Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0528

XVII European Conference ECSMGE 2019 Reykjavik on Soil Mechanics and Geotechnical Engineering

Settlement analysis of the Montesinho concrete-face rockfill dam

Analyse du peuplement du barrage en enrochement de Montesinho

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ABSTRACT: This paper studies the effect of suction in the rockfill materials and its influence in the behaviour of Montesinho *CFRD*. A three-dimensional *FEM* model has been developed incorporating the model of Oldecop and Alonso (2001) using the *MFront* software together with code-aster. The three major phases of the dam were simulated: construction, reservoir impounding and operation. In order to verify the adequacy of the model in describing the behaviour of the Montesinho *CFRD*, the results of the developed model were compared to the monitoring results. The model parameters used in this study were calibrated based in the experimental data collected from a set of experimental tests.
Comparative studies of monitoring data and simulations showed good agreement between measured settlements and computed settlements, allowing to predict the deformation of the structure in the next 10 years. Overall, the deformation of the Montesinho *CFRD* is stable and the monitoring system used to control the dam deformation is successful.

RÉSUMÉ: Cet article étudie l'effet de la succion dans les matériaux d'enrochement et son influence sur le comportement du CFRD de Montesinho. Un modèle FEM tridimensionnel intégrant le modèle de Oldecop et Alonso (2001) utilisant le logiciel MFront et le code-aster a été mis au point. Les trois phases principales du barrage ont été simulées: construction, mise en eau et exploitation du réservoir. Afin de vérifier l'adéquation du modèle dans la description du comportement du CFRD de Montesinho, les résultats du modèle développé ont été comparés aux résultats de la surveillance. Les paramètres de modèle utilisés dans cet étude ont été calibrés sur la base des données expérimentales recueillies à partir d'un ensemble de tests expérimentaux.
Des études comparatifs de données de surveillance et des simulations ont montré un bon accord entre les règlements mesurés et les règlements calculés, permettant de prédire la déformation de la structure au cours des 10 prochaines années. Globalement, la déformation du CFRD de Montesinho est stable et le système de surveillance utilisé pour contrôler la déformation du barrage est efficace.

Keywords: Rockfill; FEM; MFront; code-aster.

1 INTRODUCTION

Concrete-faced rockfill dams (*CFRD*) are a major type of rockfill dams, whose structure consist of cushion, transition, main rockfill, and secondary rockfill zones. Due to their good adaptability to topography, geology and climate, use of locally available materials, cost-effectiveness, simple construction and short construction period, they have been repeatedly constructed in recent decades, in some cases higher than 200 m.

The major concerns regarding the design and operation of these structures are related to the deformations of rockfill zones and to the stresses in concrete slabs and slab joints. Numerical methods, such as finite element method, can be used to predict dam deformation during construction and operation. However, the reliability of the results for the adopted model depends significantly on its suitability to model rockfill materials.

Several methods have been adopted for the modelling of rockfill. Xing et al. (2006) implemented the nonlinear hyperbolic model Duncan-Chang E-B in a two-dimensional finite element software, and compared to the field measurements. Zhou et al. (2011) also applied this model to analyse the measured deformations resulting from continuous monitoring of the Shuibuya *CFRD*. Li and Desai (1983) developed a finite element procedure for stress-deformation analysis of dams, where they modelled the mechanical behaviour using linear elastic, nonlinear or piecewise linear elastic (hyperbolic) and plasticity (Drucker-Prager) models. Xu et al. (2012) modified the generalized plasticity model for sand, which was based on the work of Pastor et al. (1990) and Ling and Liu (2003), in order to describe the behaviour of rockfill materials, particularly their unique pressure dependency due to particle crushing.

In this paper a three-dimensional *FEM* model was developed. The Oldecop and Alonso (2001) model were incorporated into the *FEM* program and simulated the construction, first filling and operation phases of the Montesinho *CFRD*, returning a reasonable consistency between the predicted and monitoring results. This will allow to analyse the behaviour of the dam until now and inferred the response during its operation.

2 MONTESINHO CFRD

The Montesinho dam is located in the Sabor river, in the Montesinho Natural Reserve. It is a CFRD built to provide water supply to the city of Bragança, reinforcing the current reserve of the Serra Serrada dam located approximately 3 km west of Montesinho.

