Behaviour prediction of a concrete arch dam: Finite element modelling and models of separation of effects

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ABSTRACT: The double curvature arch dam, located in the south of France, proposed for the 16th International Benchmark Workshop on Numerical Analysis (theme A) was numerically studied using computational modules based on finite element technology developed by the authors for dam analysis. The dam behavior was also assessed with regression based separation of effects models (SEM), following a hydrostatic-seasonal-temperature approach, taking also into consideration the predictions obtained with the finite element analysis that was carried out. Given that the developed numerical modules adopt preferentially 2nd order 20 node brick elements, a new numerical model of the dam and its foundation was built from the geometry files given by the organizing committee. The developed finite element model considered the contraction joints and the dam/foundation interface. A thermal analysis was initially carried out, using a transient analysis model, followed by several mechanical analyses including the gravity load, the hydrostatic pressure and the temperature variations resulting from the thermal analysis. Different nonlinear models were considered at the dam/foundation interface and at the contraction joints, and two different contact interface approaches were adopted, hard and soft contact approach. Results of the sequentially coupled thermal/mechanical numerical analyses are presented and discussed. Finally, the results of the regression based SEM predictions models are also compared, and the relevance of using the finite element inputs in the SEM is discussed

1 INTRODUCTION

The double curvature arch dam, located in the south of France, was numerically studied using computational modules based on finite element (FE) technology developed by the authors for concrete dam analysis. The dam behavior was also assessed with regression based separation of effects prediction models (SEM) following a hydrostatic-seasonal-temperature approach, Wilm and Beaujoint (1967). In the adopted displacement prediction model, the results obtained with the finite element analysis that was carried out were incorporated in the SEM, Silva Gomes and Silva Matos (1985) and Rodrigues et al. (2021).

The thermal numerical analysis was carried out with the numerical module *PAT*, Schclar Leitão (2011) and Castilho et al. (2018) which adopts a transient analysis, including Dirichlet boundary conditions (concrete/water and foundation/water) and Robin boundary conditions (concrete/air and rock/air interfaces). The mechanical analysis was carried out with two different numerical models, the finite element module *Parmac3D*, Azevedo & Câmara (2015) which uses an explicit solution algorithm based on the central difference method and a dynamic relaxation algorithm for static convergence, and adopts a soft contact approach for the interface finite element models and a FE module, *PAVK*, Schclar Leitão (2021), that adopts a global matrix static solution approach using a Newton-Raphson algorithm for nonlinear solutions, following a hard contact approach with a high penalty stiffness value for the interface finite element elements.

Given that both mechanical numerical codes, *PAVK* and *Parmac3D*, use preferably 20-node 2nd order brick elements, a new finite element model of the dam and its foundation was built from the geometry files given by the organizing committee. The contraction joints and the dam/foundation interface were included in the developed model. Firstly, a thermal transient analysis was carried followed by the mechanical analysis, using sequential coupling. In the mechanical module (*PAVK)* an elastic interface model under compression and zero cohesion under tensile loading was adopted for the contraction joints and for the dam-foundation interface. In the mechanical module (*Parmac3D)* a Mohr-Coulomb constitutive model with zero tensile strength and zero cohesion was assigned to the interface elements representing the contraction joints. For the dam-foundation interface a brittle Mohr-Coulomb model with a non-zero tensile and cohesion stress value was adopted. The authors have also developed computational models for the hydromechanical model of dam foundations, Farinha et al. (2022), but due to time constraints it was decided not to perform an analysis of this type for the prediction of piezometric heads and seepage flowrates.

Results of the coupled thermal/mechanical numerical analyses are presented and discussed. Finally, the results of the regression-based SEM are also presented, and the relevance of using the FE inputs in the adopted SEM is discussed.

