Rehabilitation of the Flumendosa arch dam by epoxy grouting

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Cracks in the upstream face of the Flumendosa arch dam in Sardinia, Italy, have recently been epoxy grouted to restore a monolithic structure. This article describes the reasons for the work and the grouting methodology followed.

The 115 m-high Nuraghe Arrubiu (Flumendosa) double curvature arch dam, on the Flumendosa river in Sardinia, was completed on 1957. It is founded on sound porphyritic gneiss rock, which has quite satisfactory geomechanical properties. The almost symmetrical dam was cast in 24 approximately 12 m-wide blocks.

Fig. 1 gives a plan of the dam and Fig. 2 gives a cross section. The dam has a maximum height of 115 m and a total crest length of 300 m. The thickness at the crest ranges from 3.77 to 6.9 m, and the thickness at the base is 29 m. The crest elevation is 270 m a.s.l., with the operating water level at 267 m a.s.l.

The owner of the dam is Ente Autonomo del Flumendosa.

During the final construction stage and immediately afterwards, a large number of horizontal cracks appeared on the upper part of the upstream face. The phenomenon progressively slowed down and, since 1971, no new cracks have been detected. To date the Flumendosa reservoir has only been partially impounded, to about 30 m below the maximum operational water level.

The causes of the cracking, which were clearly identified by a classical structural analysis, including a detailed simulation of the construction phases, consist mainly of an unacceptable state of stress caused by the temperature fields in the structure during and after construction. Consequently, as the causes related only to the construction phase and are not acting any longer, a rehabilitation project could involve the restoration of a monolithic structure by grouting the cracks using a suitable well defined technique.

1. Remedial works

The recently completed rehabilitation project consisted basically of grouting the cracks with epoxy resins.

The cracks start at the upstream face of the dam, and they generally correspond to the joints between the concrete lifts. To achieve the best result for the treatment, grouting had to be carried out during the winter, when the low temperature would cause a downstream deformation of the structure, with consequent opening of the cracks on the upstream face.

The designer for the remedial works was Lombardi Engineering Ltd of Switzerland. The main contractor was Gruppo Dipenta Costruzioni S.p.A. and the specialist contractor was Rodio S.p.A., both of Italy.

To define in detail the most suitable grouting technology, a preliminary grouting test was specified.

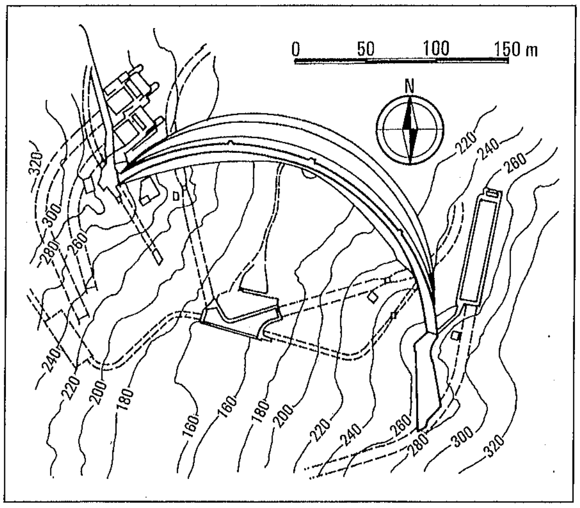


Fig. 1. Plan of the Flumendosa arch dam.