Montesinho dam has 36.5 m of height and a crest with a length of about 310 m with 7 m of width. The total volume of the embankment is of about 174 000 m^3 and consists of granitic rockfill obtained from the quarries located upstream of the dam in the reservoir area.

The reservoir as a capacity of 3.69 hm^3 (net volume of 3.53 hm^3) with a flooded area of 35.8 ha and a catchment area of 10.1 km^2. The normal water level is at 1217.50 m (above sea level – a.s.l.) and the maximum water level is at 1219.73 m (a.s.l.). The freeboard has 1.37 m, therefore the crest is located at level 1221.10 m (a.s.l.). The upstream and downstream embankments originally had a slope of 1:1.5 (v:h), however, during the construction, it was decided to include a berm in the downstream shell.

Spread over the foundation existed a thin coating of top soil or organic soil which has been removed prior to the construction of the dam. Figure 1 and Figure 2 present the plan and the cross-section of Montesinho dam. As it can be seen from the figures, the valley is asymmetrical with an average slope of 1:6.5 (v:h) above level 1200 m (a.s.l.), on the right bank, and 1:2.6 (v:h) on both left and right banks, below that level.

3 SETTLEMENT MONITORING SYSTEM

The technical characteristics of the dam, combined with the geological formations of its foundation and the surrounding area, have led to the adoption of a detailed monitoring system. It encompasses a variety of geotechnical and geodetic instruments and techniques capable of monitor the deformation of the Montesinho dam. The field instrumentation placed in the dam body included settlement gauges (capable of recording vertical and horizontal interior displacements) distributed in three important cross-sections, 1–1, 2–2 and 3–3, with cross-section 2–2 being the major monitoring cross-section of the dam (Figure 2). The concrete slab deformations were measured by three inclinometers installed in the cushion zone, at the same cross-sections: 1–1, 2–2 and 3–3. Surface deformations at the crest of the dam were measured by 12 monitoring gauges separated from each other of about 25 m. Its positions are shown in Figure 1.

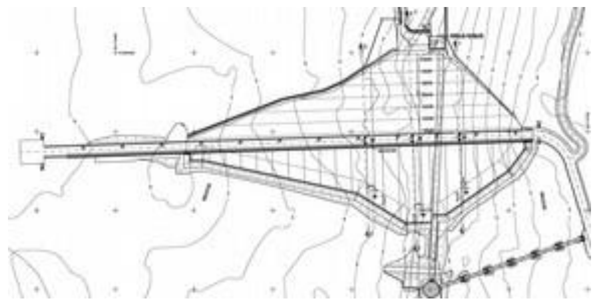


Figure 1: Plan of Montesinho dam.

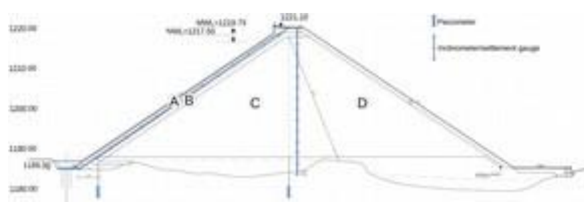


Figure 2: Layout of settlement gauges in cross-section 2-2 of the Montesinho dam.

The monitoring system also included 3 sets of 2 piezometers in the foundation of the dam. In each set, the first piezometer is located immediately after the grout curtain while the second is located near the dam axis. The purpose of this system is to evaluate the curtain efficiency.

Finally, to complement this system a total flow measuring system, near the toe of the dam is also included. During the construction of the dam regular measurements of the internal vertical displacements and water pressures in the foundation were made. The results of the former are presented below in comparison with the FEM model.

In addition to geotechnical monitoring, periodic dam inspections and geodetic surveys have been performed since the construction period. These inspections included weekly routine visual inspections and monthly main inspections performed by engineers and technical staff.

3.1 Dam embankment deformation

As expected (Gikas and Sakellariou, 2008; Zhou et al., 2011), vertical displacements in the embankment dam developed faster during the construction phase and then decreased progressively in time, during the stage of the first filling of the reservoir. The settlements monitoring system relied on different settlement gauges displayed through the body of the rockfill dam.

To better understand the progression of the settlements of the Montesinho *CFRD*, three major periods were analysed: construction (before May, 2015), first filling of the reservoir (May, 2015, until March, 2016) and operation (from March, 2016).

