The rehabilitation design of the Beauregard Dam

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Summary

The dam is the best example of the association between the "artificial" and the natural environment where it is located. For this reason one of the possible problems affecting a dam can be represented by the instability of the surrounding area, especially if not identified during the design phase.

The arch-gravity dam Beauregard in Valle d'Aosta (Italy) is an important example of this kind of problem; it is 132 m high, built between 1953 and 1962, and it has the left side of the valley characterized by a slow gravitational deformation that has generated anomalous stresses and deformations in the structure.
The reservoir generated by the barrage is subjected to a limitation of over 60 m with respect to the original normal water level.
Numerous studies, geological investigations and structural analysis of the dam-slope system have led to decide, like better rehabilitation, the demolition of the higher portion of 52 m of the dam, which will be carried out with explosives.

This publication briefly describes the characteristics of the dam, the gravitational deformation on the left side, the contents of the rehabilitation project and the description of the works started in 2011 and to be completed by the end of 2015.

Introduction

Beauregard dam (Figure 1) was realised on Dora di Valgrisenche River in the upper Aosta valley, north-west Italy. The waters are exploited in the Avise power plant (capacity: 126 MW, head: 1,040 m, max flow: 16.5 m^3/s).

The dam, built between 1953 and 1962, is a double curvature arch-gravity dam, founded on a "pulvino", 132 m high, with a crest length of about 400 m. The dam is 5 m thick at the crest level and about 46 m thick at the foundation level. The crest level is at 1772 m a.s.l., see Figure 2 and Figure 3.

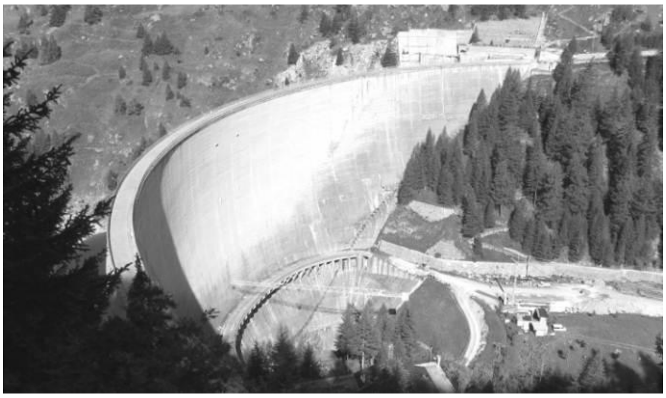

Figure 1: Beauregard Dam

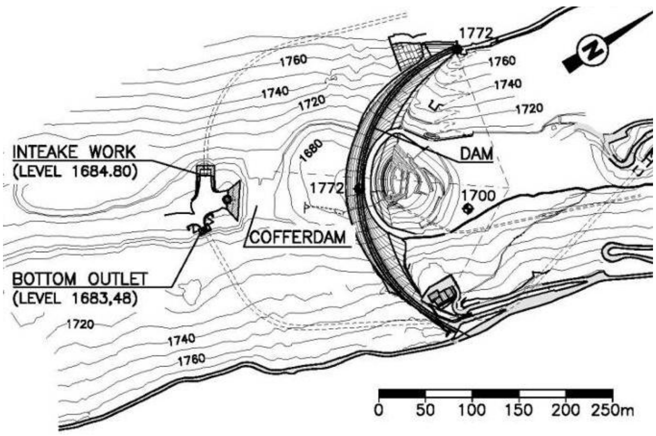

Figure 2: Plan

Geological context

The rock mass foundation of the dam is composed of gneiss and mica schist (Grand San Bernardo Series), with prasinite intercalations.

The left slope of Dora di Valgrisenche valley is characterized by a gravitational movement (Deep-Seated Gravitational Slope Deformation, DSGSD) [1]. This phenomenon is of post-glacial origin and it is very widespread on the Alpine territory. Generally DSGSD refers to a slow and progressive phenomenon of large size slope instability, not to simple landslides, with a rock mass volume of hundreds of thousands up to millions of cubic metres.

In particular, Beauregard DSGSD began about 10.000 years ago and the volume of the slope is well above 200 millions of m^3 and prolongs upstream to about 3000 m a.s.l..