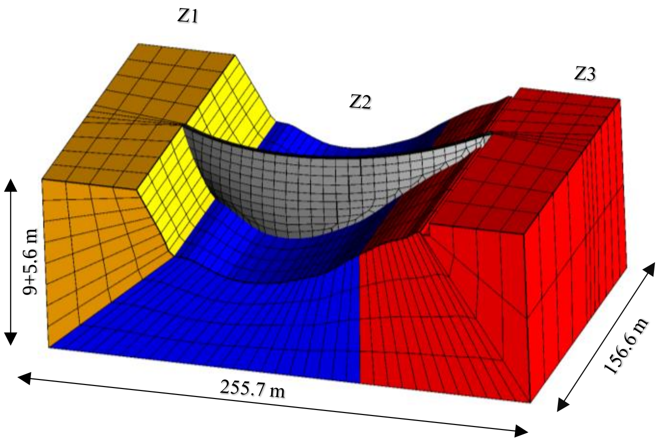
2 FINITE ELEMENT MODEL

2.1 *Model description*

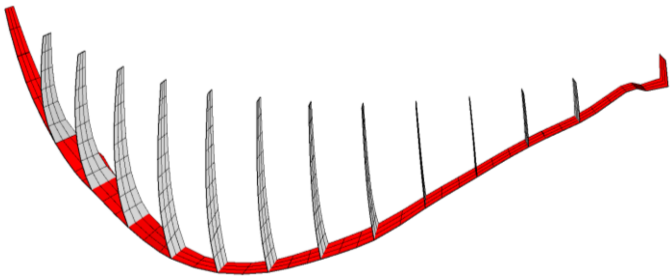
The material properties considered for both the thermal and the mechanical analyses follow closely the reference values defined in the benchmark. A thermal expansion of 1.0×10^{-5}/Cº was adopted for concrete, which is the usual value adopted in Portugal for dam concrete, Schclar Leitão (2021). Several mechanical parametric studies were carried out using different Young's modulus for the concrete dam and for the foundation, but it was decided to present only the results that adopted mechanical values close to those adopted in previous dam assessments, according to the benchmark organizers. In our point of view in order carry out a comprehensive numerical study it would be necessary to know the observed displacement field in more locations and to have more details regarding the dam concrete and its foundation. A linear elastic isotropic model was adopted for the foundation, given that the adopted mechanical modules do not have the ability to model an orthotropic material.

2.2 *Material properties and boundary conditions*

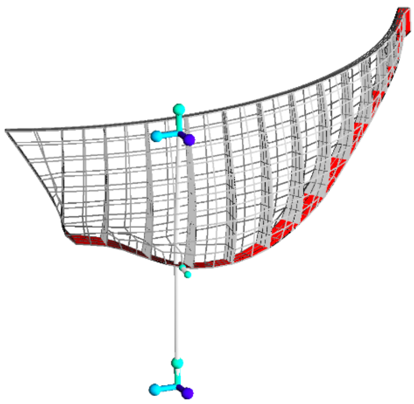
The material properties considered for both the thermal and the mechanical analyses follow closely the reference values defined in the benchmark. A thermal expansion of $1.0x10^{-5}/C^{o}$ was adopted for concrete, which is the usual value adopted in Portugal for dam concrete, Schclar Leitão (2021). Several mechanical parametric studies were carried out using different Young modulus for the concrete dam and for the foundation, but it was decided to present only the results that adopted mechanical values close to the adopted in previous dam assessments, according to the benchmark organizers. In our point of view in order carry out a comprehensive numerical study it would be necessary to know the observed displacement field in more locations and to have more details regarding the dam concrete and its foundation. A linear elastic isotropic model was adopted for the foundation, given that the adopted mechanical modules do not have the ability to model an orthotropic material.



a) 2nd order 20 node brick isoparametric elements representing the dam and its foundation (Z1 – Left bank, Z2 – Valley bottom and Z3 – Right bank)



b) 2nd order 8x8 node joint interface finite elements representing the dam/foundation interface and the contraction joints.



c) Observation points – Pendulum CB2 and CB3, including the adopted radial direction and foundation extensometer C4-C5.

Figure 1. Numerical model for thermal and mechanical finite element analysis.

Table 1 and Table 2 present, respectively, the adopted material properties for the volume finite elements and for the interface finite elements, module Parmac3D. In the mechanical module *PAVK*, a hard contact approach was adopted with a high penalty value of 2200 GPa/m for the joint interface normal and shear stiffness.