The internal settlements of the rockfill embankment were recorded at three important cross-sections, 1–1, 2–2 and 3–3, from 22 April, 2014, to 19 May, 2015, (construction period) and from 19 May, 2015, to 6 July, 2016 (first filling and operation). Figure 3 presents the internal settlements registered at cross-section 2–2 (highest cross-section) for both periods. The accumulative settlements registered reached the value of 27 mm at the level 1200.5 m (a.s.l.) at the end of construction (Figure 3a). The displacement profile resemble a parabolic shape (Gurbuz, 2011; Pagano et al., 1998), where the maximum was observed approximately at middle height, corresponding to 0.07 % of dam's height.

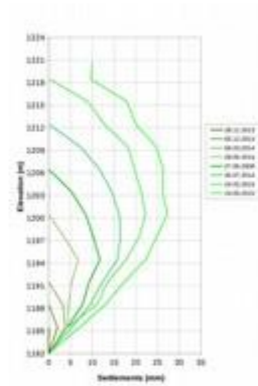
The reservoir impounding was planned to occur into two parts. It began on 8 September, 2015, with the water at level 1196.08 m, quickly increasing to the first level at 1210.19 m on 5 November, 2015 (2 months). The second part of the impoundment began on 11 February, 2016, with the water at level 1210.40 m, increasing until level 1217.69 m, on 29 February, 2016 (18 days). To better understand the embankment deformation during the reservoir impounding, a new reference was considered since 19 of May, 2015 (Figure 3b). The additional settlements were 5 mm (level 1188.5 m) or 0.01 % of dam's height. It can be concluded that the construction phase had a more pronounced effect, on embankment settlements, than the immediate impounding loading.

Figure *4* presents the evolution of the internal settlements (in relation to the settlements registered on 19 of May, 2015) and compare them with the reservoir level, for the first filling and operation periods. The settlements were analysed for level 1220 m at cross-sections, 1–1, 2–2 and 3–3. It can be seen that during this period the settlements slightly varied and no clear tendency was observed, between the embankment settlements and the reservoir level.

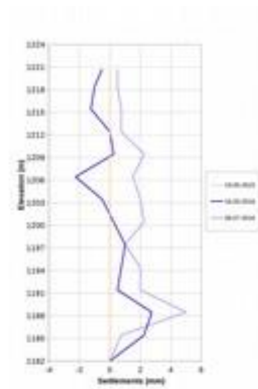
It should be mentioned that the errors that result, from using this method to monitor internal settlements in the embankment, are of the same order of magnitude of the settlements registered. Therefore, due to the dimensions of the embankment of the Montesinho *CFRD*, their settlements are expected to be small, which could explain some of the registered swelling and irregularities.

3.2 Lateral displacements registered in the embankment

As mentioned previously, the concrete slab plays the important role in *CFRD*s as the impervious element. Any crack in the slab would reduce the integrity of the seepage control system and weaken the structure, which, in the worst case scenario, may threat the safety of the dam, but most often only compromise its functionality. Nonetheless, it is the deformation of the rockfill that influences the deformation of the concrete face slab. If rockfill experiences excessive deformation after the construction of the concrete face slab, it will cause the separation between the slabs and the cushion layer or can even lead to slab cracking (Zhou et al., 2011). Therefore, in order to reduce this potential risk in *CFRD*s, the study of the rockfill deformation plays an important role to make the rockfill compatible with the concrete face. This will decrease the number of cracks and eventually improve the design of *CFRD*s.



a) Construction period.



b) First filing and operation (in relation to the end of construction).

Figure 3: Internal settlements registered in the embankment at settlement gauge nº3.

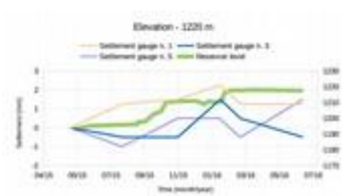
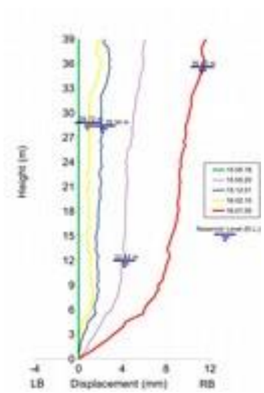


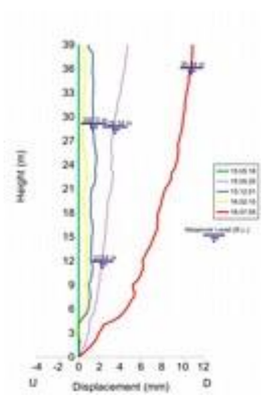
Figure 4: Internal settlements registered in the embankment during first filling and operation.