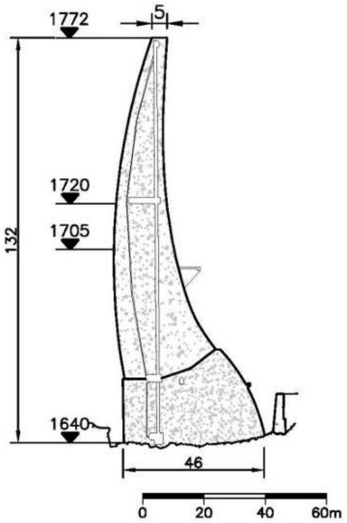

Figure 3: Cross-section at crown

Geological studies during the design stage did not point out the existence of this great gravitational movement on the left slope. During excavations and investigations for the construction of the dam it was observed that the valley left slope presented rock mass characteristics much poorer than the right, despite characterized by the same lithotypes. Besides it was observed that the gravitational movement had generated an anomalous extension of quaternary deposits, below the rock at the base of the left slope.
These deposits were interpreted first as a glacial subexcavation and later, with the dam almost completed, as a real overthrust due to the movement of the slope.
Figure 4 shows the prediction of the rock profile in the design phase, the rock profile during the excavation and the DSGSD basal area.
During the construction phases, the inclusion of glacio-fluvial sediments in the lower part of the slope requested the removal of the damaged rock and the construction of an inspectable concrete underpinning structure, also shown in Figure 4.

The importance of the project has made fundamental a heavy and accurate check of the slope, making it one of the most monitored in the world, both in terms of quality and quantity of data, with a series of observations that has now reached 60 years.
The slope is currently monitored with a complex control system, composed by pendulums, an automatic topographical survey system, surveys on the ground, GPS measurements, measurements with radar interferometry from satellite and ground.

The measurements confirm that the observed DSGSD is a coherent movement at a rate of approximately 0,5÷1 cm/year. The component of the maximum displacement is about 100 m, relative value of both the overlap of the glacial deposits and the valley bottom, and the vertical displacement of the upper part of the mountain. It was found that the front of the moving portion corresponds to the original surface modeled by the glacier: this means that the DSGSD has never crossed the valley; movements obtained from geological and geomorphologic elements, are the maximum ones.
The mean movement speed, evaluated on a geological scale, is therefore equal to 100 m in 10,000 years, which is about 1 cm / year. It can be said that the currently measured speeds are residual velocities of a phenomenon which in the past was faster.

There are no reasons to predict a dissimilar evolution in the future and a sudden and abrupt acceleration of the present movement.

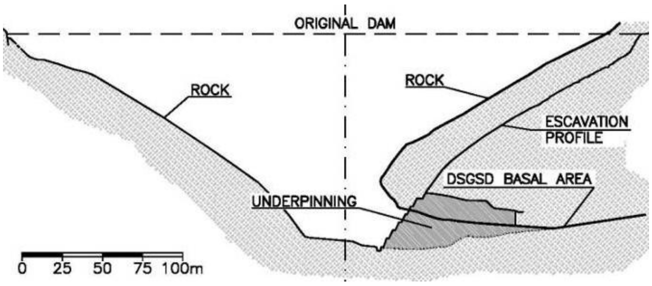

Figure 4: Downstream view

The reservoir and the dam deformation

Since the first fillings of the reservoir, significant movements of a large portion of the slope on the left abutment were observed, affecting also the dam.
Consequently, on the acceptance phase the normal water level was limited at 1730 m a.s.l.; later this level was further reduced to 1710 m a.s.l., then at 1705 m a.s.l. and finally to 1702.50 m a.s.l., 62.5 m less than originally planned. Consequently, the volume decreased from the original 70 hm^3 to 2.3 hm^3 today.

In fact, at the beginning of the experimental fillings (1958), the pendulums installed in the dam body showed anomalous movement upstream and towards the right bank, due to the DSGSD that creates growing stresses that were not foreseen in the original design.
In particular, the average movement of the upstream/downstream component of the cross-section pendulum is strictly correlated to the historical reservoir levels, especially from the first years of operation:

- 14 mm / year during the first period of fillings called "high" (1770.00 m s.m.);

- 7 mm / year during the period of fillings called "average" (1730.00 m s.m.);
- 3 mm / year during the period of fillings called "low" (1710.00 m s.m.).

