Waterproofing of Pracana Dam

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ABSTRACT: The application of a PVC geocomposite on the upstream face of the Pracana dam, proved to be a good waterproofing system in order to reduce the rate of deterioration of the concrete, as well as to improve and contribute to the structural safety of the dam.

1. Description of the site

The Pracana Dam is located on the river Ocreza, which is a right bank tributary of the river Tejo, in the center of Portugal. The main characteristics of the hydroelectric scheme are:

- a concrete gravity buttress dam, 60m high and 245 m long at the crest (elevation 115.00 above sea level) with 12 buttresses 13.0 m wide (diamond shaped heads type), and 3 massive blocks at each abutment. The total concrete volume of the dam is 129,000 m3 ;
- a powerhouse located dowstream, adjacent to the dam, with two units of 7.5 MW each (average annual output 38.7 GWh) ;
- a shaft spillway on the right bank (discharge capacity of 1,650 m3/s) ;
- a bottom outlet -discharge capacity of 52 m3/s.

Promoted by a small hydroelectric company, the dam construction was accomplished between 1948 and 1951. EDP (Electricidade de Portugal,SA) took possession of the dam in 1977.

2. Problems

The structural behaviour of the dam showed various anomalies, which began being detected soon after the reservoir was first filled in 1952, and increased continuously eve since.The anomalies consisted mainly of extensive cracking on the dam body. This caused considerable leakage towards the downstream face, which in 1971 led to limit the exploitation level to elevation 109.00.

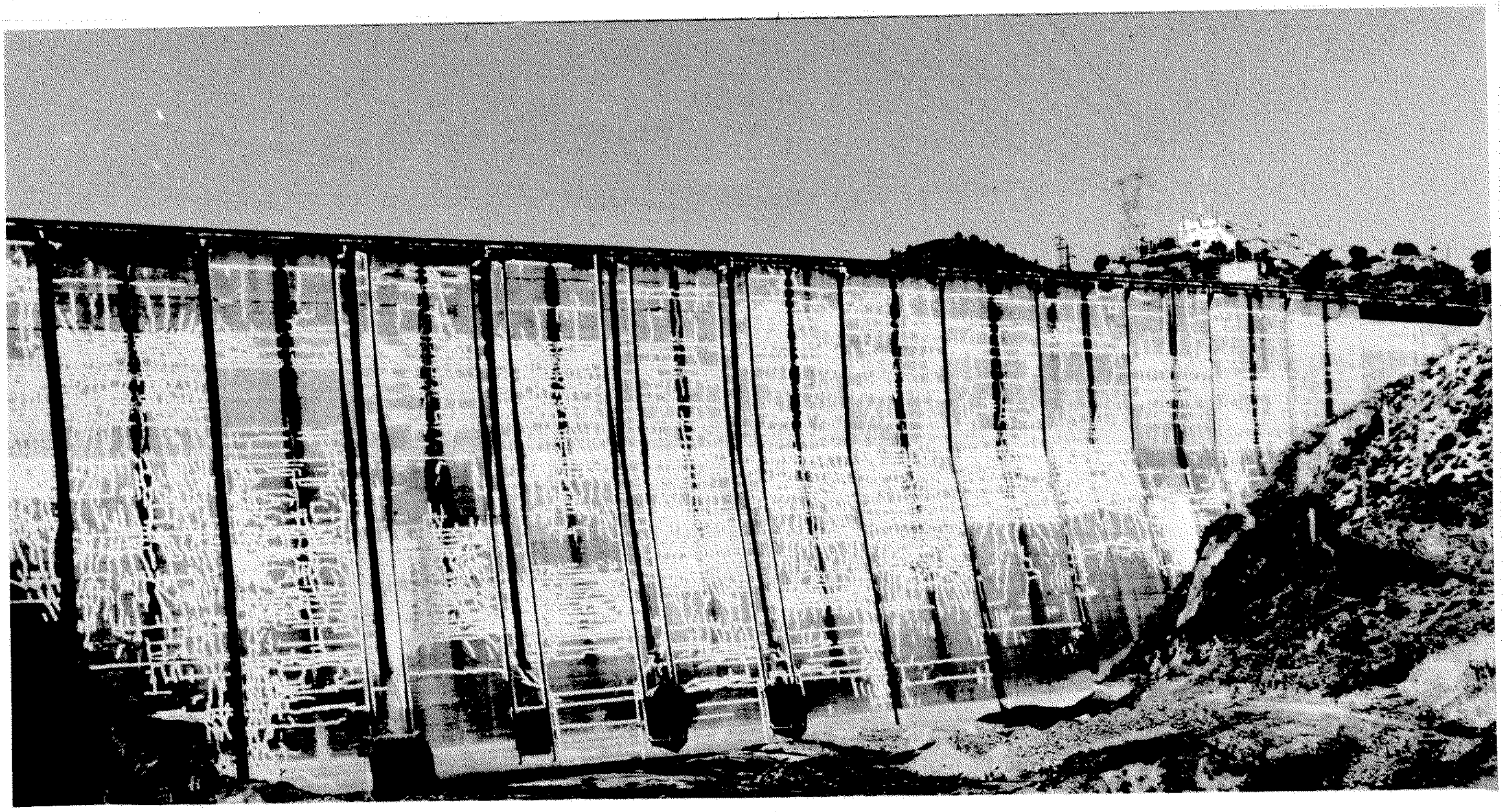
Taking advantage of the low water level in 1972/3, repairworks were carried out on the upstream face, which consisted in the sealing of the cracks. However, those works proved to be inneffective in a short time, and the Authority therefore kept the restriction of the exploitation level to 109.00.

