Laouzas dam: behavior of a thin concrete arch dam located in a wide valley and foundation stability improvement

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Abstract

Through the example of Laouzas dam owned by Electricité de France, this paper presents the mechanical behavior of a thin concrete arch dam located in a wide valley. From the first impoundment of the reservoir, this dam was affected by an opening of the rock-concrete interface near the central cantilevers. The reinforcement of the monitoring system, in particular the installation of piezometers at the downstream part of the dam-foundation contact, enhanced the progression of pore pressure in this zone beyond the generally admitted hypotheses. In order to explain such situation and to evaluate the consequences, finite-element analyses taking into account hydro-mechanical modeling were performed. They helped in understanding the observed phenomena and described the conditions of the dam-foundation thrust transmission towards downstream in the central part of the foundation. On Laouzas dam, after study of different solutions of reinforcement, local foundation reinforcement downstream of the central blocks was decided and implemented.

Keywords: Arch, Concrete, Reinforcement, Finite-element.

1. INTRODUCTION

Through the example of Laouzas dam owned by Electricité de France, this paper presents the mechanical behavior of a thin concrete arch dam located in a wide valley. From the first impoundment of the reservoir, this dam was affected by an opening of the rock-concrete interface near the central cantilevers. The reinforcement of the monitoring system, in particular the installation of piezometers at the downstream part of the dam-foundation contact, enhanced the progression of pore pressure in this zone beyond the generally admitted hypotheses. In order to explain such situation and to evaluate the consequences, finite-element analyses taking into account hydro-mechanical modeling were performed. They helped in understanding the observed phenomena and described the conditions of the dam-foundation thrust transmission towards downstream in the central part of the foundation. On Laouzas dam, after study of different solutions of reinforcement, local foundation reinforcement downstream of the central blocks was decided and implemented.

2. PRESENTATION OF LAOUZAS ARCH DAM, DESIGN AND OBSERVED BEHAVIOR

Laouzas dam, part of Montahut Hydraulic Scheme, is a 52 m high concrete arch dam built on the Vèbre River, in the south-east of France (Figure 1). This scheme is currently owned and operated by Electricité de France (EDF). The dam, whose construction was achieved in 1965, is located in a wide valley: [Width of the valley]/[Height of the dam] ratio close to 5,5.

The dam is founded on sound granite affected by a low density of cracks. In the central part of the valley, the dam is embedded in 4 to 5 meters of sound rock.

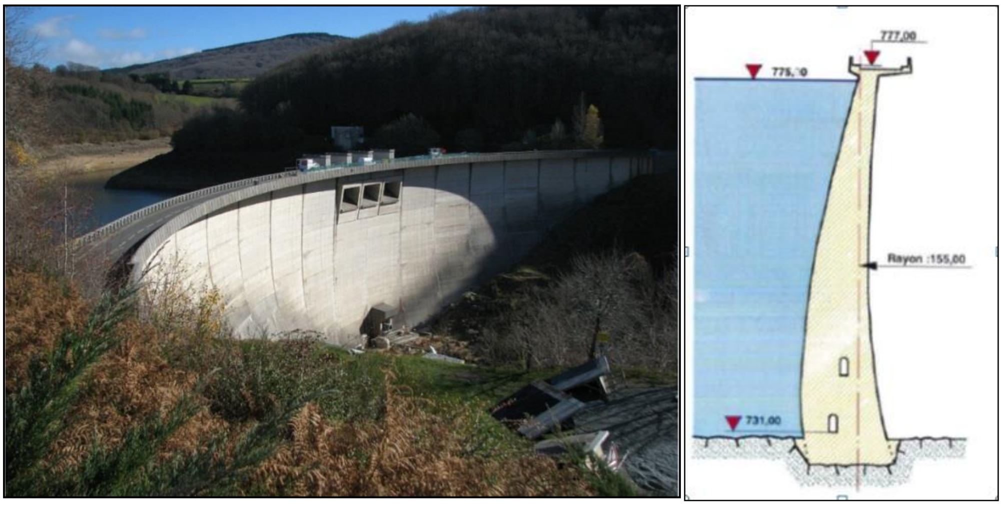


Figure 1. downstream view of the Laouzas dam and central cantilever design.