In the mechanical module (*Parmac3D)* a Mohr-Coulomb constitutive model with zero tensile strength and zero cohesion with a friction angle of 45º was assigned to the interface elements representing the contraction joints. For the dam-foundation interface a brittle Mohr-Coulomb model with a non-zero tensile stress (2.0 MPa) and a nonzero cohesion stress (6.0 MPa) with a friction angle of 45º value was adopted.

Table 1. Material properties of the volume elements.

Material	Young's modulus E (GPa)	Poisson´s ratio ν (-)	Density ρ (kg/m3)
Concrete	22.0	0.20	2400
Foundation - left bank (Z1)	1.0	0.20	2700
Foundation - Valley bottom (Z2)	1.0	0.20	2700
Foundation - right bank (Z3)	10.0	0.20	2700

Table 2. Material properties of the joint elements – Module *Parmac3D*.

Interface	Normal stiffness k_n (GPa/m)	Shear stiffness k_s (GPa/m)
Concrete/Concrete	220.0	88.0
Concrete/Foundation (Z1)	10.0	4.0
Concrete/Foundation (Z2)	10.0	4.0
Concrete/Foundation (Z3)	100.0	40.0

In the thermal analysis the Dirichlet boundary conditions (concrete/water and foundation/water) and the Robin boundary conditions (concrete/air and rock/air interfaces) were adopted. In the mechanical analysis the nodal displacements at lateral boundaries of the foundation and at the base of the foundation were prevented in module *Parmac3D* simulations and in the *PAVK* simulations only the node displacements at the base of the foundation were prevented.

2.3 *Numerical analysis sequence*

The thermal analysis allowed the definition of the thermal field in the concrete dam and foundation every forthnight from the 1st of January of 2000 to the 31st of December of 2017.

In the mechanical analyses that were carried out the gravity loading, the hydrostatic pressure and the thermal field were applied at each loading stage that represent a 15 days behaviour. In the nonlinear analysis, a dynamic relaxation algorithm using an explicit central difference scheme was adopted at each load step in the *Parmac3D* module and a Newton Raphson algorithm was adopted in the *PAVK* computational module that adopts a global stiffness matrix static solution.

3 MODEL OF SEPARATION OF EFFECTS

3.1 *Model description*

A Separation of Effects Model (SEM) based on a hydrostatic-seasonal-time (HST) model, Wilm and Beaujoint (1967), was adopted for the prediction of the observed data (pendulum and foundation displacements, piezometric head and total seepage flowrate). As mentioned before, in the prediction of the displacement fields, the results obtained with the finite element analysis that was carried out were incorporated, Silva Gomes and Silva Matos (1985) and Rodrigues et al. (2021), namely the numerical displacement predicted at the points of observation due to the imposed temperature field assuming an elastic behaviour. The adoption of the FE elastic prediction due to the temperature field was found to lead to a better agreement between the SEM model prediction and the observed data. The incorporation of the FE predictions within a SEM model requires that a FE model is available and that the numerical results are constantly updated with the new water level and temperature values. The adopted SEM was based on the following functions:

$$\mathrm{Pr}\,ediction\ (h,T,t) = \underbrace{f_1(h)}_{a_1h+a_2h^2+a_3h^3+a_4h^4+a_5h^5} + \underbrace{f_2(T)}_{\substack{a_6\cos(s)+a_7\sin(s)+a_8\sin^2(s)+a_9\cos(s)\sin(s)\\ or\\ a_6\,FE_{prediction}(T)}} + \underbrace{f_3(t)}_{a_{10}\log(1+t/300)} + k \tag{1}$$

The same SEM model was adopted for the long- term and for the short-term predictions using the provided data, namely the water level (h), and the monitored data throughout 13 years of observation (2000-2012).

3.2 *Warning levels*

The safety margin reference values were chosen according to the team members experience, mostly for pendulum displacements interpretation. The warning levels were chosen given the standard deviation of the difference between the predicted values, adopting a SEM model, versus the monitored data that was supplied by the benchmark organizers. An interval of +- 3 times the standard deviation was adopted in all sensors.

