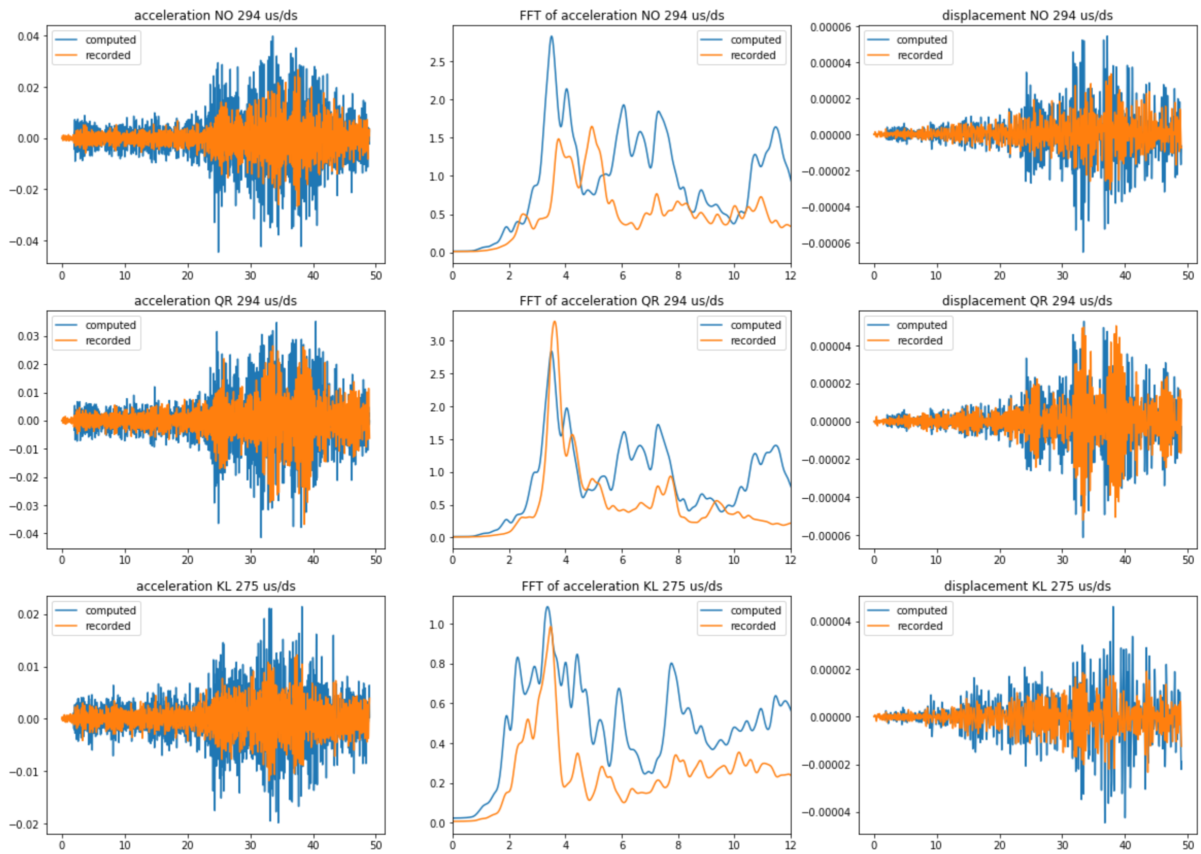


Fig. 10 (cont.) - Cabril dam. Recorded and computed seismic accelerations (*Code_Aster).*

Finally, a graphical tool (Fig. 11) that evaluates specific ratios between recorded and computed response is presented for the sensors RB_{xyz} and $KL294_{xyz}$. The peak accelerations, peak displacements, the acceleration spectrum in multiple frequency bands and the energy are shown in a circular chart for both comparison with *DamDySSA* and *Code_Aster.*

These results show that a very good agreement has been achieved between recorded and computed response for RB_{xyz}, while a reasonable comparison was obtained for $KL294_{xyz}$ in the upstream-downstream direction. However, the results from FE analysis are generally overestimated, particularly in the cross-valley and vertical directions of $KL294_{xyz}$, even when high damping ratios (over 10%) are used in the dam and foundation.

Also, it is possible to see that both approaches used in *DamDySSA and Code_Aster* for simulating the foundation lead to quite similar outcomes, which shows both models are appropriate for numerical modelling of dam-reservoir-foundation systems and for seismic analysis of arch dams. Nevertheless, additional analyses (not presented here) taking into account the existing crack at the upper part of the dam showed that it might have a strong influence on the results, even for low/medium amplitude earthquakes. More studies on this matter are required to investigate and confirm such assumption.

Within this scope, further investigation is required for large dams under low/medium and high amplitude earthquakes, particularly concerning the required damping ratios to fit numerical results to the measured response.

