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REHABILITATION OF THE PIAN TELESSIO DAM (IT) AFFECTED BY AAR-REACTION[1]

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1. INTRODUCTION

The Pian Telessio arch gravity dam located in the Orco valley is 80 m high with a total crest length of 515 m. The dam is impounding a reservoir of 24 mio. m^3 of capacity. Figure 1 shows a typical section of the dam completed in 1955 after approximately 5 years of construction. The foundation of the dam is located in sound gneissic rocks relatively compact and with limited fractures.

The dam is equipped with an overflow spillway on the left abutment, whereas the bottom outlet is located on the right flank. No major appurtenant works are located in the dam body. During the first 20 years of operation the behaviour of the dam corresponded to the expected one: mainly reversible deformations and very limited permanent deformations. At the end of the 70' perma-

[1] Réhabilitation du barrage de Pian Telessio affecté par la réaction alcali-granulat

nent displacements were noticed in the upstream direction. These deformations were recorded first at the dam crest and later at lower elevations.

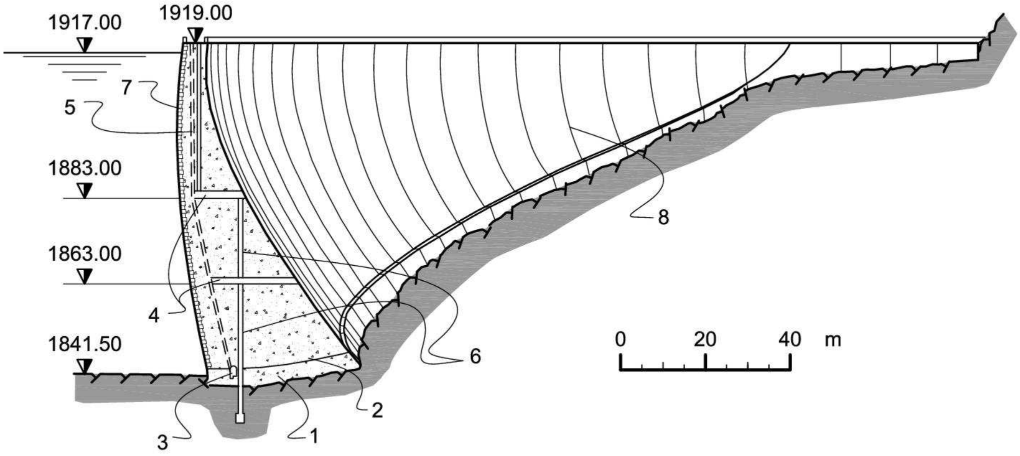


Fig. 1
Pian Telessio dam: typical dam section
Barrage de Pian Telessio: section type du barrage

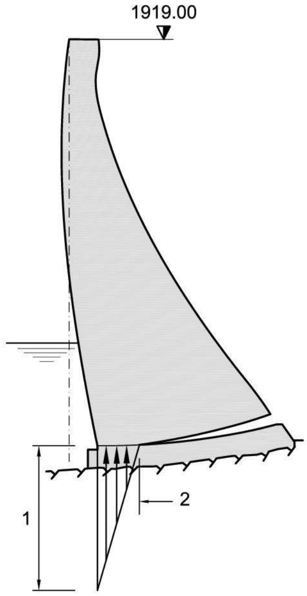
1. Pulvino
2. Peripheral joint
3. Drainage gallery
4. Inspection gallery
5. Drainage hole
6. Pendulum
7. Facing
8. Contraction joints

1. Pulvino
2. Joint périmétral
3. Galerie de drainage
4. Galeries d'inspection
5. Drain
6. Pendules
7. Revêtement en maçonnerie
8. Joints de contraction

Various analyses have been carried out both numerical and on the concrete of the dam body in order to establish the causes and the consequences of the concrete swelling on the stability and safety conditions of the structure. Without indicating the details of these studies, the relevant conclusions were the following:

– The permanent deformations are due to swelling phenomena caused by an AAR reaction. This swelling is not uniform and is more significant at the upper half of the dam compared to the lower portion. The progress of the phenomena is relatively slow (around 10 µm/m/year) but compatible with several other observations made in the last decade in the European Alpine region.
– The permanent deformations are affecting stress distribution within the dam. The influence of these deformations on the stresses is more relevant than the influence of the reservoir elevation. As a consequence, any safety consideration of the structure has to take into consideration the ongoing swelling process. The most significant influence on the

stress distribution is the increase of the arch compressive stresses as well as the increase of the compressive stresses at the upstream toe of the perimetral joint. Figure 2 shows the cinematic behaviour of the dam with the schematic increase of the compressive stresses along the perimetral joint.