Observed values with a difference from the prediction values higher than 5 times the standard deviation should be immediately analyzed. It is important to assess the reason behind this difference, which can be due to equipment failure or due to a change in structural behavior that was not being included in the prediction model (damage due to swelling) or it can be an acceptable behaviour not represented by the model prediction.

In the analysis that was made for this dam and for the data that was received, it was found that a value of +- 3 times the standard deviation significantly reduces the days with warning levels along the 2000-2012 monitoring period. It was assumed that the monitored behaviour between 2000 to 2012 was a normal behaviour. To point out that an interval of +- 3 times the standard deviation is meaningful when the SEM predictions are in excellent agreement with the observed data, which as is later shown does not occur when analysing the seepage observed data, nevertheless a similar value was adopted.

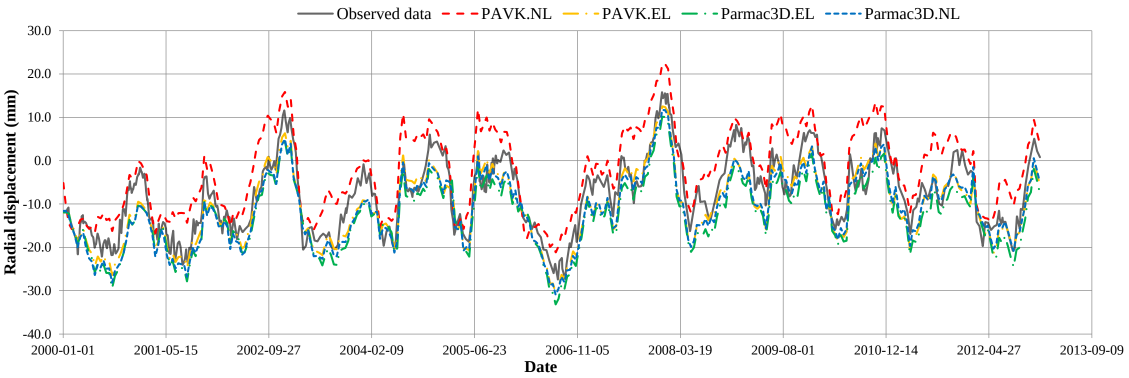
4 MAIN RESULTS

4.1 *Finite element predictions*

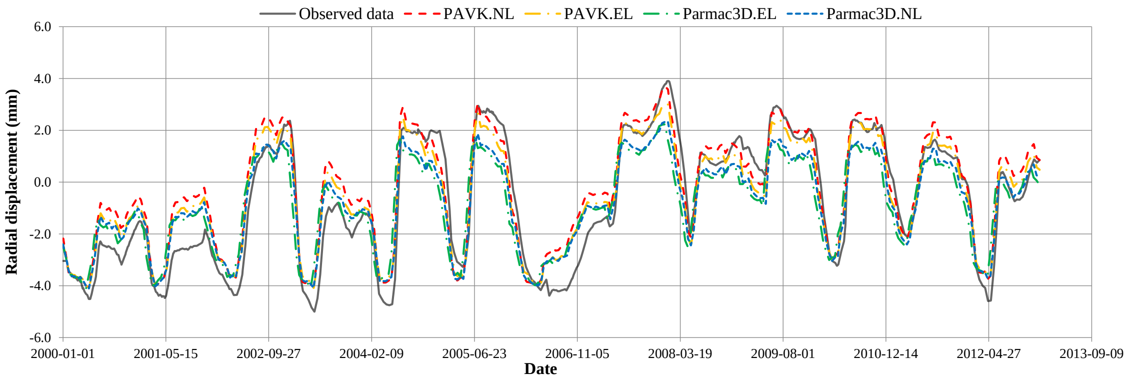
Figure 2 compares the displacement field FE predictions from the 1st of January 2000 to the 31st of December 2012 with the pendulum observed data. It is shown that the *PAVK* elastic mechanical model predicts a response in close agreement with the *Parmac3D* mechanicals models (elastic and nonlinear). From the obtained numerical results it is clear that the different support conditions adopted in each mechanical model do not have a meaningful influence on the predicted response. Nevertheless, the nonlinear response predicted with the *PAVK* module does lead to a slightly different response, which was expected as the nonlinear behaviour adopted in the dam/foundation interface is much more brittle (no tensile or cohesion for positive gap) than the model adopted in the PARMAC3D nonlinear mechanical model (maximum tensile and cohesion values up to failure).