Measured response vs DamDySSA & Code_Aster

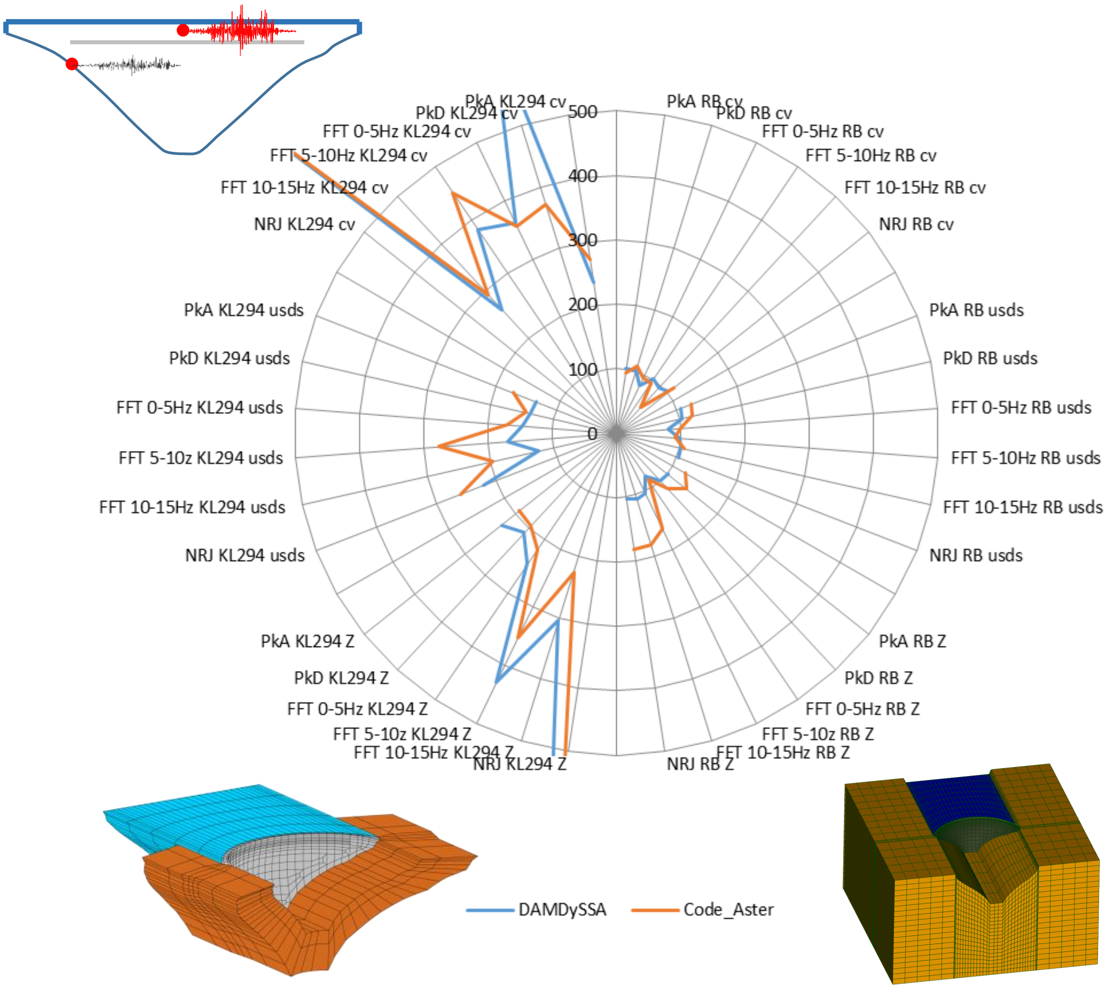


Fig. 11 – Comparison of measured and computed response (*Code*_Aster and *DamDySSA).*

5. CONCLUSIONS

A study on the seismic response of Cabril dam was presented in this paper, by comparing seismic monitoring results, namely measured accelerations during an earthquake event on September 4, 2018, and numerical results from FE analysis. The programs *DamDySSA* and *Code_Aster,* based on models that simulate the dam-water dynamic interaction, are used. *DamDySSA* simulates the foundation based on the substructure method, while *Code_Aster* considers the mass of the foundation and viscous spring boundaries.

By analysing the presented results, a reasonable comparison between measured and computed response was achieved with both programs using high damping values, except for the cross-valley and vertical components at the top of the central section. But peak acceleration ratio between the records at the crest and near the abutment shows surprisingly low ratios in these direction (lower than 1.0) that will need to be investigated further. Also, considering that the measured response near the dam-rock interface with sensor RB_{xyz} was used as seismic input in *DamDySSA*, the FE analysis enabled to reproduce better the measured response at that location. In *Code_Aster*, given the seismic input was introduced at the bottom of the foundation, vertically propagating, the computed response at RB_{xyz} slightly differs from the recorded one. Overall, although based on different models, *DamDySSA* and *Code_Aster* enabled to achieve similar results in this paper.

For the case of Cabril dam, additional analyses considering the effect of the existing crack at the upper part of the dam are required to investigate its influence on the seismic response, even for low/medium amplitude earthquakes.

In general, further investigations are required to study the damping ratios required to fit numerical results to the measured seismic response of large dams, under low/medium and high amplitude earthquakes.

This paper has also shown the value of using monitoring data from SSHM systems in large ands and numerical results from FE analysis to study the seismic behaviour of large concrete dams, aiming to better understand the measured response and investigate important factors in numerical modelling (e.g. dam-water interaction, foundation behaviour and damping).

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