The "high" and also the "average" fillings have probably accelerated the movement of the slope, but this statement is not reliable because the period of observation of the "high" fillings was short. These accelerations, hence, cannot be extrapolated on the long term.
With lower fillings the gravitative movement is influenced by natural meteoric phenomena and its value is of the same order of the DSGSD for 10,000 years.

The total deformation of the dam crest, from the end of construction to the present days, is 210 mm. It is evident that such a deformation caused a stress state at the downstream toe of the cantilevers that produced the opening of a series of cracks on the dam facing, resulting in a main crack with sub horizontal trend in coincidence of the central blocks (~ 1695 m a.s.l.), going up on the abutments.

Numerical evaluations of the structural behaviour of the dam

A numerical model of the dam-slope system was developed to investigate the structural behavior under the effect of the gravitational movement of the left side, simulated with the progressive constant translation impressed to a rocky wedge set on the sliding surface, which in its terminal part underpasses the underpinning concrete works.

The model was designed to reproduce the behavior of the structure from the construction to its present state. This procedure (back analysis) is based on the minimization of the differences between the observed measurements on the structure (displacements and stresses) and the results provided by the numerical model. Calibrated models can be used to predict the future behavior of the dam. In particular, it has been investigated the possibility that in the future a global structural instability could appear.
The quality of the results has been checked with the good correspondence between measured and calculated deformations in the simulation of the current situation and also with the comparison of the stress computed in the underpinning structure and at the bottom of the dam, with those found with the site investigations (flat jacks).

The results have shown that the stress state in the structure reaches peak values that, with the progress of the slope movement, decrease with the reduction of the stiffness of the structure caused by the accumulated damage. This happens without instability phenomena or loss of the structural equilibrium.
It can be excluded a "brittle" evolution of the effects of the accumulation of energy absorbed by the structure, induced by the continuous action of the slope slow movement.

Preliminary design choices

Actions induced by the DSGSD caused the damage of the dam, that makes impossible its complete structural and functional recovery, even if the deterioration of the structure does not sign a possible collapse.
In addition, the continuous movement of the slope will make worse the conditions of the highest part of the dam, promoting a progressive damage to the lower part of the more “squat” arches and of the "pulvino".

Consequently, it was decided to proceed with the "release" of the thrust in the abutment-abutment direction, in order to avoid the incremental effects of the slope movements.
Several schemes were examined, including the execution of one or more vertical cuts in the dam and the complete demolition of the upper part.
Numerical analyses, simulating different solutions, have shown that the best design choice is the demolition of the upper part of the dam up to 1720 m a.s.l.
Furthermore, it has still examined the execution of a vertical cut for the possible structural separation of the lower part of the structure.

Based on the results of the model, the demolition of the upper part of the dam can be considered the most efficient solution.
Finally in the post-demolition stage, the structure will assure its stability as a gravity dam.

Design

Before starting the interventions on the dam, some works were performed in order to reduce the movements of the DSGSD and better control the operation of the reservoir.
In particular:
- water drainage and water channeling that overflowed the Lakes of Morion, forming waterfalls that flow on the detachment cliff of the DGPV and the diversion and channeling of the messy surface water flow on the left side of the valley;
- increase of the discharge capacity of the riverbed immediately downstream the dam;
- construction of a spillway with changeable sill elevation (between 1702 m a.s.l. and 1705 m a.s.l.) which uses an existing by-pass tunnel as a discharge channel.

The rehabilitation project of the dam regards its partial demolition and the realization of all the necessary complementary interventions for a full operational capability of the plant and the final settlement of the area.

At the beginning of September 2011 the installation of the yard began.

Year 2011: temporary cofferdam

To operate safely in the area immediately upstream the dam, where the demolition material will be partially stored, it is necessary to build up a protection against the reservoir waters.

To this aim, it was then designed a provisional cofferdam that reaches 1705 m a.s.l. that guarantees the safety of the site, as well as the operation of the Avise power plant during the execution of the works.

The new spillway and the works on the downstream riverbed allows a safe operation of the reservoir during the works with the top water level at el. 1702 m a.s.l.