The predicted pendulum numerical responses have a reasonable agreement with the observed data. Given the time constraints it was decided not to perform a parametric study in order to find the mechanical parameters that lead to a better agreement with the observed data. For this type of analysis, it is important to have more than one pendulum lines observations in order to proper calibrate the dam and the foundation elastic properties.

Regarding the foundation displacement sensor C4-C5, Figure 3, it is possible to observe that the *Parmaca3D* mechanical models, elastic and nonlinear, predict a numerical response closer to the observed data than the response predicted with the *PAVK* mechanical models. This is due to the fact that in the Parmac3D mechanical module a soft contact approach is adopted, and the dam/foundation interface has a much higher deformability, when compared to the *PAVK* module. A similar result would have been obtained with the *PAVK* module if a more discretized foundation was adopted closer to the dam/foundation interface with a lower Young's modulus. A soft contact approach is from the physical point of view less rigorous, but it has the advantage of allowing the interface to contribute to the overall displacement field, which sometimes can lead to a better numerical prediction with a less refined discretization when compared with mechanical modules that adopt a hard contact approach.



a) Pendulum CB2



b) Pendulum CB3

Figure 2. Observed versus numerical pendulum displacement field time series – 1st of January 2000 to 31st of December 2012.

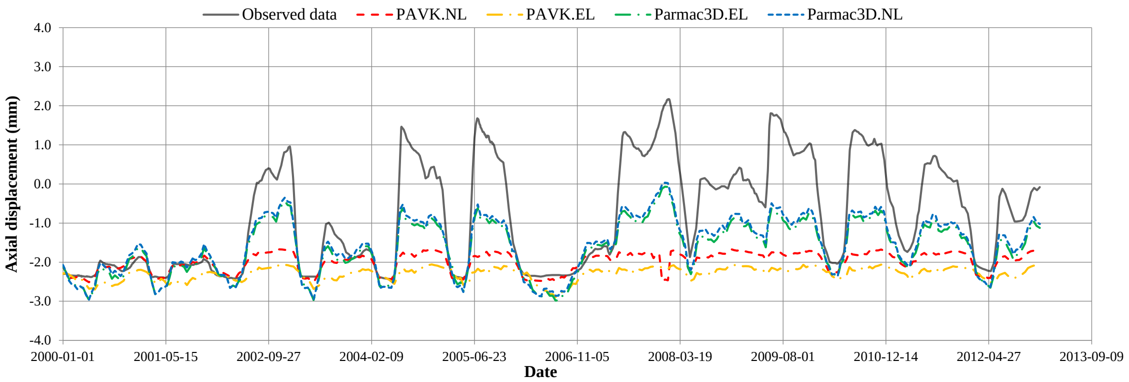


Figure 3. Observed versus numerical displacement field time series – Foundation displacement sensor C4-C5 – 1st of January 2000 to 31st of December 2012.

Figure 4 shows the damage at the dam/foundation joint interface integration points predicted with the *Parmac3D* module. Given the adopted brittle interface model, the damage is either 1, cracked integration point, or 0, which means that the integration point is still under an elastic behaviour. It can be seen that the *Parmac3D* nonlinear model predicts an extensive cracking at the dam/foundation in the vicinity of the right bank (foundation zone Z3). To further understand if this really occurred it would be important to analyse data collected in monitoring equipment installed in this area.

The presented finite element predictions clearly show that the thermal/mechanical coupled response in the linear regime can be performed with the available modules. Similar results have also been obtained within viscoelastic and damage regime. In our point of view the principal numerical focus should be in the development of models that also consider the hydromechanical response, Braga et al. (2022).