The monitoring of the rockfill embankment can be an effective method to characterise and analyse deformation. It has also proven to be very helpful for warning of some abnormal behaviour of the dam, as well as for understanding its deformation mechanism (Gikas and Sakellariou 2008; Zhou et al. 2011).

Figure 5 shows the cross-valley horizontal and upstream-downstream displacements registered in the embankment, for cross-section 2–2. The inclinometers are anchored into the bedrock. The maximum cross-valley horizontal displacement was equal to 11.6 mm (5 July, 2016), at 39 m above the base of the inclinometer toward the right abutment. It was obtained during the dam operation.



a) Left-right abutment.



b) Upstream-downstream.

Figure 5: Lateral displacements registered in the embankment from May 2015 to July 2016. Vertical inclinometer nº 3.

The upstream-downstream maximum displacement registered was equal to 11.0 mm (5 July, 2016), toward the downstream direction. The maximum was obtained at 39 m above the base of the inclinometer located in cross-section 2–2, during operation.

All results considered, it can be concluded that the rockfill embankment deformation is compatible with the concrete face. The displacements observed in the concrete face were considerable acceptable and may lead to a reduced number of cracks in the slab. Therefore, its impervious capabilities were guaranteed.

4 CONSTITUTIVE MODEL

The structural analysis software *Code-Aster* was used to perform the *FEM* elasto-plastic analyses on the Montesinho *CFRD*. *Code-Aster* is an open source software package for civil and structural engineering, developed as an in-house application by the French company Électricité de France (*EDF*). In October 2001, it was released under the terms of the *GNU* General Public License. *Code-Aster* runs on GNU/Linux workstations or clusters.

Using *Code-Aster*, a model of the Montesinho *CFRD* and its dam site area was prepared in order to study the deformations and the stress-strain behaviour of the dam. Three basic models have been analysed based on three major periods of the dam: its staged construction, the first filling of the reservoir and the dam operational lifetime.

4.1 Geometry setup

After analysing the results of the structure monitoring, it is necessary to compare them with the observed deformations obtained from *FEM*. This comparison will allow to verify the structure's behaviour and the adopted design parameters.

The geometry of the model of Montesinho *CFRD* was divided into two parts (Figure 6): the foundation and the dam, and was performed using a python script written by (Marcelino et al. 2015). The foundation was generated from a set of blocks with a triangular base and top. The *FEM* model extends 103.0 m in the upstream and 50.8 m in the downstream directions, whereas the depth of the model is almost thrice the maximum height of the dam (102.4 m). On the other hand, the dam geometry was generated as a regular solid and cut by the foundation, using a boolean cut geometric operation. By doing this it was possible to adjust the dam geometry to the surface of the foundation. The final generated blocks were independent, but compatible.

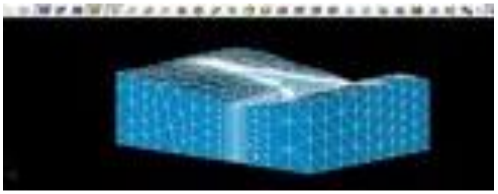


Figure 6: Montesinho CFRD numerical model

In this study, the numerical modelling was performed under three-dimensional conditions. Since the stress and strain paths were relevant to the rockfill behaviour, the construction of the dam was made in layers (Naylor et al. 1981). On the other hand, in order to correctly account for the deformation of the dam being built, the model needs to consider the displacements of the existing layers, not the one being placed. Therefore, the dam model was also split in layers by means of several cutting planes, allowing for an arbitrary user-defined number of layers (Marcelino et al. 2015).

4.2 Finite element mesh generation

The generated mesh consisted of approximately 17K nodes and 83K tetrahedra elements. From those, about 30K elements were used to build the 15 layers of the dam itself. In order to allow the definition of the boundary conditions and the construction sequence, groups of nodes, faces and elements were defined in this module. Following the Naylor proposal (Naylor et al. 1981), to correctly account the deformations during construction, the displacements of a newly constructed layer were dismissed. With this method the model was capable of having null displacements in the crest, when the dam was completed, since in reality each layer is always built up to the designed level.