	OPERATING CONDITIONS	COMPRESSION AT HEEL OF DAM [MPa] AVERAGE	COMPRESSION AT HEEL OF DAM [MPa] MAX	OPENING OF PERIPHERAL JOINT [%]
	INITIAL STATE (DEAD LOAD)	2.3	3.8	34
END OF 2006	EMPTY RESERVOIR - SUMMER	13.7	15.4	90
	EMPTY RESERVOIR - WINTER	7.4	11.0	79
	FULL RESERVOIR - SUMMER	2.5	3.3	39
	FULL RESERVOIR - WINTER	1.5	1.7	0

Fig. 2
Compressive stresses at the upstream toe of the dam.
Contraintes de compression au pied amont du barrage.

1. Compression stress — *1. Contrainte de compression*
2. Limit of joint opening — *2. Limite de l'ouverture du joint*

In order to counter the swelling of the concrete, various options have been evaluated. The considered and realized final concept includes basically the cutting of the upper half of the dam using diamond wires. The 16 slots have a length between a minimum of 21 and a maximum of 39 m. The slots have been realized with diamond wires of 10 mm up to 16 mm diameter. The basic concept is to release the elastic stresses in the dam related to the swelling process and establish a static situation close to the original one (after injection of the vertical joints). Once the swelling stresses have been released, the slots are grouted in order to re-establish the structural continuity of the arches. This grouting is done similarly to the classical injection of vertical joints of arch dams with some special constructive solutions required for the slots sealing.

The final design of the rehabilitation works was carried out in 2004 with the approval procedure by the Italian dam supervision authority completed in July 2007. After some preliminary activities carried out in autumn 2007, the main works started in spring 2008 and were completed in the autumn of the same year.

The measures carried out during the slot cuttings were extremely useful to compare the measured deformations with the expected ones, in particular as regards the closing of the cutting slots.

2. GENERAL PROPERTIES OF THE DAM

The Pian Telessio dam is located in the Orco Valley impounding a reservoir with a normal water level at 1917 m a.s.l. The double curvature arch gravity dam has a total height of 80 m with a crest length of 515 m. The crest thickness is 5.7 m whereas the maximum base width is 35 m corresponding to 45% of the maximum height. With a total concrete volume of 380'000 m^3 the slenderness factor of the dam is rather high attesting the optimised design of the structure. The profile of the dam has been selected in order to optimally withstand the hydrostatic loads. However this geometry results in tensile stresses at small or no impounding at all, in order of which the dam has been equipped with a perimetral joint as often designed according to Italian practice.

The dam is equipped with one perimetral inspection gallery located within the perimetral joint and two horizontal control galleries. These galleries are equipped with a drainage shafts collecting seepage waters especially at the upper section of the dam.

The monitoring system of the dam has been gradually increased in order to better evaluate the permanent deformations of the dam. The monitoring instrumentation includes basically 4 pendulum sections.

In addition the dam is equipped with joint metres, clinometers and a geodetic grids as far as the measurement of deformations are concerned. To improve the prediction of the dam deformation, additional thermometers were installed in the concrete in order to better evaluate the thermal field.

3. BEHAVIOUR OF THE DAM DURING THE LAST 35 YEARS

After the dam was put into operation in 1955, the behaviour observed during the first 20 years was in agreement with the expected one. As shown in Figure 3, since almost 1980 a permanent deformation in the upstream direction in particular at the centre of the dam crest was recorded. Approximately 15 years later the permanent deformation was no longer questionable and investigations were started to identify their causes.