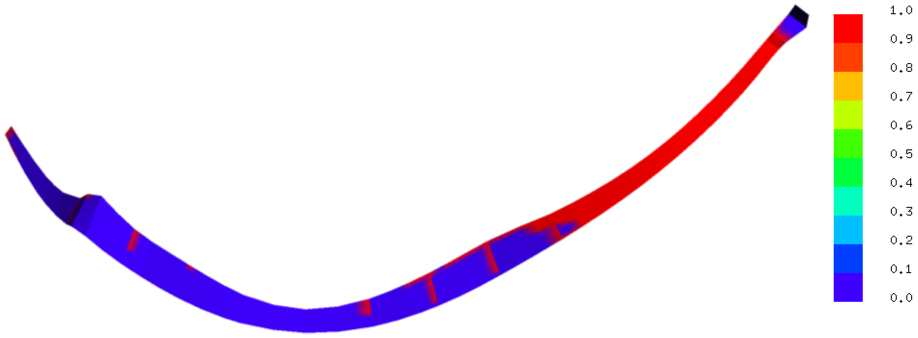


Figure 4. Damage distribution at the dam/foundation interface predicted with the mechanical module Parmac3D – Nonlinear model – 31st of December 2017.

4.2 *Separation of effects predictions*

Figure 5 shows the pendulum displacement field SEM calibration period and the SEM predictions from the 1st of January 2012 to the 31st of December 2017, following the usual HST approach (SEM.HST) and a hybrid approach adopting the FE analysis radial displacement field associated to the temperature field as the function representing the temperature effect (f_2 (t)). Figure 5 also shows the observed data from the 1st of January 2000 to the 31st of December 2012 adopted to calibrate the SEM model through a regression analysis. With the introduction of the FE predicted radial displacement the correlation coefficient was slightly increased from 0,93 to 0,95, as shown in Figure 5, where the SME.HST.FE slightly higher peaks are predicted when compared with the traditional SEM model.

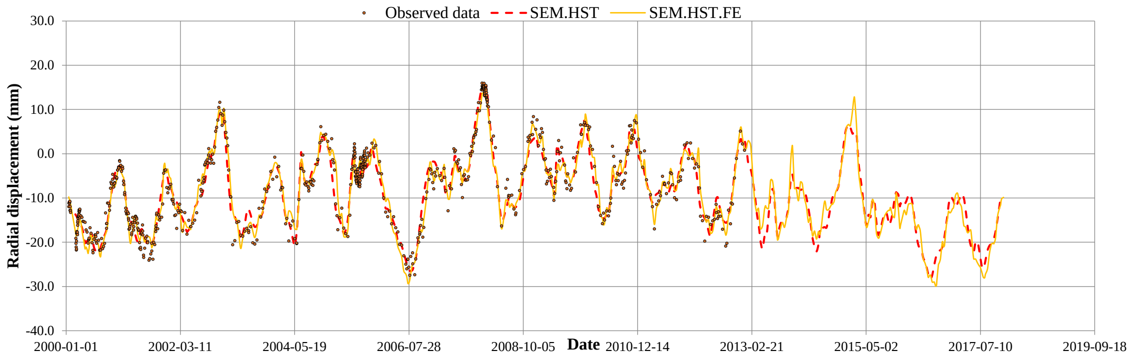


Figure 5. Observed versus SEM prediction pendulum CB2 displacement field time series – Calibration: 1st of January 2000 to 31st of December 2012 – Prediction: 1st of January 2013 to 31st of December 2017.

Figure 6 shows the radial displacement at pendulum CB2 SEM function associated to the water level influence (f1 (h)) and the FE radial displacement predictions adopting the module Parmac3D for both a linear and a nonlinear model. It can be seen that with the introduction of the FE predicted radial displacement, the water level influence slightly changes, being the SEM.HSM.FE predicted curve stiffer for water levels higher than 15 m, when compared to the response predicted with SEM.HSM.