Considering that vertical tensile stresses would occur at the upstream toe of the dam, the design of the dam included a horizontal joint located close to the toe of the upstream face of the 4 central cantilevers. This joint runs from the upstream face of the dam to the upstream face of the lower drainage gallery. To avoid initiation of cracks in the concrete, the base of the central blocks is densely reinforced by rebars. The join has proved to be inefficient and a fissure has progressively developed at the interface between concrete and foundation of the central blocks.

Since the first impounding of the reservoir, significant drain discharge was observed in the lower drainage gallery (up to 410 l/min in 1969), on the downstream face of the dam, and immediately downstream, mainly due to the opening of the rock-concrete interface in the central part of the dam. Irreversible displacements of the structure were recorded by the monitoring system, namely at the base of the central blocks. Joint re-grouting was performed during the period end 1969 - end 1971 along with sealing of some cold concrete joint on the upstream face of the dam, leading to temporary positive effects on the behavior of the dam. In 1982 and 1983, in order to reduce the drain water discharge in the lower gallery, a new drainage system was bored immediately downstream of the dam and the existing drains in the lower drainage gallery were plugged. During the 1990', the dam was placed under close supervision, due to the progression of irreversible displacement, and additional monitoring system and drainage were installed.

At the end of winter 2005/2006, the combination of cold weather conditions and high reservoir level leads to the highest displacement and leakage rate ever observed by the monitoring system equipping the dam. Following this event, a limitation of the reservoir level in winter (5 m under the normal water level) was decided. Meanwhile, studies required to fully understand the behavior of the dam and assess its safety were performed [1].

In 2007, the installation of additional interstitial pressure cells at different locations in the vicinity of the concrete/foundation contact enhanced the progression of the rock/concrete interface opening and the diffusion of the interstitial pressure towards downstream beyond the generally admitted hypotheses. In parallel, complementary geological & geotechnical investigations and 3D finite-element analyses of the dam & foundation were performed by the Hydro Engineering Center of EDF.

3. FINITE-ELEMENT ANALYSIS OF THE DAM

In order to represent the observed behavior of the arch dam, a 3D nonlinear finite-element (FE) model using joint-elements at the dam-foundation interface and able to take into account the hydro-mechanical linkage was developed, first, using the FE software Gefdyn, and then with the open-source FE software Code_Aster (developed by EDF). Only the analyses performed with Code_Aster are presented in this paper.

The non-linear model computes crack openings and its propagation, uplift pressure and its diffusion which leads to extend the initial crack. For this purpose, joint elements are implemented, in the numerical model (Error! Reference source not found.). At the dam/foundation and abutment/foundation interface, these zero-thickness elements behave mechanically with high stiffness in compression and zero stiffness in tension. The tangential stiffness at the dam/foundation interface becomes equal to zero once the joint opens. The mechanical behavior of the dam-abutment interface follows a Mohr-Coulomb law.

In the joint-elements, effective state of stresses is considered. The propagation of the uplift pressure is modeled according to the Poiseuille law (or cubic law), considering that the flow increases with the cube of the crack opening.

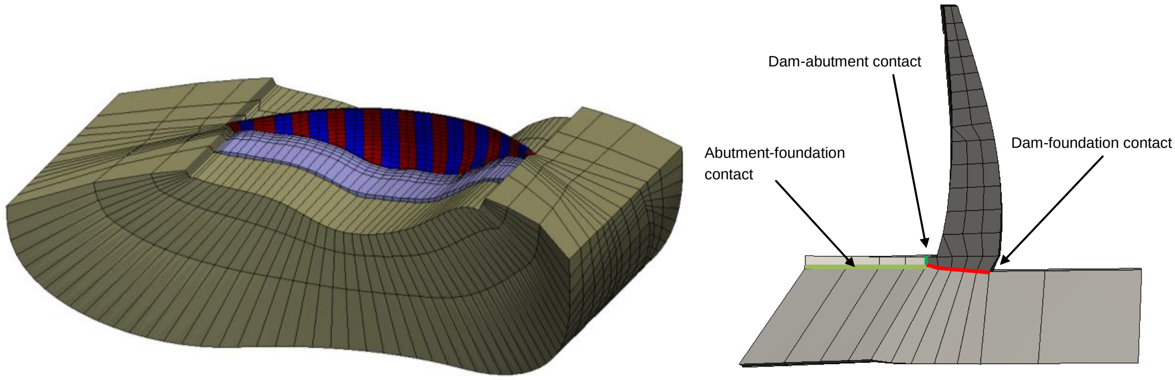


Figure 2 mesh of the dam, foundation and abutments and introduction of joint-element.