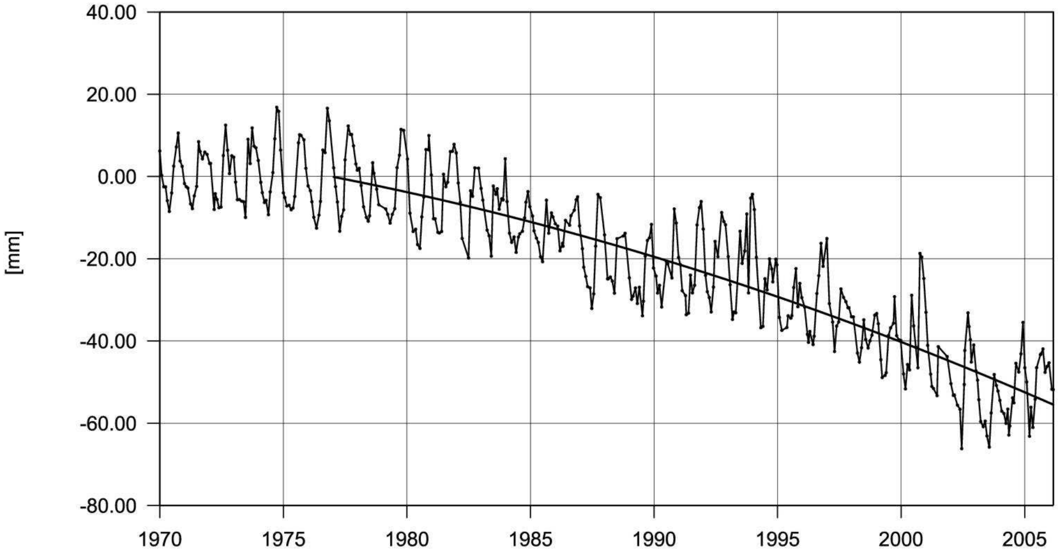


Fig. 3
Radial crest displacements since 1970 (+ downstream, - upstream)
Déplacements radiaux en crête depuis 1970 (+ amont, - aval)

In many other cases, the analysis was carried out by exclusion of potential factors ranging from movements of the valley flanks, variations of the uplift pressures to potential instrumentation errors.

Laboratory tests on concrete samples indicated a potential for AAR reactivity but the presence of an ongoing AAR reaction could not be clearly identified. It should also be pointed out that in many other dams in the alpine region no typical AAR fractures nets are visible on any part of the dam itself or on the appurtenant structures.

Following a complete analysis of the available information, and some additional investigations carried out in the 90', it could definitively be asserted that the permanent deformations of the dam are caused by an ongoing AAR reaction.

According to the measured deformations, the concrete swelling is more significant in the upper half of the dam whereas in the lower half practically no concrete swelling occurred. Although the causes of this difference is not totally understood, it is probable that the different composition of the concrete aggregates between the upper and the lower part of the dam body is causing a different swelling behaviour. At the crest elevation the effective swelling ratio reaches 10 µm/m/year whereas nearly no swelling occurs in the region of the dam base.

In addition to the permanent deformations some horizontal cracks appeared in the upper inspection gallery developing progressively into one single continuous crack (Fig. 4).

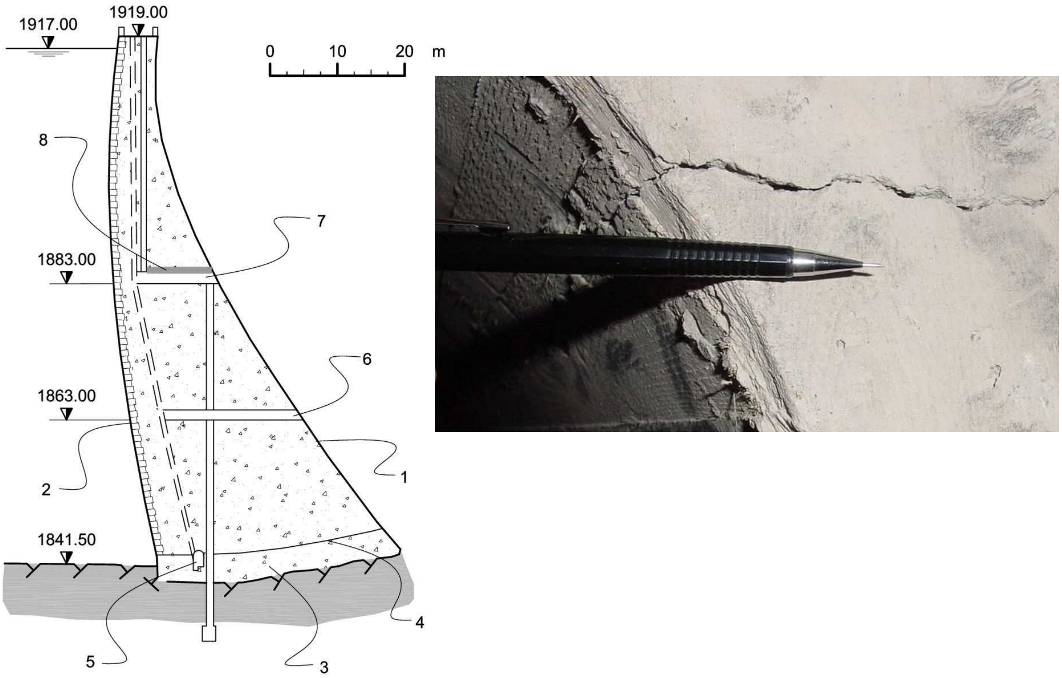


Fig. 4
Crack in the upper gallery.
Fissure dans la galerie supérieure.