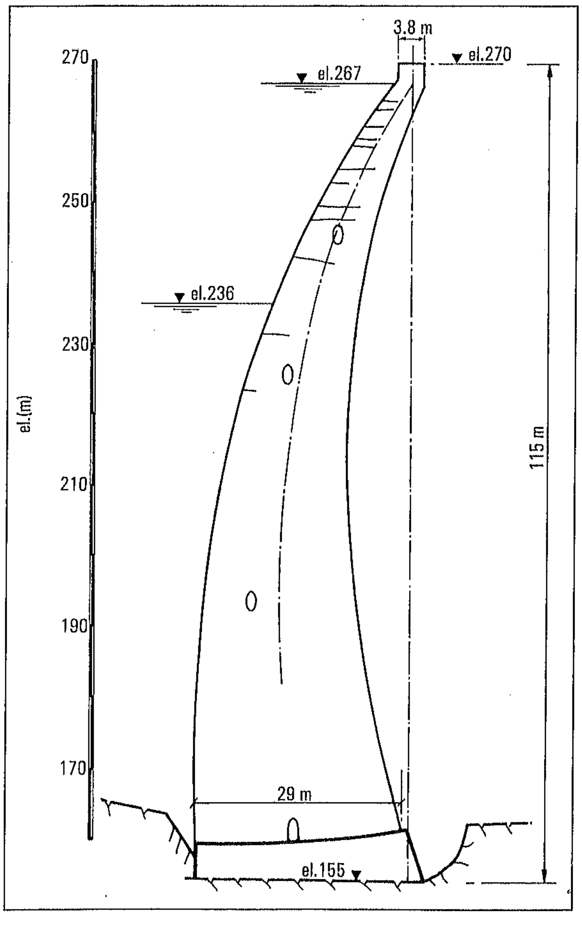
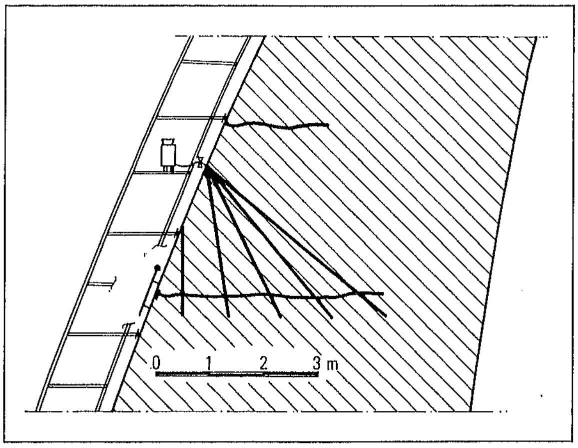


Fig. 2. Section through the 115 m-high Flumendosa dam.

Fig. 3. The layout of a fan of holes crossing a single fissure.



1.1 The grouting test

The preliminary test was carried out during the summer of 1995.

Although the test had to take place during summer, in different conditions, the result was quite useful in providing a first approximation of the epoxy resin characteristics and the main grouting parameters (pressure, rate of flow and quantities), as well as the working sequence.

First, scaffolding was erected at 1.9 m vertical intervals along the upstream face of block no. 17, from el. 220 m to the dam crest level.

The extension of each crack between els. 238 and 270 was determined by diamond core-drilled holes, 46 mm in diameter (type A), almost to the downstream face. A video camera (22 mm in diameter) introduced into the drill holes was used to detect the shape of the cracks, as well as to examine the frequent anomalies such as honeycombing.

Consequently, additional diamond grouting holes, 46 mm in diameter (type B), were designed for each crack using a computer program. They were drilled in number, length and inclination so as to ensure the suitable homogeneity of the treatment as far as sealing and consolidation were concerned.

After completion of the drilling, any water present in the cracks was thoroughly sucked away using air-pumps, to dry the concrete as much as possible and to ensure better adherence of the epoxy resin, which was subsequently injected on the concrete surface.

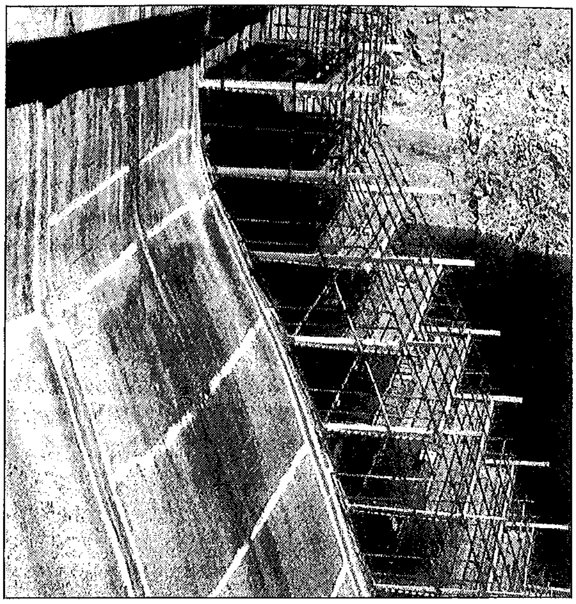
Before the fissures at the upstream dam face were grouted, they were thoroughly carved, cleaned and sealed. A synthetic mortar strip was provided in which