In 1977, EDP decided both to perform a thorough assessment of the structural safety of the dam and to collect and analyse all the data wich could contribute to explain the dam behaviour. The research was carried out in cooperation with L.N.E.C. (Laboratorio Nacional de Engenharia Civil - Lisbon) and the authors of the initial project .

The dam stopped opperation in 1980, mainly due to the following :

- the safety assessment revealed a low value of the safety sliding factor along the most unfavourable horizontal cracks in the highest buttress;
- the hydrological reassessment showed the insufficient capacity of the spillway to control the newly estimated extreme floods.

The monitoring of the dam behaviour showed a continuous expansion of the concrete measured by no-stress strain meters, and large non - reversible displacements measured by geodetic methods - horizontal displacements towards the downstream face with increasing rate of 1.2 mm/year, and vertical upward displacements with increasing rate of 1.0 mm/year, were reported up to 1980. Analytical simulations of the structural behaviour by the finite elements method showed a good agreement between the calculated and the measured displacements, when different expansion



rates in the heads and in the webs of the buttresses were considered.
Thermal variations in concrete, during the construction and during the first filling of the reservoir, and the swelling of concrete, were supposed to be the main causes of cracking. Differential settlements due to the foundation heterogeneity, wich was not subjected to any consolidation treatment during the construction, as well as other detected construction deficiencies (use of cement from different origins, heterogeneity of the aggregates, compacting of concrete, downstream foundation conditions of some lateral buttresses) were perhaps additional causes of the buttress cracking and of the deterioration of the dam.
In despite of the negative results of the tests made on the aggregates to evaluate potential alkali reactivity during the 70's, the petroghraphic analysis carried out in 1988 revealed the existence of alkali-aggregate reaction which was confirmed by expansibility tests.

3. Conclusions for the dam rehabilitation

It was not possible to achieve a rigorous diagnosis of the causes of the dam deterioration which would be fully acceptable to all the technicians and entities involved in the studies. However, it was clear that several causes probably contributed to the anomalies observed.
A pragmatic solution was therefore imposed to repair the dam. A set of works was planned, which would take into account and tackle the multiple issues pointed out as the most probable causes of the dam behaviour.
Thus, the main conclusions that form the basis of the repair project (1985) were:

- there were evidences of expansion phenomena in the concrete which, although they were not completly diagnosed at that time, were considered as the main cause of the dam deterioration ;
- whatever the phenomena involved could be, it would only develop in the presence of the water infiltrated from the reservoir;
- stability conditions of the dam would be suitable if the effect of uplift in the cracks of the buttress heads could be avoided;
- the integrity of the dam concrete should be achieved;
- a global foundation treatment should be undertaken in order to consolidate and watertighten the foundation rock;
- in addition to the existing spillway a new one should be built to control extreme floods and to enable a quick drawdown of the reservoir;
- a careful programme of dam monitoring should be set up.