Time was not considered in the material behaviour, so a constant construction rate was adopted, dividing the embankment in equal layers.

The *FEM* analysis considered the combination of two types of loads to model the first filling of the reservoir: gravity load and water pressure. The first one was applied by assigning the unit weight of the materials. To model the stages of first filling of the reservoir and the operating time of the Montesinho *CFRD*, the static water pressure was applied as a surface load on the upstream embankment, in accordance with the reservoir level.

5 PARAMETER IDENTIFICATION

In order to consider the effect of suction in the behaviour of the rockfill of Montesinho, the elastoplastic model presented by Oldecop and Alonso (2001) was adopted. This elasto-plastic model takes into account the test results and the underlying fracture propagation framework. Tests showed that the compression behaviour of rockfill was somehow similar to the one of an unsaturated soil, since compressibility decreased with increasing suction. However, some differences between rockfill and unsaturated soils should be pointed out, e.g., that there are regions (stress and suction states), in the case of rockfill, where its behaviour do not depend on water content.

The model of Oldecop and Alonso (2001) was developed using *MFront* and incorporated in *Code-Aster* software, verifying its adequacy to describe the behaviour of the Montesinho rockfill, by comparing the numerical results with the deformations of the embankment during construction and first filling of the Montesinho *CFRD*. The model parameters were calibrated based in the experimental data (Manso, 2017). The details and equations of the model are fully presented in the work of Oldecop and Alonso (2001) and will not be described in this paper.

In order to test the *MFront* software, firstly the Oldecop material law was modelled and its results analysed. The tool *Mtest*, a part of the *MFront* tools (Helfer et al., 2015), can easily simulate the mechanical behaviour over a material point, in order to analyse the response of the constitutive behaviour to stresses or strains. The simulation was performed and, since the output did not return any error and completed the simulation, it was possible to analyse the results. After this procedure, this software was used to model the pretended rockfill compressibility behaviour. Table 1 summarises the adopted model parameters, computed from the test results, for suction formulation, which were used to analyse the behaviour of the Montesinho dam.

Material type	**Behaviour**	**Parameter**		**Value**
Foundation	Linear Elastic	E	[Pa]	$15 \cdot 10^{7}$
		ν		0.2
		ρ	[Kg/m3]	2194
Rockfill	Oldecop and Alonso	λ_i	[MPa^{-1}]	$2.34 \cdot 10^{-3}$
		λ_0	[MPa^{-1}]	$2.50 \cdot 10^{-3}$
		α_ψ		$2.53 \cdot 10^{-4}$
		σ_y	[MPa]	0.194
		κ	[MPa^{-1}]	1.64
		κ_ψ	[MPa^{-1}]	$1.23 \cdot 10^{-5}$

Table 1: List of material properties for the Oldecop and Alonso model.

6 *NUMERICAL MODELING* ANALYSIS

6.1 Embankment deformation during construction

After the construction of each layer of the rockfill embankment, the settlements were determined. They were evaluated in cross-section 2–2, that was presented before. The monitoring results date from 19 May, 2015, corresponding to the final period of construction and beginning of the first filling.

The behaviour of the embankment is characterised by a low level of deformation during the construction, which is in close agreement with other embankments found in the literature and other embankments monitored during construction. Figure 7 shows the deformation contours of cross-section 2–2, where the settlements were increased 1000-fold. It can be seen that the maximum settlements were obtained at the middle height of the embankment. Although the *FEM* model returns relatively smaller settlements than the ones obtained with field measurements, they are in accordance with similar rockfill works and, predictably, the safety and serviceability of the dam is assured for the expected loads.

6.2 Embankment deformation during first filling

The same numerical model was used to predict the behaviour of the *CFRD* during the first filling. This phase of the loading was divided in 5 steps. The stress and deformation states obtained during embankment construction were adopted as the initial state in this analysis, not considering the effect of creep. Figure 8 shows the settlements in the dam for full storage (water level 1217.5 m). The maximum displacement calculated is less than 1 cm, obtained in the middle of the dam, near the highest cross-section. Near both abutments, the level of deformation in expected to be less than 2 mm, for cross-sections 1–1 and 2–2. Figure 9 presents the estimative of the horizontal displacements, in the upstream-downstream direction, where the dam exhibits an overall downstream movement of about 1 cm, near the central cross-section. On the other hand, the model predicted right-left abutment displacements between 3–5 mm, presented in Figure 10.