Table 1: Maximum pressure values

Elevation (m)	Pressure value (MPa)
220 - 240	8.0
240 - 245	6.5
245 - 250	4.5
250 - 255	3.0
255 - 260	2.0
260 - 265	0.8

Table 2: Characteristics of the epoxy resin

	Below el. 250	Above el. 250
Resin	RODUR 2000m	RODUR 500m
Temperature (°C)	20	20
Density (kg/l)	1.1	1.1
Viscosity (cps)	2000-3000	1000
Potlife/Certain time (min)	> 120	> 120
Compr. strength (MPa)	> 50	> 50
Tensile strength (MPa)	> 20	> 20
Youngs Modulus (MPa)	> 1000	> 1000



Erection of the scaffolding on the upstream face.

plastic pipes were inserted to check the grout, and to act as air vents.

Grouting was then carried out in stages for each crack, through a single inflatable packer placed in each hole about 1 m above the fissure, starting from the innermost holes and continuing towards the upstream face (Fig. 3 shows the layout of a fan of holes crossing a single fissure).

The propagation of the grout mix was controlled by observing leakage through adjacent grout holes, and through the air vents on the upstream face.

The injection process was stopped as soon as clean resin flowed from the pipes or was occasionally visible on the downstream dam face.

During the work, the main grouting parameters (pressure, flow rate and quantity) were continuously optimized so as to ensure the best possible result of the treatment.

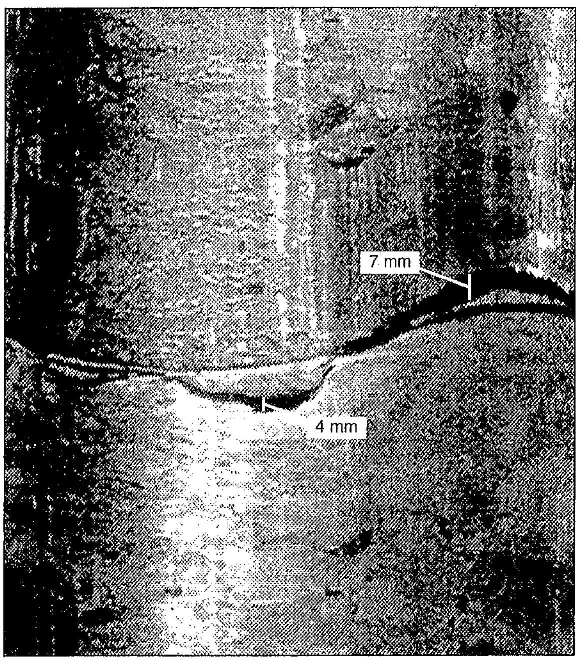
The grouting test was carried out in 34 days. It involved drilling 95 holes (43 of type A, 52 type B, a total of 404 m) and the injection of 2.5 t of resin.

1.2 Grouting procedure

The grouting technology (essentially the epoxy resin composition, the operative grouting pressures and the spacing of the grout holes) could be optimized by the preliminary field test, so that it was possible to determine the required mechanical characteristics of the polymerized product, and adequate penetration of the grout into the cracks. In particular the highest allowable grouting pressures were defined, to avoid any damage to the dam structure.