The FE model is calibrated from statistical analysis of the measured dam's displacement by adjustment of the elastic properties of the concrete and the foundation. Creep of the concrete is also taken into account in the study due to its contribution to the irreversible downstream displacement of the crest of the dam.

The FE analyses confirm that the hydrostatic load is responsible for the opening of the rock-concrete interface and the diffusion of the uplift pressure in the downstream direction. This behavior is enhanced by the increase of the dam's displacement toward downstream due to creep and to winter thermal conditions. Error! Reference source not found. shows the opening computed by the FE model at the dam/foundation interface due the normal hydrostatic load, under winter thermal conditions and creep: in that situation, with an opening of about 16 mm at the upstream toe of the dam, the full uplift pressure expands under the central cantilevers of the dam and the thrust can no more be transferred from the cantilevers to the foundation by the horizontal interface. The embedment of the structure in the sound rock foundation plays then a major role for stability.

The FE analyses compute the thrust from each cantilever to the underlying and downstream foundation. As shown in Error! Reference source not found., the thrust from the cantilevers is distributed between the underlying foundation (in red) and the downstream abutment (in blue). For the central cantilevers, due to the uplift pressure expansion and the model's assumption that no tangential forces are transmitted when the joint is open (which is probably slightly overestimated considering the irregular shape of the dam/foundation interface), all the thrust is transmitted through the downstream abutment (around 700 t/m for the 3 central cantilevers.

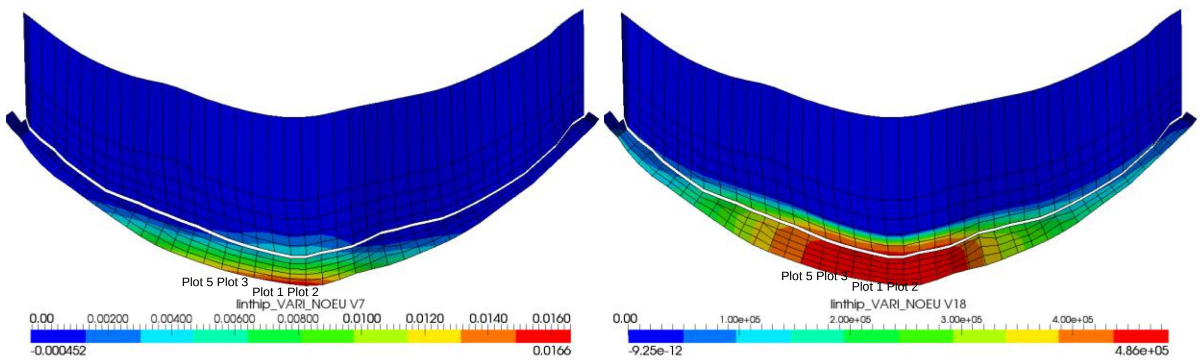


Figure 3 opening of the joint elements (left) and uplift propagation (right) on the dam/foundation and abutment/foundation interface (view from the top).

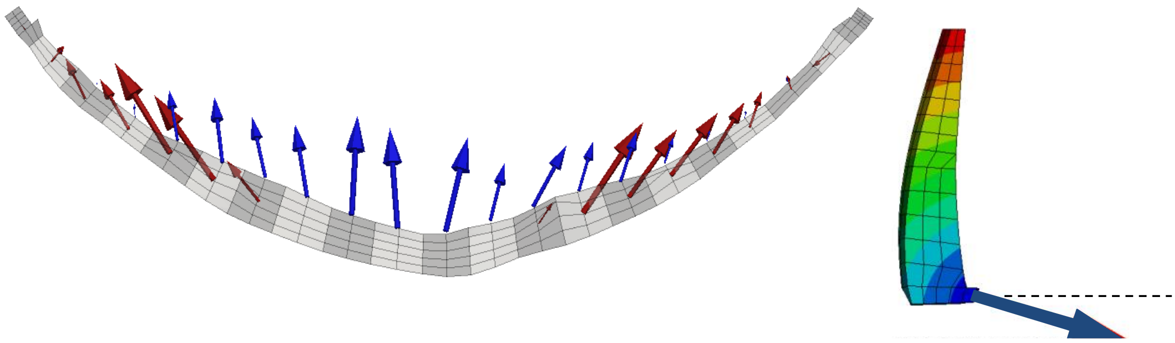


Figure 4 thrust from cantilever to foundation (underlying in red, downstream in blue) on the dam-foundation interface mesh (left) and view from the side of the central cantilever.