Figure 5 shows schematically the cross-section of the cofferdam with the crest at el. 1705 m a.s.l. At the end of the work the cofferdam will be removed down to el. 1698.00 m a.s.l.

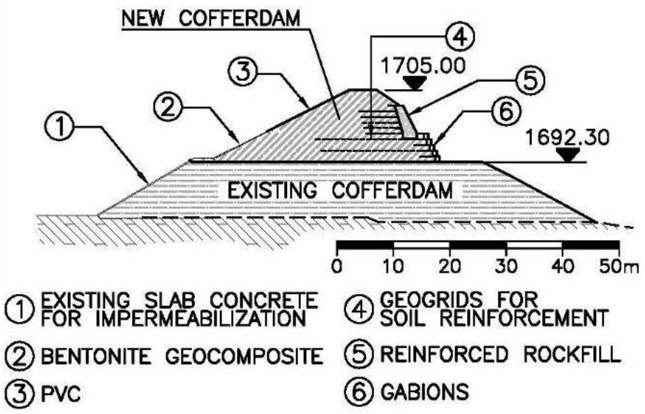

Figure 5: Cross section of the cofferdam

The cofferdam, built with material of the alluvial deposits of the original excavation of the dam, has been set on the crest of the still existing ancient cofferdam (realized for the construction of the dam), after the removal of about 2 m thick deposit of silt that piled up in 50 years of operation. The waterproofing of the upstream face, having a slope of 2 horizontally on 1 vertically, is obtained below el. 1698 m a.s.l. with a bentonite geocomposite protected by "Reno" mattress. Above that elevation it has been installed a PVC liner protected with a steel fabric reinforced geomembrane. Due to the limited dimensions of the crest of the old cofferdam, the downstream slope is realized by gabions and rockfill. The core of the embankment is reinforced with geogrids and geotextiles commonly used in reinforced earth works.

The different types of materials used above el. 1698 m a.s.l. (at the end of the works the cofferdam shall be removed above this elevation) were chosen during the construction phase, in order to have a faster construction and consequently reducing the period of out of service of the power plant.

As it was necessary the closure of the power plant for the construction of the new cofferdam, the period of these works was selected in November, when the natural inflows are historically lower, to minimize the production loss.

The embankment of approximately 25,000 m^3 of reinforced structures has been completed within 25 consecutive calendar days in November 2011 (Figures 6, 7 and 8).

Figure 6: Excavations for new cofferdam construction

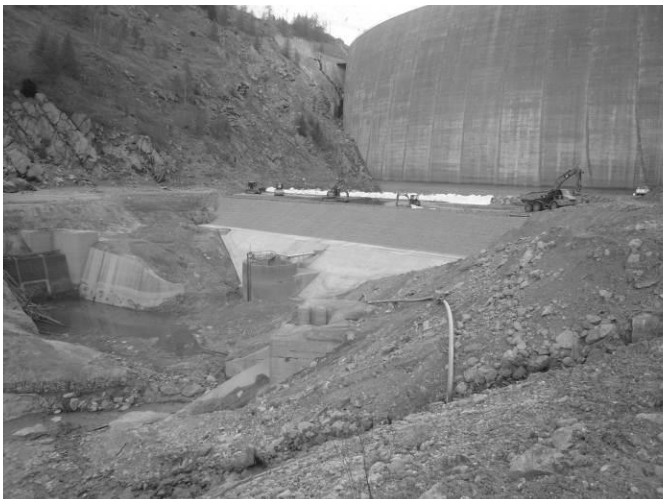

Figure 7: Cofferdam upstream view

Figure 8: New cofferdam at the end of construction

Year 2012: structures at the downstream toe of the dam
During the demolitions, the resulting material will be stocked upstream and downstream the dam in the two depressions that were made with the excavations for the construction of the dam, as shown in Figure 9.