4. Repair Works

4.1. Struts between the buttresses

Two sets of struts were built between the buttresses at the foundation level. This was done considering that some of the buttresses had fairly superficial foundations, that the banks were steeply sloped and that the foundation rock was anisothropic as far as deformations are concerned.

4.2. Upstream plinth

A new upstream plinth was built, in order to connect the waterproofing intervention performed on the upsteam face of the dam and the waterproofing intervention of the foundation. This obliged to take into account some special measures of construction, concerned with the waterthigtness of its joints, and of the perimetral joint between the plinth and the dam

4.3. Foundation treatment

The foundation treatment consists mainly of:

- consolidation treatment, between the existing upstream grout curtain and a new downstream barrier curtain.
- new grout curtain, carried out from the plinth surface;
- reinforcing the bond between rock and concrete with grouting and also watertightening grout under the plinth and the head of the buttresses;
- a new drainage system.

4.4 Concrete treatment

The concrete treatment was divided into two phases depending on the width of the cracks:

* first phase called Individual Crack Treatment for cracks over 0.5 mm, which were grouted with cement ;
* second phase called Mass Treatment, for cracks below 0.5 mm, concerning a sistematic pattern of holes injected with epoxy resin.

5. Waterproofing system on the upstream face

5.1. Basic solution

Considered as one of the fundamental actions in the repair project, this system had two main objectives:

- to prevent any contact between the reservoir water and the concrete, in order to reduce progress in its deterioration, and consequently the rate of expansibility,
- to prevent any effect of uplift on the cracks in the buttress heads, and thus guarantee suitable safety conditions for the dam.

In addition to the properties normally required for this kind of waterproofing liner (a very low permeability factor, appropriate deformability, durability, etc.), the following were also required in this specific case:

- the capacity to absorb relative movements between the edges of any old or new crack, along the vertical joints separating the buttresses and along the joint between the dam and the upstream plinth;
- the possibility of making watertight connections in the membrane contours, and near the many special features of the facing (intakes, bottom outlet and new spillway, supports for the trashrack and stoplog guide rails. and the plinth).

For this reasons EDP initiated a prequalification and a final tender for design, supply and installation of the lining, in which proposals were made for solutions including adherent and non-adherent membranes.
The chosen solution, with a patented fastening system (Sibelon Systems/Dighe CSE), consisted of a 2.5 mm thick PVC membrane with a 500 gr/m2 geotextile coupled to it in the manufacturing stage, installed and fastened to the facing in vertical strips about 2 m wide by special stainless steel profiles. Relatively short fastening profiles were used (1.5 m), in order to accomodate small relative movements between the profiles and the face. The PVC geocomposit e was installed over a high-density polyethylene (HDPE) geonet 4mm thick. The geonet was fastened to the upstream face before the geocomposite was installed, and it performed as a drainage layer between the geocomposite and the upstream face of the dam.

5.2. Considerations of the waterproofing intervention on the upstream face

The complete waterproofing of the dam body took into account the peculiar geometry of the upstream face. We point out :

- the diamond shaped head of the buttresses formed, between and along its joints, a 3 m deep and 1 m wide cavity, increasing the surface in 40%. It was decided to fill this volume with concrete, to recreate the joint between buttresses, preventimg leakage towards the downstream face, and to make the upstream face even;
- from the heel of the dam up to level 94.50, the upstream face has a slope of 0.3:1.0 (H:V) and from level 94.50 to crest level (115.00), it is vertical;
- the existence of two intakes of the old units, where the geocomposite is attached with watertight sealing all along its perimeter;
- a bottom outlet with an horizontal grid where a special work included the execution of a steel watertighteness profile all along the perimeter of its entrance;
- the watertight system ends, near the foundation, in a cavity on the upper part of the plinth where the pipes of the upstream face drainage and of the plinth drainage itself were located.