Figure 6 also shows that the adopted FE model, linear and nonlinear, has a significant influence on the predicted response. The SEM water level prediction can be used to calibrate the FE material properties but a higher number of observed dam displacements and a better description of the dam foundation zoning and properties need to be made available in order to proper calibrate the FE model. with SEM.HSM.

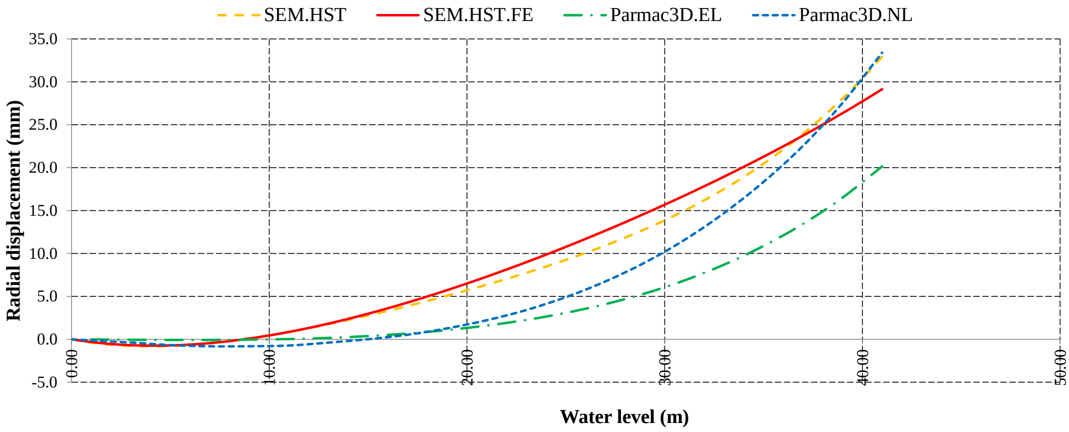


Figure 6. Pendulum CB2 radial displacement evolution with water level - SEM predictions versus FE predictions.

Figure 7 shows the total seepage flowrate SEM calibration period and the SEM predictions from the 1st of January 2012 to the 31st of December 2017, following the usual HST approach. For this type of data the lowest correlation coefficient of 0,50 showing that the adopted SEM model does not satisfactory explain the observed behaviour. Note that in the several attempts that were made the rainfall data and the derivative of the water level, Desideri (1985) were adopted in the SEM models but it was not possible to obtain a better correlation with the observed data. There is no perfect match between the rainfall peaks or 1st derivative peaks with the observed seepage values. Nevertheless, a similar SEM model has been shown to give a good agreement for seepage data, Farinha (2010), nevertheless for this better agreement it was important to separate the seepage values into two more than a zone and also to address the seepage origin. The difficulties in carrying out a successful SEM prediction show that the current SEM models for the interpretation of the hydraulic response need to be further improved in order to have better predictions.

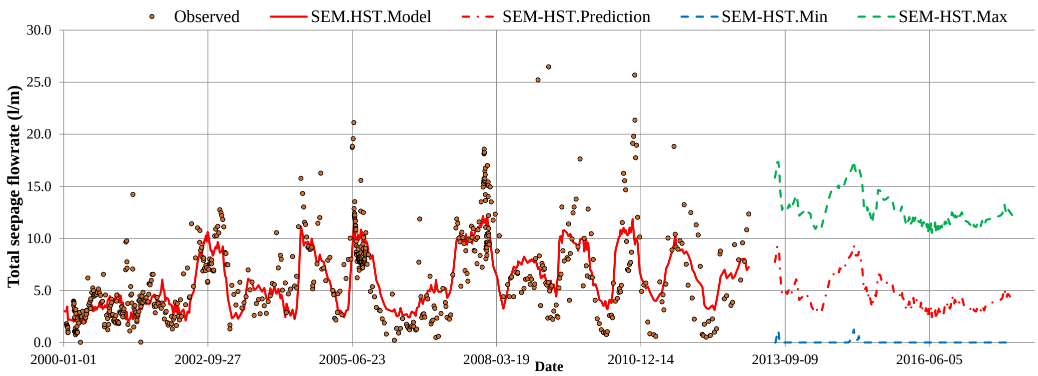


Figure 7. Observed versus SEM prediction total seepage flow rate time series – Calibration: 1st of January 2000 to 31st of December 2012 – Prediction: 1st of January 2013 to 31st of December 2017 – Including warning levels