1. Downstream face	*1. Parement aval*
2. Upstream face	*2. Parement amont*
3. Pulvino	*3. Pulvino*
4. Peripheral joint	*4. Joint périmétral*
5. Drainage gallery	*5. Galerie de drainage*
6. Lower gallery	*6. Galerie inférieure*
7. Upper gallery	*7. Galerie supérieure*
8. Fissure	*8. Fissure*

With a total permanent deformation at the centre of the crest arch of nearly 55 mm, and some cracks developing into the structure, numerical analyses were carried out in order to evaluate the static behaviour of the structure and the present and future safety conditions.

The numerical analyses were carried out in 2002 in order to simulate as good as possible the observed permanent deformations of the dam with the purpose to establish the corresponding stress distribution. Various attempts were necessary to obtain a plausible stress distribution, which might reflect the effective status of the dam. The analysis clearly showed that a thermal similarity of the swelling process is inadequate, but that more accurate models are difficult to establish due to the complexity of defining properly the constitutive parameters. The model finally adopted takes into account the effect of the compressive stresses that reduce the free expansion rate [1]. The effective expansion rate is thus anisotropic and has the same direction as the principal stresses.

According to these analyses the maximum compressive stresses in the upper arches are reaching 11 MPa, whereas maximum tensile stresses reach 2.3 MPa at the downstream dam face. Furthermore due to the progressive opening of the peripheral joint, the vertical compressive stresses at the upstream dam toe reach approximately 10 MPa for the usual operating conditions with maximum values occurring in case of an empty reservoir during summer.

Although the safety conditions of the dam are presently not compromised, the progressive deterioration of the static conditions of the dam would result in the mid term into a no compliance of the Italian dam regulation.

According to this situation it was decided to limit the operational conditions of the dam in order to avoid situations with the maximum compressive stresses both in the upper arches but especially at the upstream toe of the dam base. An operating instruction was adopted since October 2003, with a limit for draw down. The proposed limit was variable during the year: at higher elevation in summer (1905 m a.s.l.) and lower in winter (1870-80 m a.s.l.). The limit in winter increased progressively because of the continuous expansion.

4. REHABILITATION PROJECT

The operating instruction was not acceptable on the long term and it was decided to propose a rehabilitation project. The rehabilitation must primarily allow recovering an usual and comfortable stress condition in order to guarantee the safety of the dam for all operating conditions. Various options for the rehabilitation of the dam were evaluated and compared in terms of efficiency, feasibility and costs. The proposed solution provides the execution of a certain number of vertical slot cuttings in order to relief the compression in the arches in the upper part of the dam.

The upper part of the dam is temporarily transformed into a structure formed by independent blocks, similar as the original situation during construction of the dam before joint grouting. In order to allow the recovery of the full reservoir volume it is successively necessary to close the slot cutting and re-establish the arch effect in the whole structure.

The rehabilitation project does not try to avoid the further expansion, since today there is any certain method to achieve this. Therefore it must be taken into account that a similar rehabilitation has to be repeated in the future.

The slot cutting allows to compensate and eliminate the lengthening of the arches occurred during the last 25 years because of the chemical expansion. This lengthening originated a rotation of the structure upstream and the related opening of the peripheral joint with the consequence of stress concentration at the heel of the dam. The slot cutting allows the recovery of the original state of stresses equally in the upper part as at the dam base.

The concrete cutting with diamond wire is a technique that was already used successfully on other dams as Mactaquac in Canada or Chambon in France. The particularity of Pian Telessio is that the dam needs at end the arch effect so that a slot grouting is required.

The project proposes the execution of 16 vertical slots with variable height of 21, 31 and 39 m (Fig. 5). The distance between adjacent slots is around 26 m and the total cutting surface arises up to 3500 m^2. Table 1 resumes the main characteristics of the cuts.

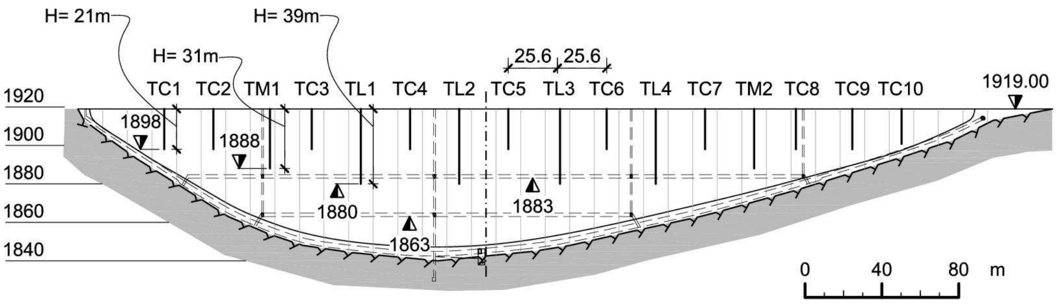


Fig. 5
Position of slot cuttings.
Position des sciages.