In addition to all foundation treatment done, the zone between the plinth and the foundation rock was grouted, in order to create a barrier for the seepage water underneath the foundation plinth.

5. 3. Anchorage of the waterproofing system

5. 3. 1. Vertical anchorage and tensioning ribs

The anchorage of the geocomposite which rolls to the face of the dam is obtained with metal vertical components, set at an inter-axis of 185 cm, which allows both the pre-tensioning of the geocomposite and the drainage of water which might collect behind the geocomposite.
The patented system consists of two geometrically compatible profiles, AISI 304 stainless steel , made to fit one inside the other so as to form a continuous rib. The internal profile, 1.5 mm thick, which is installed on the upstream face of the dam, has a U-shaped section, with both sides folded so as to form two small wings. The external profile, 2 mm thick, which fits on the abovesaid one, is U-shaped,with divergent wings whose ends bend internally in order to form two additional small wings.
The profiles are anchored to the face of the dam by means of threaded rods and chemical phials , set at an inter - axis of 400 mm approximately .
The anchorage system is completed by a PVC strip , 2.5 mm thick and 400 mm wide, which covers the external pretensioning profile. The strip is heatwelded to the underlying geocomposite longitudinally to the profiles.
The PVC strip has the same characteristics of the PVC of the geocomposite, but it has no geotextile.
In order to absorb all movements between the various "blocks"of the system (by "blocks" we mean not only the buttresses separated by joints and the new foundation plinth, but also the volumes delimited by the cracks which have appeared in the dam body), installation of the profiles has been planned so that they are not placed near those discontinuities; in this way, the high elasticity of the geocomposite takes care of absorbing all elongations due to any mutual movement.

5. 3. 2. Flat metal profiles

At the change of slope at level 94.50, and at every change of direction which could bring about the forming of "ropes" on the membrane, a tensioning flat metal profile has been provided: such profile consists of an AISI 304 steel flat profile, 50 x 3 mm, anchored by means of expansion dowels to the underlying concrete.
The flat profiles are covered by a PVC strip, 2.5 mm thick and 150 mm wide.

5. 3. 3. Watertight sealing

In order to avoid the seepage of the reservoir water inside the upstream face concrete, the membrane is attached all along its perimeter with a watertight seal which consists of an AISI 304 steel profile, anchored to the dam face with chemical phials, threaded rods, washers and bolts every 15 cm.
The surface of the concrete on which the profiles press the geocomposite has been prepared with a layer of epoxy mortar; there is a synthetic rubber strip between the profile and the geocomposite.
Two different types of profiles were used : a flat one with a 80 x 8 mm and a length of 2,000 mm, and a C-shaped with a section of 70 x 36 x 4 mm and a length of 2,000 mm.

5. 3. 4. Metal connection devices and rails supports

In order to have continuity in the waterproofing between the geomembrane and the metal sheathing of the pipes for the intakes and bottom outlet, suitable metal connection devices were installed in correspondence of the openings on the upstream face
The abovesaid devices have been designed so as to be watertight welded to the metal lining inside the pipes while, on the external side, the edges have been designed in order to provide watertightness between the metal sheet and the PVC facing by means of a flange device.
As the support platings of the rails, which guide the protection structures for the inlets must not hinder the continuity of the upstream face waterproofing, a similar system to the one adopted for the metal connections devices has been adopted.
A square plate of 460 x 460 mm , on which the rail support has been attached, is anchored on the concrete facing of the dam compressing the geocomposite, with a steel profile fixed on the underlying plating by steel bolts with suitable gaskets.
The steel plate is connected to a special structure which has a variable height, to switch the rail support, in order to allow the concordance, with a 50 m-radius, between
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the planes on the upstream face.