In practice, the technology was refined by compromising between various parameters. The high mechanical characteristics of the resin are guaranteed by a viscous product, which in turn requires high pressures to achieve a sufficient penetration. Furthermore, the composition of the resins was modified to obtain the correct set and adherence to the concrete structure, including in the presence of water. Any voids and 'honeycombs' could jeopardize the drying up of the concrete.

On the basis of the results of the grouting test and thanks to an additional test carried out in December 1995, staged maximum pressure values (see Table 1) and two different resins (see Table 2) were selected for various elevations of the dam.



Picture 1. A typical crack recorded by video camera.

1.3 Implementation

When the scaffolding on the upstream face of the dam was in place, the main grouting work began, starting from el. 220. The same technology as for the preliminary test was used, with the following schedule:

- Type A drilling: 15 September - 30 November 1995;
- Type B drilling: 15 October 1995 - 10 January 1996; and,
- Grouting: 10 January - 28 March 1996.

1.3.1 Preliminary investigation

The preliminary investigation was carried out through 1030 type A holes, 2 to 7.5 m long and inclined at 10° to 45° from the vertical.

In each hole, an investigation was carried out using the Borehole Image Processing System (BIPS), which made it possible to:

- show the borehole surface through 360°C in colour and in real time on a monitor, and accurate geometry of any existing discontinuity;
- carry out a statistical analysis of the data recorded; and,
- print out the data relating to any defects detected.

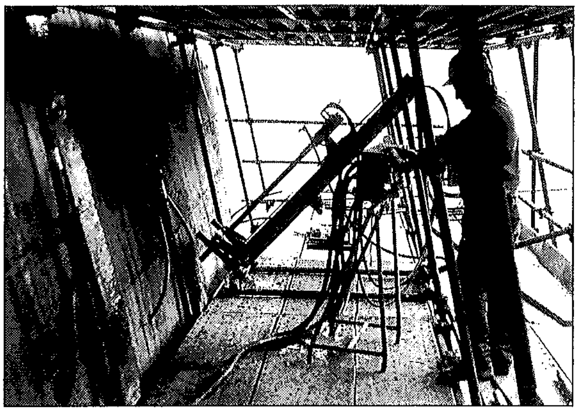
As a result, the geometrical features of each crack could be defined and plotted. 178 cracks, mostly sub-horizontal and for a total area of 7820 m^2, were detected and accurately recorded. The single crack surfaces varied from a minimum of 1.5 m^2 to a maximum of 123 m^2. Their open widths were in general about 2 mm, and occasionally up to 7 mm.

The video camera investigation, carried out on 4620 m of holes and registered on video cassettes, also showed a high number of honeycombs, up to 100 mm thick, mostly above the lift surfaces.

Picture 1 shows a typical crack recorded by the video camera. Fig. 4 shows the position of the cracks detected in block VIII of the dam.

1.3.2 Complementary drilling

For each crack defined by the preliminary investigation, complementary grout holes (type B) were designed and drilled so as to obtain a pattern of grout holes crossing the crack surface (including type A



Typical layout of the drilling equipment.

holes) spaced at about 1.35 and 1.45 m along the longitudinal and cross directions, respectively.

After drilling, each hole was dried using an air-pump. Two subsequent drying operations were carried out in the same way before the grout packer was installed and just before grouting. An average pumping time of about 4.5 h was spent for grouting each crack.

1.3.3 The packer

In each hole, a packer consisting of a polyethylene cone inserted in a rubber seat was installed about 1 m above the crack. The packer was connected to the surface by a 1/2 inch (12.5 mm)-diameter PVC pipe, reaching 1 m over the upstream face of the dam. The annular space between the pipe and the hole surface was filled with cement mix. A valve at the end of each pipe allowed for quick connection to the grout pump.

1.3.4 Treatment of the crack outcrops

As had already been done on the test block, each crack was thoroughly cleaned, sand-blasted and sealed at the upstream dam face, by a cement mortar strip in which plastic pipes had been inserted to ensure the discharge of air and control of the resin outflow. A total of 4200 linear metres of cracks were treated in this manner.