Slot type	Name	Height [m]	Surface [m^2]
Short	TC1 - TC10	21	148
Medium	TM1 - TM2	31	263
High	TL1 - TL4	39	385

Table 1
Characteristics of the slot cuttings.
Caractéristiques des sciages.

The cutting equipment is composed by a drive wheel placed on a scaffold fixed on the downstream face of the dam. The diamond wires passes through the dam in a drillhole of 60 mm, previously carried out with core recovery in order to minimize deviations, and reach the upstream dam face. Sheaves allow driving the diamond wire along both faces. The diamond wire starts cutting on top and proceeds downward (Fig. 6).

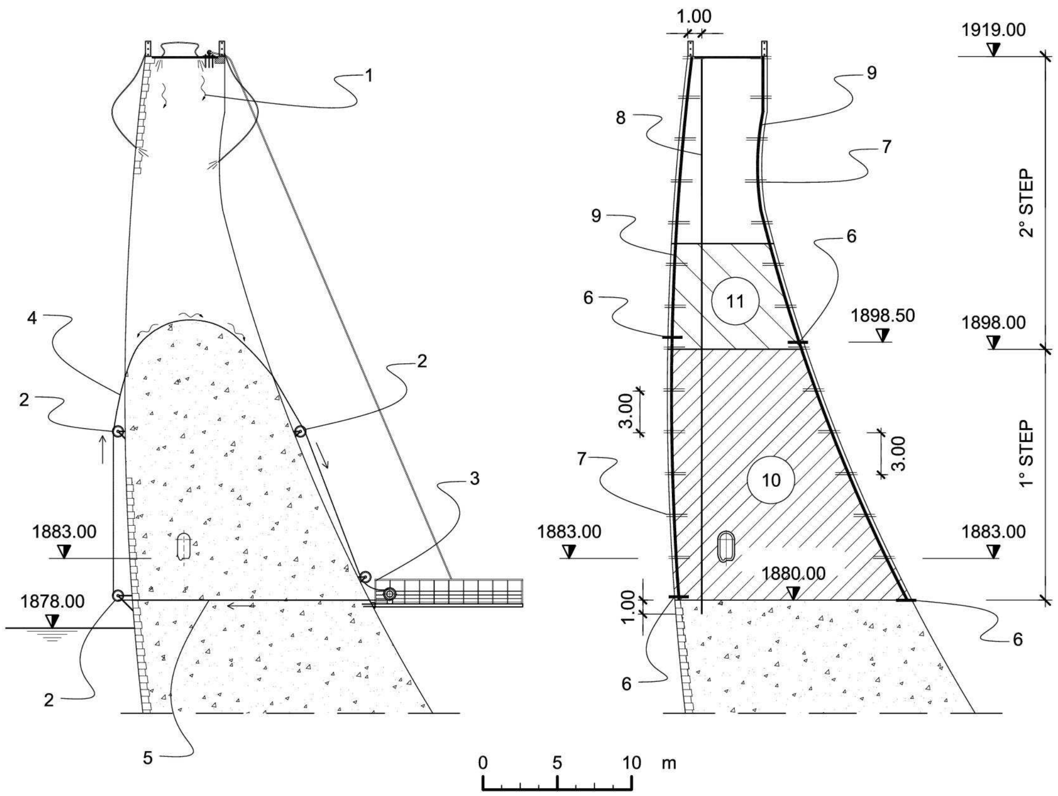


Fig. 6
Construction phases: slot cutting and grouting.
Phases de construction: sciage des plots et clavage des joints.

1. Wash water
2. Sheaves
3. Drive wheel
4. Diamond wire (∅ 10/16 mm)
5. Drillhole ∅ 60 mm
6. Grouting pipes
7. Return pipes
8. Sealing element (rubber cylinder)
9. Water stop

1. *Eau de refroidissement*
2. *Poulies de renvoie*
3. *Machine d'entraînement du fil*
4. *Fil diamanté (∅ 10/16 mm)*
5. *Forage ∅ 60 mm*
6. *Tuyau d'inspection*
7. *Events*
8. *Dispositif d'étanchéité*
9. *Couvre joint*

For the final part of the cutting the lower sheave at the upstream face is eliminated and the cutting continue from upstream toward downstream.