5. 4. Drainage included in the waterproofing system

The drainage of the waterproofing system consisted mainly of:

- drainage of the water arriving behind the PVC geocomposite (condensation and/or leakage), to be collected and discharged downstream;
- possibility of localizing any rupture of the geocomposite by measuring the flow, received by four independent drainage compartments, of the water which might collect behind along the 4mm thick geonet.

At the bottom of each compartment, an extra 8 mm thick HDPE geonet was installed, as well as a "by-pass" behind the membrane's lower watertight fastening, connected to a drain installed in the plinth cavity.
Any filtration water is collected in these drains with a downstream outlet showing the respective water flow at each compartment.
Immediatly above the "water-stop" of the joint between the plinth and the dam, a perimetral drain was also created to collect any filtration water from the foundation.
This drain also has a downstream outlet in order to measure the corresponding flow.
A wire system was installed to enable the future use of a geoelectric method to detect occasional leaks on the geomembrane surface. Using a suitable "sensor probe", sliding on the geomembrane, any anomalies in the electrical field can be detected. The coordinates of such anomalies will give the exact discontinuity point in the geomembrane.

5. 5. Quality Control

During the works, a careful control over the materials and the execution procedures was implemented.
The materials used were certificated by official laboratories, according to Italian and American Standards on:

- every stainless steel profile;
- geonet, 4 mm and 8 mm thick ;
- raw-materials for the PVC geomembrane;
- geocomposite, 2.5 mm thick ;
- geotextile areic mass;
- chemical phials.

A complete assessment of the characteristics of the geocomposite was performed.
In order to be able to investigate which kind of relationship may exist between the laboratory index tests and the results from the field, an extensive testing of the PVC geocomposite was performed in the "Politecnico di Milano" Laboratory and in the ENEL-CRIS Laboratory, both in Milan, about accelerated ageing test.
The testing cycles requested by EDP were:
Cycle A: a 12-hour-testing cycle, including 8 hours of U.V.B. exposure at 45°C and 4 hours in condensation water at 40°C.
Cycle B: a 12-hour-testing cycle, including 8 hours of U.V.B. exposure at 60°C and 4 hours in condensation water at 40°C.
The testing results showed no detectable changes in values about the mechanical characteristics of the geocomposite, which confirmed and improved the results from the field test carried out by ENEL -CRIS on a geocomposite that was used on the upstream face of a high altitude dam, after 12 years of service.
The results of the extensive testing programme on the PVC geocomposite requested by EDP will allow this company, to compare the results of the testing samples from the upstream face of the Pracana dam with the results of the testing cycles on the fresh material at the time of installation.
The execution was scheduled to verify:

- the identification of each material arriving at the job site ;
- the dimensions of all types of steel profiles, rolls of PVC geocomposite and rolls of PVC geomembrane;
- the distance between vertical anchorages profiles and their plumb;
- the anchor of all stainless steel threaded rods;
- the tools for welding the geocomposite;
- every welding of the geocomposite sheets.
- the tightening of all bolts of the watertightness perimeter sealing, by means of a dynamometric key.

5. 6. Overall intervention data

The following table records the quantities for each of the main elements that constitute the waterproofing system:

- Geocomposite	m2	7,904
- Geonet	m2	7,700
- Tensioning profiles	m	4,270
- Watertight sealing profiles	m	1,210
- Metal flat profiles	m	244
- HDPE 100 pipes for compartment drainage	m	180
- HDPE drainage pipes of the foundation plinth	m	260

6. Performance

The refilling of the reservoir started in December 1992, and the maximum operating level at elevation +114.00 was reached in January 1994.
No problem was detected in the behaviour of the dam and its foundations, and the measured displacements are close to the values previewed by mathematical models, assuming the integrity of the concrete structure.
As far as the upstream waterproofing system is concern, the total flow measured in the downstream outlets for the maximum water level is 30 l/min, which is considered to be an excellent result, as it perfectly matches the expectation of the design.

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