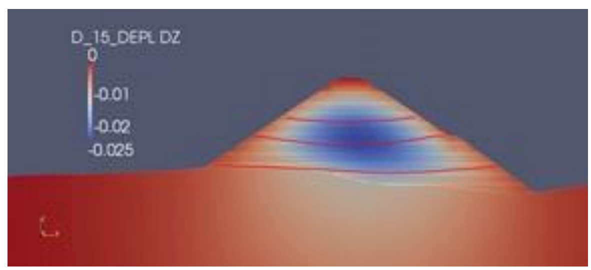


Figure 7: Internal settlements calculated at different levels. Cross-section 2–2.

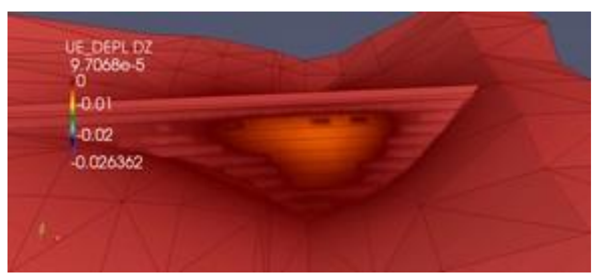


Figure 8: Settlements due to the first filling.

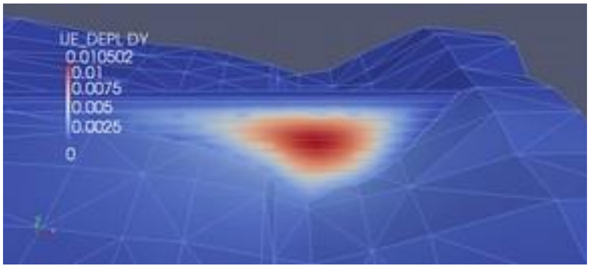


Figure 9: Upstream-downstream displacements.

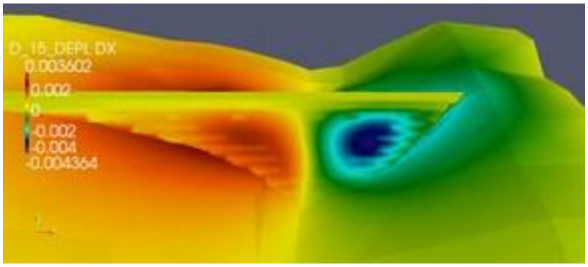


Figure 10: Right-left abutment displacements.

7 CONCLUSIONS

The monitoring of geotechnical structures, such as *CFRD*'s, is very important to access its serviceability and safety. During the construction of Montesinho *CFRD* a set of monitoring equipments were installed to control deformation of its rockfill body. Posteriorly, monitoring records of settlements at the crest and inside the dam body allowed to analyse the behaviour of the rockfill embankment. This analysis showed that the settlements were acceptable, for this type of structure, and that their maxima occur at the central cross-sections of the embankment, around middle height.

After the construction of the Montesinho *CFRD* was completed, the analysis of the behaviour of the rockfill embankment, during the first filling of the reservoir, showed that the settlement rate decreased and tended to stabilize, comparing with the period of construction.

The *FEM* model, based on the experimental results, proved capable of properly modelling the deformability of the rockfill used in the Montesinho *CFRD*, using the formulation of Oldecop and Alonso. Then, the behaviour of the rockfill embankment were numerically simulated during the construction and reservoir filling processes. The simulated settlements trends and values at the monitoring points were consistent with the field measurements, proving the accuracy of the proposed numerical procedure, and that it can be used to analyse the embankment behaviour.

It can be concluded that the Montesinho *CFRD* settlements were be very small, and that its deformation is essentially stable. Therefore, the construction techniques and the monitoring system installed to control the dam deformation are successful and it is predicted that the behaviour of the dam will stabilise, considering the expected loads acting upon the structure, and serviceability problems are not expected (in normal situations).

To sum up, a *3D FEM* model can be capable of faithfully predicting embankment settlements and general dam behaviour, during any phase of a dam (construction, first filling and operation). The validation of such numerical model, or assessment of a constitutive model, requires high-quality experimental data collected from a carefully executed testing programme. Such data may be obtained from full-scale field testing or laboratory-based research.

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