4. Studies of reinforcement of the dam and foundation

In parallel with the analyses of the behavior of the dam and foundation, various solutions of reinforcement or treatment of the dam and foundation were studied in order to restore the normal operation of the scheme (suppression of the reservoir level limitation during winter).

4.1. Sealing works of the dam/foundation contact at the upstream toe of the dam

The construction of an anchored plinth at the upstream toe of the dam associated with a new grout curtain and a membrane on the upstream face of the dam was studied. This solution is proven to be very effective to reduce the opening of the dam-foundation contact and maintain the thrust through the underlying foundation of the structure, and therefore limit the diffusion of uplift.

This technical option was not implemented, mainly due to risks and uncertainties which might affect the construction works, among which:

- Flood management during the time allocated to the works in the vicinity of the upstream toe of the dam,
- Uncertainties related to the depth of the fractured rock at the upstream toe of the dam, particularly on the left bank which affect the determination of the volume of excavations, the volume of grout to be injected, the efficiency of the grout curtain, and, as a corollary, the duration allocated to the works,
- Full emptying of the reservoir required to perform the works has great environmental, societal and operational impacts considering that the works would be planned over 2 years,
- Uncertainties related to the impoundment of the reservoir at the end of the works which may lead to a low water level on the edge of winter.

4.2. Installation of active rock anchors

Bringing an additional vertical stress to reduce the opening of the dam/foundation contact, by using high capacity active rock anchors was studied. These anchors could be installed from the crest of the dam or from the lower drainage gallery.

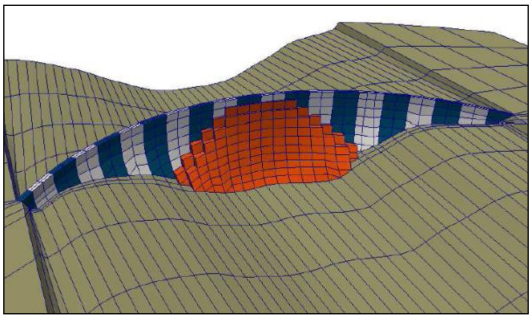
The emptying of the reservoir is not required to perform the works; therefore this option would reduce environmental and societal impacts and impose lower constraints on the scheme management.

However, finite-element analyses show that, to have a significant positive impact on the dam's behavior, the required density and capacity of rock anchors is beyond which can realistically be installed.

This technical option was therefore abandoned.

4.3. Stabilization of the dam with downstream concrete block

Stabilization of Laouzas dam by concrete blocks in contact with the downstream face of the dam was studied. Lateral or central reinforcement options were considered (Figure 5).



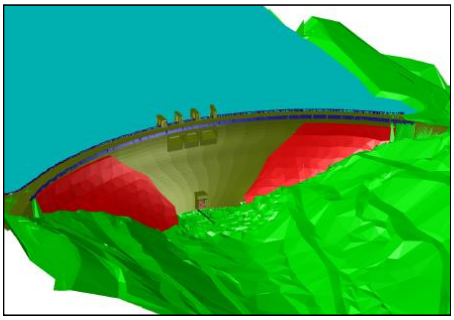


Figure 5 central and lateral downstream reinforcement of the dam.

Both solutions lead to favorable results relating to the reduction of the opening of dam/foundation contact and improve the transmission of the thrust on the foundation.

For the lateral block option, the depth of the fractured rock on the left abutment requires to perform deep excavations whose execution has an impact on the scheme management (significant lowering of the water level in reservoir during excavation works).

The central block reinforcement requires less excavation but interacts with the surface gated spillway and the bottom outlet.

The link between the existing arch dam and the new structure downstream has to be carefully designed in order to prevent any deterioration of the dam itself whose behavior is considered satisfactory to date.

For the central reinforcement: an adjustable device between the dam and the downstream reinforcement has to be designed to avoid any hard points which would crack the arch dam. In addition, a procedure has to be defined for reservoir impounding and progressive load transfer to the downstream structures.