5 CONCLUSIONS

The double curvature arch dam, located in the south of France, was numerically studied with thermal and mechanical computer codes purposely developed by the authors for dam analysis. The predicted displacement field numerical responses have a reasonable agreement with the monitored data. Due to time constraints, it was decided not to perform parametric studies in order to obtain an even better agreement. In previous studies where the research team has been involved it was found to be important to perform the parametric studies for more than one location of pendulum lines.

The difference between a soft contact approach and a hard contact approach for the interface elements was discussed. It was shown that even if a soft contact approach is not as physically correct as the hard contact approach, it can lead to a better overall agreement. Nevertheless, the results show that in the vicinity of the dam/foundation interface a more refined discretization with lower Young's modulus should be adopted in order to have a better agreement with the observed response at the dam foundation.

The presented finite element predictions clearly show that the thermal/mechanical coupled response in the linear regime can be performed with the available modules. Similar results have also been obtained within the viscoelastic and damage regime. In our point of view the principal numerical focus should be in the development of models that also consider the hydromechanical response.

The dam behavior was also assessed with separation of effects regression based prediction models following a hydrostatic-seasonal-temperature approach. During the displacement analysis it was found to be relevant to adopt in the SEM model the results obtained with the finite element analysis, namely the response obtained with an elastic model for the imposed temperature field. The prediction analysis that was performed also shows that the current SEM models for the interpretation of the hydraulic response need to be improved in order to have better predictions.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

Farinha, M.L.B. 2010. Hydromechanical behaviour of concrete dam foundations. In situ tests and numerical modelling. *Phd. Thesis, IST, Lisbon, Portugal*.

Farinha, M.L.B., Monteiro Azevedo, N., Schclar Leitão, N,.; Rocha de Almeida, J., Oliveira, S. 2022. Sliding Stability Assessment of Concrete Dams Using a 3D Discontinuum Hydromechanical Model Following a Discrete Crack Approach. *Geotechnics 2* :133-157.

Castilho,E., Schclar, N., Tiago, C., Braga Farinha, M.L. 2018. FEA model for the simulation of the hydration process and temperature evolution during the concreting of an arch dam, *Engineering Structures*, 174: 165-177.

Desideri, A. 1985. Modeli statistici previsionali delle misure piezometriche nella diga di Oroville. *ISMES G(550) qI8, no. 214*, Bergamo, Italy (in Italian).

Monteiro Azevedo N., Câmara R. 2015. Dynamic analysis of concrete dams: fluid structure displacement based interaction models. *Dam Engineering* Vol. XXV (4): 113-132.

Rodrigues, M., Oliveira, S., Lima, N., Proença, J. 2021. Displacement Monitoring in Cabril Dam Using GNSS. *Dam Engineering*. Volume XXXI (3): 149-165.

Schclar Leitão, N. 2011. Environmental thermal actions – Thermal analysis of Alto Lindoso dam. In *Proceedings of the 6th International Conference on Dam Engineering*, Lisbon, Portugal.

Schclar Leitão, N. 2021. Study of the cracking process in an arch dam. In *Proceedings of the Congresso Nacional Reabilitar & Betão Estrutural 2020*, Lisbon, Portugal (in Portuguese).

Silva Gomes, A., Silva Matos, D. 1985. Quantitative analysis of dam monitoring results. State of the Art,

applications and prospects. In *Quinzième Congrès des Grands Barrages,* Lausanne, Switzerland.
Willm, G., Beaujoint, N. 1967. Les méthodes de surveillance des barrages au service de la Production Hydraulique d'Életricité de France. Problèmes anciens et solutions nouvelles. In *IX Congress ICOLD. R.30 Q.34,* Istanbul, Turkey.