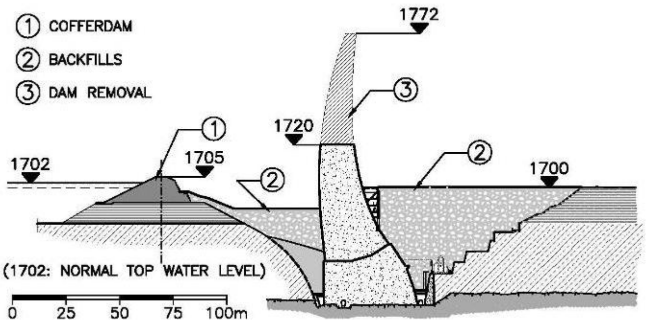

Figure 9: Storage of the material demolition

This allows the storage on site of the whole resulting material and ensures the support effect at the foot of the valley slopes originally provided by the quaternary deposit when it was present in the river bed.
The disposal of the demolition material downstream the dam must not preclude the accesses to the existing dam galleries and must allow the inspection of the lower part of the dam and the area of the facing where cracks appeared. It must also allow the inspection and maintenance of the outlet valves and of the seepage pumping station.
For that it has been planned to build three access shafts and a structure of inspection to the cracked area of the dam facing.

The first well, called "main shaft", is 40 meters high and has a circular section, with an internal diameter of 7.4 m. Its purpose is to allow the connection with the system of existing tunnels in the dam and the handling of electromechanical elements.

The second well, called "service shaft to the intake gate", is founded at el. 1679 m a.s.l. in front of the entrance of the tunnel to the gate of the penstock. The shaft is 20 m high and has an internal diameter of 4 m, for maintenance of the intake gate.

The third shaft allows the access to the bottom outlet. The underground work is 10 m high and it has been designed to allow the access to the gallery of the gate chamber of the bottom outlet. The shaft, besides the stairs, has sufficient space for the movement of the gates in case of extraordinary maintenance.

Finally some inspection rooms were designed to allow the inspection of the dam facing, beneath the console at el. 1700 m a.s.l., in the zone where the sub-horizontal cracks appeared. These inspection rooms will be protected against the demolition material by a vertical wall which will create a cavity between the dam and the demolition material storage.

During the year 2012 all the preliminary works for demolition as the realization of the planned facilities at the downstream toe of the dam (pits and inspection chambers of the cracks) were made and all reinforced concrete works have been completed (Figure 10, 11 and 12).
The protections, needed during the demolition of the dam, were installed for new outlets pipes, for the structures downstream the dam and for the guard house. The first explosion tests were also performed in order to evaluate the monitored seismic-acoustic data and possibly to refine or modify the plan of blasting before the demolition, expected in spring 2013.

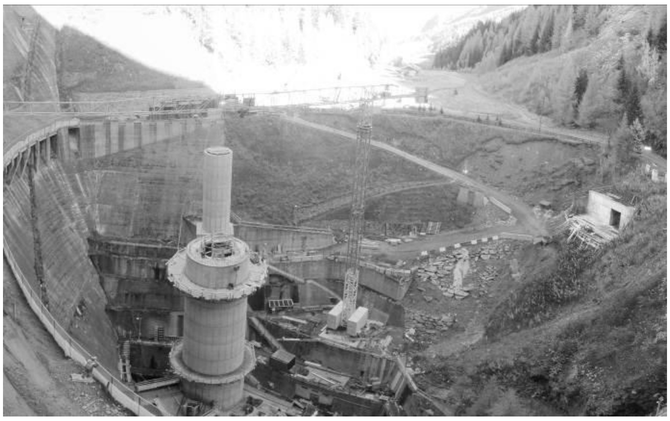

Figure 10: New structure at the downstream toe of the dam during construction

Figure 11: Main shaft during construction

Figure 12: Inspection shafts

Works scheduled in 2013 and 2014: demolition of the upper part of the dam

The dam will be demolished from the crest at el. 1772 m a.s.l. down to el 1720 m a.s.l.; the new elevation of the crest has been verified against possible landslides from both sides of the valley, falling into the reservoir. In fact it has been verified that el. 1720 m a.s.l. is safe even in the case of landslides with the reservoir at the new maximum water levels.

The operating methodology that has been selected as more suitable to destroy 160,000 m^3 of concrete, is a controlled blasting: the explosives shall be installed in a dense mesh of perforations located and directed according to a specific study, which ensures the control of blasting and the orientation of the fall trajectory of the material produced by the explosion.

It was considered that blasting was better than using breakers installed on excavators, due to the reduced continuous noise.

The operating specifications were established in order to ensure effectiveness and the caution necessary in this operating procedure.