The central reinforcement presented some interest but was judged somewhat risky with respect to the potential alteration of the arch dam behavior. In addition, the works has an incidence on the scheme management: temporary lowering of the water level in the reservoir, period of time allotted to the calibration of the device transferring the load thrust…

3.4. REINFORCEMENT OF THE DOWNSTREAM CENTRAL ROCK ABUTMENT

Considering that the concrete arch dam itself behaves perfectly well under loading (finite-element analyses show an acceptable state of stress in the concrete, visual inspections of the dam do not bring to light any non-conformity) and that every attempt to adapt the existing structure by adding concrete blocks or rock anchors can potentially modify the behavior or deteriorate the existing structure, the study focuses on the assessment of the capacity of the central rock abutment to sustain the thrust from the existing arch, especially as the quality of the rock in the center of the valley is extremely good.

This technical option, which is the one implemented, is described in the following chapter.

4. CONTAINMENT AND DRAINAGE OF THE DOWNSTREAM CENTRAL ROCK ABUTMENT

Following the event of 2006 (combination of a high water level in the reservoir and winter condition leading to the highest opening of the dam/foundation contact and therefore additional downstream displacements of the central blocks (which were totally reversible) & high drainage discharge) and the first finite-element analysis that highlights the near-horizontal thrust on the central rock abutment, a structure dedicated to containment and drainage of the rock located immediately downstream of the 2 central cantilevers was constructed in 2008-2009: two reinforced concrete beams housing, each, 5 pre-stressed anchors and a dense drainage network (Error! Reference source not found.). The anchors are 3 m spaced and are designed for a nominal tension close to 4000 kN. The aim of this reinforcement is to prevent the decontainment of the upper edge of the rock and the spreading of the uplift pressure.

The structure designed is evolutionary. It allows the installation of additional rock anchors and the densification of the drainage network. The structure hosts instrumentation devices: leveling points, rock extensometers, interstitial pressure cells, and gauges measuring the residual tension in the rock anchors.

2D finite-element analyses were performed to assess the stability of the rock abutment based on the thrust estimated by the 3D finite-element analyses of the dam and taking into account the rock fracturing and the topography.

Figure 6 view of the downstream beam and of the installation of the anchors.

Additional refined finite-element analyses performed in 2013-2014 show that the downstream reinforcement of the foundation needs to be extended to the adjacent cantilevers (each side of the two central ones), which also transfer a significant thrust to the rock abutment. This work has begun during summer 2016 and will be achieved in mid-2017.

Simultaneously a densification of the monitoring network is carried out. Additional direct and inverted pendula, and rock extensometers, tele-operated, are currently installed.

A test rise of the reservoir water level up to Normal Water Level took place at the end of winter 2017. The analysis of data collected by the monitoring system and the comparison to the predictions of numerical modeling assessed the satisfactory behavior of the dam.

5. Conclusions

In February 2006, the combination of cold winter condition and high water level in the reservoir have led monitoring devices to record historical maxima in terms of displacement of the central cantilevers of Laouzas dam and drainage discharge, and have raised questions regarding the behavior of this thin arch dam located in a wide valley.

After the decision taken, in 2006, to limit the water level of the reservoir during winter, and the construction, in 2008-2009, of the first phase of the reinforcement of the downstream rock abutment facing the two central cantilevers, almost 10 years were required, through the installation of additional monitoring devices, additional geological and geotechnical surveys, observational method and complex non-linear finite-element analyses, to collect the data and fully understand the mechanism driving the behavior of Laouzas dam and its foundation.

In this case, the analyses show that the hydro-mechanical coupling and the downstream central rock abutment play a major role in the diffusion of the forces from the arch to the foundation. The detailed surveys carried out confirm the pertinence of the foundation reinforcement constructed in 2008-2009 downstream of the central cantilevers and highlights the necessity to extend this structure to the adjacent blocks.

The understanding of the behavior of the dam and its foundation allowed the design of the best reinforcement solution, suitable for the specificities of the site and taking into account environmental, societal and operational requirements.

6. References

1. Bourdarot, E. and Hoonakker, M., "*Le comportement des barrages-voûtes en vallée large expérience tirée des barrages de Laouzas et Vouglans*", 24th International Conference on Large Dams, Kyoto, 2012.