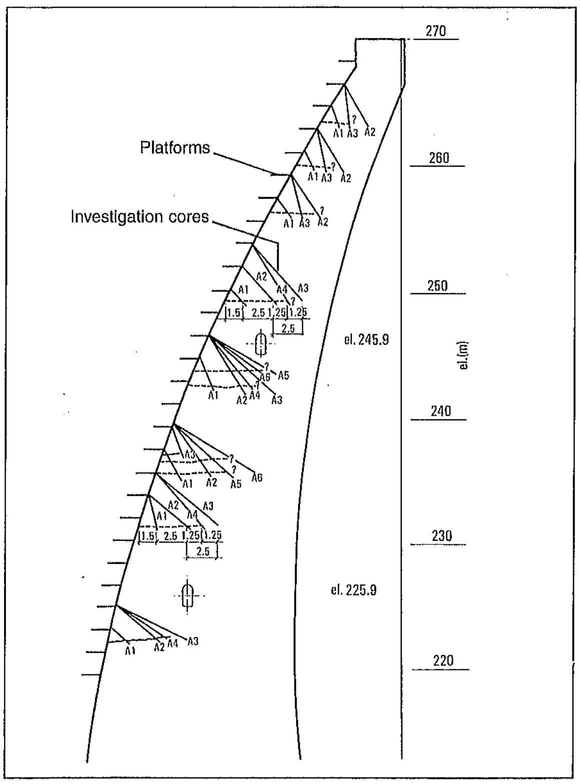


Fig. 4. Cracks detected in one block (VIII) of the dam.

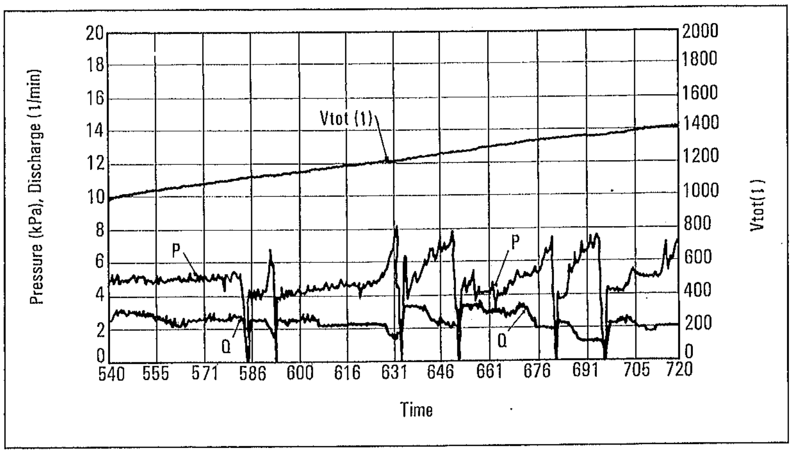


Fig. 5. A graph obtained by the PAGURO® system, measured in real time, which plots the resin flow rate (Q), the quantity of injected resin (V_{tot}) and the pressure (P) applied.

1.3.5 Grouting

The grouting treatment was progressively carried out in each of the 24 blocks of the dam, corresponding to all the cracks which had been recorded, starting from the deepest elevations upwards.

For each crack, the grouting was done, starting from the deepest holes in the central area of the block, and continuing progressively through the adjacent holes towards the lateral joints and the upstream face, with the aim of reaching the design pressure.

For every crack, one hole was grouted at a time. In the event of leakage of the resin through an adjacent hole or through a pipe inserted in the upstream seal, this was plugged and, in the case of adjacent holes, subsequently grouted. This procedure allowed for the grout flow along the crack to be checked accurately.

The grouting of a crack was considered to be complete as soon as the resin leaked through all the pipes (at 1 m spacing) along the seal of the upstream dam face.

In each working phase:

- the main grouting parameters were recorded accurately by a computer program (PAGURO® system); and,
- the deformation of the concrete structure was read by two couples of strain gauges, located at the fissure being grouted and at the one above.