The demolition is scheduled for layers 5.2 ÷ 6.0 m high. The perforations for the installation of the explosive will be vertical, with a diameter of 64 mm and spacing of about 1,5 m.

Each blasting operation shall require about 630 kg of explosive for the destruction of 2500 m^3 of concrete.

Each hole is triggered with "Nonel" detonators and micro delays of 25/1000 of a second to reduce the number of charges simultaneously exploding and consequently limit the produced vibrations.

The characteristics of the explosion have been studied by experts, both in the design stage and in the current implementation phase, taking into account the effects of explosions: 1) the vibrations caused by microbursts, 2) the noise and the overpressure in the air 3) the projecting of the explosion debris.

1) According to the studies that have been realized, the vibrations caused by microbursts are far below the limits established for the protection of buildings following various foreign regulations, in particular the recent and modern Swiss standards (the Italian legislation does not consider the argument). In any case, the Technical Specifications impose safety limit values to the vibration speeds that must be followed for the dam body and for the valley slopes. Since the first explosion test, the vibrations will be measured with eight triaxial seismographs, located in the dam, on the slopes and in a near village.

2) As it regards the noise, there will be no concern as it is known that it is the unexpected noise that can trouble people. This will be excluded since the population living in the surrounding area will be adequately warned. Regarding instead the real overpressure, the calculated values are considerably less than any limit reported in the literature.

3) The distance to which the explosion debris can be projected, based on the studies carried out, is less than 30 m, therefore of absolute safety both in respect of the population, of the buildings and of existing works.

Records and observations of the effects of explosion tests, performed with reduced charges and then gradually increased, confirm the studies and do not suggest any changes in the scheme of fire.

The demolition will start in spring 2013, for 15 working months (two summers), with weekly blasts of about 2,500 m^3. The demolition of the dam will be concluded at the end of 2014.

Works scheduled in 2015: final settlement works

The debris material at the downstream toe of the dam will be arranged to el. 1700 m a.sl., where the present plane will be extended to the cantilever of the downstream face of the dam and three shafts will be completed and covered. Finally the only works not covered by the blasted materials shall be the access to the larger shaft (elevator and stairs), the access to the shaft to the bottom outlet and the entrance to the catwalks of the fissures area.

In 2015 the new crown of the dam, the structures downstream the dam and related equipment, the new deep outlet in the dam body, the embankments for the dam abutments will be also completed.

At the end of the works, the cofferdam will be removed to el. 1698 m a.s.l., in order to ensure the continuity of the surface of the lake up to the dam.

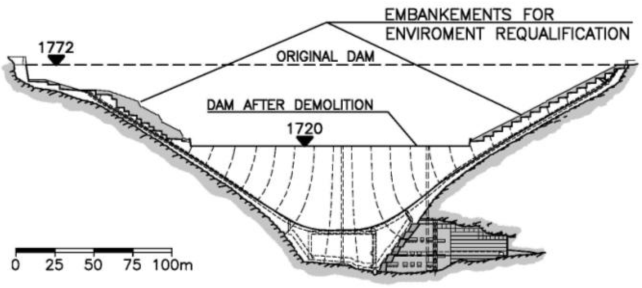

Figure 13: Final settlement

All the works including the removal of the yard and the final settlement will be completed by the end of 2015 (Figure 13).

Conclusions

The left slope of Valgrisenche valley (Italy), where Beauregard dam was built, is characterized by a gravitational movement (Deep-Seated Gravitational Slope Deformation, DSGSD). Consequently, the dam is subjected to a damage of the dam, making impossible its operation at the original design levels or its structural and functional recovery, even if the deterioration of the structure does not point out a possible collapse.

The demolition of the upper part of the dam (it will be lowered by 52 m, blasting 160.000 m^3 of concrete) is considered the most efficient solution as also the deformation state of the remaining structure improves. Finally, after the demolition stage, the structure will behave as a gravity dam.

The rehabilitation project of the dam regards not only its partial demolition but also the realization of all the necessary complementary interventions like the temporary cofferdam (indispensable to operate in the area upstream the dam during the demolition) and the structures located at the downstream toe of the dam to permit, after the demolition, the inspections of the galleries and the maintenance of the lower part of the dam.

The works started in September 2011 and are planned to be concluded at the end of 2015.

References

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