In order to guarantee the permeability of the slots also in case of some limited movements (openings), a special sealing element is placed inside of each slot. The sealing element consists in a tube composed by soft rubber. The thickness of the tube wall is around 1 cm. The rubber tubes are inserted in vertical boreholes carried out in correspondence of each slot cutting.

The proposed sealing method allows to minimize the impact of the works on the upstream dam face, that is coated with stones. The adopted solution has a sufficient elasticity in order to absorb limited slot openings and the tube is protected inside the dam from external conditions (ice, low temperatures, water).

In order to facilitate the final grouting procedure the minimal opening of the slots was fixed at 6 mm. By taking into account a closure of the slots the during cutting process, the diameter of the diamond wire was 10 mm for the short slots and 16 mm for the medium and the long slots.

Prior to start with the grouting the slots were cleaned and waterstops placed on both faces in order to avoid losses of cement grout. The ideal grouting period lies between the spring and the summer period. The grouting was limited in elevation up to 20 m with the purpose to minimize its pressure. Return pipes placed at regular distances allow following adequately the grouting process.

5. REHABILITATION WORKS

The rehabilitation works started in September 2007 with the installation of the construction plant and some preparatory activities. In 2007 only two short slots TC9 and TC10 were completed. The dam site was closed at the end of November 2007 for the winter break until the end of March 2008.
The cutting works were afterwards concentrated during the period between April and July. Short slots have been executed prior to the medium and long slots.

After an initial period consecrated for the optimisation of the cutting equipments, a satisfactory execution process was be achieved. The average cutting advancing rate reached around 8 m^2/h. The cutting of the short slots took generally 3-4 days and the long ones 2 weeks. Two independent slot cutting equipments turned almost 7-8 h/day each. At the end of the cutting works the surfaces of the slot were very smooth and perfectly polished. It was possible to check visually through the slots openings the vertical precision of the cutting.

For the installation of the sealing elements it was necessary to execute a vertical perforation in correspondence to each slot. The boreholes, completed without core recovery, were able to follow the slots without the need of any special drive tool. The perforation caused however the filling of the slots with concrete chips. It was necessary to re-cut all slots in order to get again a clean and open space for grouting works

The sealing elements, composed by a rubber tube, could easily be inserted in the vertical borehole and filled with cement grout in order to obtain adherence with the borehole surface. With a pressure of 0.7 bars the external diameter of the tube reached 150 mm, passing clearly the borehole diameter of 130 mm. The slots were grouted separately on both side of the sealing element. The maximum height of each grouting phase was limited a maximum to 20 m.

The grouting works proceeded as expected. Only the waterstops on both dam faces, required to contain the cement grout, could never perform fully satisfactory. So, to limit further the pressure, the height of the grouting fields was reduced in some slots at 10 m.

The cement grout was composed by cement 52.5 with a W/C ratio of 0.6 and 2% of water reducing agent. The Marsh-Standard test was around 1 minute and the bleeding was 1.5% after 90 minutes.

Figure 7 illustrates the construction program carried out. The whole rehabilitation of the dam could be completed at the end of August 2008 after only 8 months of works.

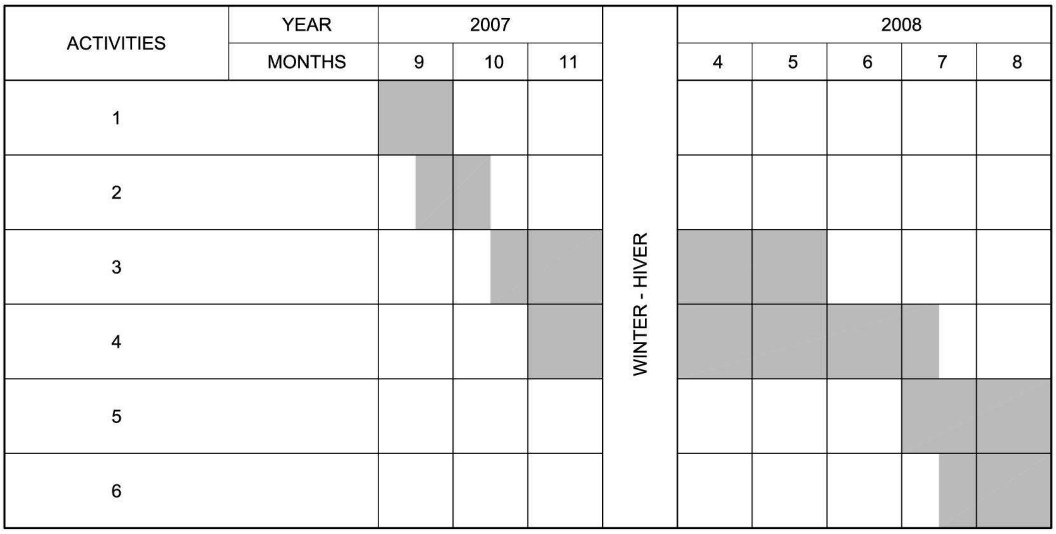


Fig. 7
Construction program.
Programme des travaux.