It should be mentioned that a limit to the opening of the cracks, based on structural considerations, was set by the designer.

Fig. 5 is an example of a graph obtained by the PAGURO® system. This system is able to take measurements in real time, and can plot the rate of flow, the quantity of the injected resin as well as the pressure applied.

Three double-action pumps, specially conceived for the specified epoxy resins, operated simultaneously on the site.

For the single cracks, the resin takes varied from 14 to 1790 kg, with an average of 9.25 kg/m^2 (10.6 kg/m^2 for the cracks filled by RODUR® 2000 below el. 250 and 8.1 kg/m^2 for the ones treated by RODUR® 500 above that elevation). The grouting flow rate varied from 0.4 to 3 l/min.

As regards the grout volumes taken by the cracks, it should be pointed out that the presence of voids and honeycombs in the concrete makes their statistical evaluation quite difficult; this is because a significant percentage of the resin was required to fill the voids rather than to seal the cracks.

A high degree of homogeneity in the grout absorption for the different cracks in the dam blocks was recorded.

Table 3: Drilling and grouting quantities

Drilling	Number of holes	Total length (m)
Type A	1030	5120
Type B	1320	5768
Total	2350	10 888
Grouting		Quantity (t)
RODUR®2000		36.6
RODUR®500		37.2
Total		73.8

1.3.6 Work quantities

The drilling and grouting quantities are shown in Table 3.

1.4 Checking of the result

The treatment and results were checked by:

- laboratory tests on the resins;
- water pressure tests in the boreholes;
- cored investigation holes; and,
- laboratory tests on the samples extracted.

The laboratory tests on the resin samples were carried out by the Politecnico di Milano and confirmed the values specified for viscosity, pot-life, deformability and strength.

The 368 investigation holes (65 to 85 mm diameter) for a total length of 1669 m, of which 220 m were cored, confirmed the good results of the treatment (correct filling of the cracks and good contact between resin and concrete).

The laboratory tests on the tensile strength of the cored samples confirmed the mechanical properties of the resin and its satisfactory adherence to the concrete.

The 225 water tests carried out after the treatment through a single inflatable packer placed at the hole collar (with a water pressure 1.5 times the future pressure of the impounded reservoir) confirmed the almost complete tightness of the structure. (In only eight tests a low residual permeability was recorded locally in correspondence with honeycombs.)

2. Conclusions

The rehabilitation of Flumendosa arch dam by intensive resin grouting of the cracks, the honeycombs and any kind of voids can be considered extremely successful. The dam is now being progressively impounded, and is thus recovering its original storage capacity.

This case history confirms the good results which can be obtained by using epoxy resins to restore the continuity of mass concrete structures.

However to obtain this kind of good result, a number of conditions must be fulfilled:

- the concrete must be inherently sound, and affected only by a limited number of cracks, voids or honeycombs, so that the volume of grout required is reasonable in relation to the volume of the concrete (for example, not more than one litre of resin per cubic metre of concrete, and preferably significantly less);
- a detailed and careful structural analysis must confirm that the repaired structure will be able to satisfy the requirements and, especially, be able to offer sufficient permanent conditions in safety;
- this analysis must also define the main parameters for the grouting procedure, in particular the temperature of the concrete and the optimal water elevation at grouting time;

• also, the sequence of the grouting stages, as well as the pressures to be used, need be exactly defined;
• the design of the grouting requires a lot of additional studies which will lead to the selection of the type of resin, the spacing of the boreholes, the sequence of the holes to be grouted, as well as more details;
• the procedures to be followed for the test, the check of the properties of the resins and of the concrete mass before and after treatment must be exactly defined;
• in addition, the criteria for evaluating the results of the rehabilitation project must be clearly stated and followed; and,
• finally, the behaviour of the dam after rehabilitation must be analysed in detail.

Provided these conditions are fulfilled, there is a great opportunity for the rehabilitation of concrete dams using epoxy resin grouting. In many cases, such treatment can be proposed and successfully carried out. ◊

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