1.	Construction plant	*1.*	*Installations de chantier*
2.	Field tests	*2.*	*Champ d'essais*
3.	Auxiliary works	*3.*	*Travaux auxiliaires*
4.	Slot cutting	*4.*	*Sciage du béton*
5.	Slot sealing	*5.*	*Etanchement des joints*
6.	Slot grouting	*6.*	*Clavage des joints*

The impounding program proposed to reach the normal water level in 4 steps with a progressively higher elevation. The first step corresponds to elevation 1904 m a.s.l., i.e. 13 m below the normal water level and 26 m above the maximum water level allowed during the rehabilitation works. This first step corresponds to the water level reached during the first impounding in 1955 without having been grouted the joint.

The water level started to increase slowly since the 10th of August and at the end of August reached the bottom of the short slots. The lower part of the long and medium slots have been grouted at first in month July.

6. BEHAVIOUR OF THE DAM DURING AND AFTER REHABILITATION

The behaviour of each cut was monitored during cutting and grouting as well as during the subsequent phase of impounding (increasing of water level). Two target points have been placed at the crown downstream and upstream in correspondence to each cutting.

The measurements indicated that the closure of each cut is instantaneous and depends directly on the advancement of the cutting works. Any evident delayed response was observed. This linear elastic behaviour was confirmed on all slots. The total closure induced by the cutting works reached 70 mm. Long slots closed around 8 mm, short one about 3 mm.

The measurements indicate as well an interaction between adjacent slots. In some cases during the cutting of the long slots, the adjacent short slots showed a small opening.

The slots showed a progressive closing between the beginnings of May until mid August due to the increasing of temperatures. This progressive closure reached a total of 30 mm. The total closure of the slots was thus at beginning of the grouting around 100 mm.

During grouting different slots showed some openings even if the grouting pressure was sufficient to compensate the dead load of the cement grout. These openings were mainly determined by the closure of adjacent vertical joints. The total registered value of openings during grouting was 40 mm.

The total closing of the slots induced by the proposed works was finally around 60 mm. The structural analysis indicated a global closure of 65-70 mm. The comparison between expected and actual behaviour was satisfactory for the slot closing.

The monitoring of the movements of the slots was carried out by instrumentations specifically installed for the rehabilitation works. Beside them, the usual instrumentations of the dam were active during the whole rehabilitation period. In particular the pendulum allowed measuring of the displacements in radial and tangential directions. During the slot cutting, the effects on the radial displacements were not clearly visible, while the structural analysis indicated a displacement of the crown towards downstream.

A downward displacement was visible during the phase of water level increasing. The value of permanent displacement towards downstream reaches currently around 10 mm. A final evaluation of the rehabilitation is presently not possible since the recovery of the full reservoir capacity is first required.

The usual instrumentations of the dam were also able to monitor the behaviour of the principal cracks observed in the dam as well as the peripheral joint. The effect of the slot cutting is not clearly visible on the behaviour of all cracks. It can however be formulated that the expected behaviour is very uncertain to define, since the local conditions of each crack may vary noticeably.

The other monitoring devices, such as uplift pressures or seepages measurements, do not allow any conclusion about the behaviour of the dam during the rehabilitation. No changes were observed according to the expected behaviour.

The monitoring of the dam was completed with the measurements of stresses with flat jack tests. First stress measurements have been carried out in October 2007 before slot cutting. The tests results indicated horizontal stresses, in the direction of the arches, variable between 0.8 and 1.7 MPa at the crest and between 2.3 and 3.4 MPa at the downstream face 13 m below the crest. These results matched very well with the structural analyses. The water level during the tests was at elevation 1895 m a.s.l.

Flat jack tests have been repeated during slot cutting, i.e. with all slots open, and after the rehabilitation during the impounding. Both these measurement campaigns did not indicate a clear reduction of measured horizontal stresses. The values lied between 2 and 3 MPa. This result is surprising since the horizontal stresses with open slots should be near zero. This discrepancy shows the difficulty to measure stresses in a large structure as a dam.

At the preparation of the present contribution the impounding of the reservoir is still ongoing. Hence, final considerations on the efficiency of the rehabilitation works are at present not possible. However based on the currently available results, the cutting allowed to compensate most of the swelling occurred during the last 20 years of the dam. It is presently unclear at which frequency a rehabilitation will have to be repeated in order to limit the permanent deformations of the dam within an acceptable range.

7. CONCLUSION

Apart the crack in the upper gallery, the dam did not show any damage. There was no evident appearance of expansive reaction (typical cracks, reduction of concrete properties). However, its presence could be clearly identified with the monitoring device (pendulum). The presence of an AAR reaction was also confirmed by laboratory investigations.

According to the structural analysis, the expansion rate lied around 10 µm/m/year. The expansion had also a very slow rate. The total expansion reached almost 250 µm/m.

The rehabilitation of the dam was required in order to relief the compressive stresses. The safety margins were lower with empty reservoir than with full capacity. In summer with empty reservoir the upstream rotation of the dam reaches the maximum value, producing a concentration of vertical compressive stresses at the heel. These stresses did not satisfy the safety margin compared to the relative low compressive strengths of the concrete. The critical element was not a direct consequence of the expansion but a secondary consequence induced by the structural behaviour of the entire dam body.

Slot cutting was found to be the unique reasonable solution to relief the stresses. An upstream impervious membrane was not proposed as complementary solution to avoid further expansion, since its effect is not certain. The expansion will thus continue and in the future a similar remedial action will be required.

The behaviour of the dam during the rehabilitation was for certain aspects different from the expected one. This difference could not be clearly explained. The slot cutting closed as expected but the downstream displacement was lower as estimated in the structural analysis. The factors governing the expansion rate need to be better identified in order to improve the understanding of the cinematic of this type of reactions.

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SUMMARY

The Pian Telessio arch gravity dam has been built between 1950 and 1955 in the framework of the hydroelectric development of the Orco Valley located north of Turin.

After a 20 years period of a normal behaviour corresponding to the expected one, permanent upstream deformations were recorded starting from the end of the 70'. After various investigations, the deformation of the dam in the upstream direction was attributed to the concrete swelling related to an AAR reaction. The total permanent displacement has reached 55 mm at the centre of the dam crest corresponding to a total swelling of 250 μm/m.

The swelling causes both an increase of the horizontal compressive stresses of the arches as well as an opening of the peripheral joint of the dam. This opening when combined with a low reservoir elevation resulted in a significant increase of the compressive stresses at the upstream contact surface between the dam body and the "pulvino" foundation.

The rehabilitation project included the realisation of vertical slots using diamond wires placed parallel to the existing vertical joints followed by an injection of the slots once the compressive stresses have been released.

This contribution presents the relevant aspects of the rehabilitation works, which have been carried out mostly in 2008. It is in fact the first arch-gravity dam to be rehabilitated by using the diamond wire technique widely used for the rehabilitation of gravity dams affected by similar phenomena.

RÉSUMÉ

Le barrage-voûte de Pian Telessio a été construit entre 1950 et 1955 dans le cadre du développement hydroélectrique de la Vallée Orco au nord du Turin.

Après une première période de 20 ans pendant laquelle le comportement a été parfaitement réversible et régulier, le barrage a commencé depuis la fin des années '70 à se déplacer vers l'amont. Ce phénomène est provoqué par une réaction alcali-granulat qui conduit au gonflement du béton. Le déplacement irréversible vers l'amont atteint en clef de voûte environ 55 mm. L'expansion totale effectivement développée est estimée à 250 μm/m.

Le gonflement du béton engendre une augmentation des contraintes horizontales dans les arcs et le déplacement de la partie supérieure vers l'amont. La rotation qui en découle mène à l'ouverture du joint périmétral du pulvino du côté

aval. En condition de retenue basse en été, cette rotation conduit à une sensible augmentation des contraintes de compression au pied amont du barrage.

Afin de garantir la sécurité du barrage, une réhabilitation s'est avérée nécessaire. Le projet d'assainissement proposé prévoit le découpage de la moitié supérieure du barrage suivi par une injection des nouveaux joints verticaux cröes afin de rétablir l'effet voûte. Les travaux de réhabilitation comprennent au total 16 découpages dont les plus longs atteignent une hauteur de 39 m.

Cette mesure intervient évidemment sur les effets du gonflement et non sur les causes et ne représente donc pas une solution définitive. La répétition d'une intervention similaire doit être prise en compte dans un délai qui sera à optimiser en fonction des résultats définitifs de cette première réhabilitation.

L'article présente les éléments principaux des travaux de réhabilitation qui ont été effectués principalement en 2008. Il s'agit en effet du premier découpage d'un barrage poids-voûte en utilisant la technique du fil diamanté. Cette dernière a été appliquée avec succès pour assainir plusieurs barrages poids subissant des phénomènes de gonflement similaires.