Safety reassessment of multiple arch dams in Italy: general considerations and presentation of a case-study

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ABSTRACT: The tradition of Italy in the dam field, in the modern age, starts at the beginning of 1900. Among the first structures built in the country, the typology of multiple arch dams occupies a significant position in particular for the link with the parallel evolution of the reinforced concrete production at the beginning of the last century. In general, these dams have been built using reinforced concrete for the multiple arches and reinforced concrete and masonry for the buttresses. The problems that the dam engineer has to cope with in the safety reassessment are in general the following: a) insufficiency of the capacity of outlets due to the limited availability of hydrological data at the design stage; b) ageing and deterioration of the materials due to environmental conditions and possible chemical-physical phenomena; c) limited strength of the structures with reference to seismic loads not considered at the design stage; d) problems related to the fulfillment of the present Italian Standards which have been updated several times. In the paper, after the presentation of some general aspects related to multiple arch dams and to safety reassessment problems, the case-study of Molato dam is presented.

1 GENERAL INFORMATION ON MULTIPLE ARCH DAMS IN ITALY

Italy is a country with a long tradition in the field of dam construction and operation dated in the modern age between the end of 1800 and the beginning of 1900, with two periods of significant increase in construction activity that ranges between 1920-1935 and 1950-1965.

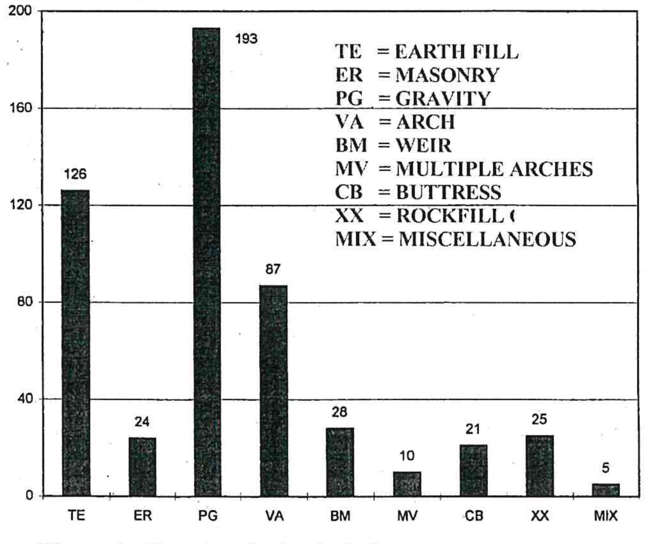

Figure 1. Dam typologies in Italy

Figure 1 shows the total number of dams grouped into different typologies (the total number shown in Figure 1 is equal to 519 according to the Italian definition of large dams before 1998; subsequently, it has been assumed the ICOLD definition of large dams and the total number has become 508) and Figure 2 shows the trend in dam construction since 1880 (Dam Italian Service, 1996).

It is worth of mention the construction of multiple arch dams that ranges between 1915 and 1925 (there is only the case of Rutte dam which construction started in 1949) tightly connected with the parallel expansion in the use of reinforced concrete for several civil works.

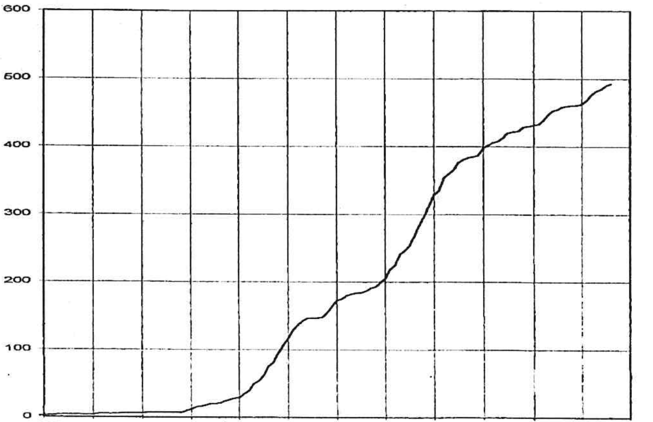

Figure 2. Trend of dam construction in Italy

This dam typology, after an initial success, was subsequently almost abandoned presumably for the following reasons:

- the Gleno (a multiple arch dam) disaster which occurred in 1923 caused by the insufficient stability of the manufactured base foundation in the center of the structure;
- the evidence of construction problems related to the appearance of cracking patterns due to thermal effects induced by the wide surfaces exposed to environmental conditions;
- tightly linked with the previous aspect, problems related to the deterioration of the concrete caused by atmospheric agents and frost action combined with the poor quality of cements and with the porosity of the concrete due to limitations in the vibration technologies.

Ten dams of this typology have been built in Italy and most of them are still in full operation. Tables 1, 2 and 3 show the main characteristics of them.

Table 1. General data on multiple arch dams in Italy.

Name	Construction Period	Region	Elevation m a.s.l.	Purpose
Combamala	1915-16	Piemonte	915	H
Riolunato	1918-20	Emilia	690	H
S. Chiara	1918-24	Sardinia	111	H/I
Pian Sapeio	1921-26	Liguria	950	H
Molato	1921-28	Emilia	362	I/H
Pavana	1923-25	Emilia	472	H
Lake Venina	1923-26	Lombardia	1824	H
Fontanaluccia	1925-28	Emilia	777	H/I
Ozola	1925-29	Emilia	1229	H
Rutte	1949-51	Friuli	814	H

H = Hydroelectric; I = Irrigation

Table 2. Site characteristics of multiple arch dams in Italy.

Name	Silting	Seismicity	Foundation
Combamala	negligible	NC	Limestones
Riolunato	considerable	Low	Limestones
S. Chiara	negligible	NC	Trachyte
Pian Sapeio	negligible	NC	Dolerite
Molato	moderate	NC	Sandstones
Pavana	negligible	Low	Sandstones
Lake Venina	negligible	NC	Quartz schists
Fontanaluccia	negligible	Low	Sandstones
Ozola	considerable	Moderate	Sandstones
Rutte	negligible	Moderate	Dolomites

NC = not classified seismically

For almost all dams, rehabilitation works have been carried out, in particular for:

- reduction of seepage in the foundation and the abutments by means of waterproofing works;
- reduction of leakage in the joints by caulking;
- maintenance works for facings exposed to atmospheric agents and frost (applications of thick gunite layers or relining with other materials, e.g. sand stone blocks);
- periodical low-pressure grouting in places which show signs of leakage;
- modifications and/or reparations of the discharge outlets;
- removal of the sediments in the reservoir.

It is worth mentioning the earthquakes which hit the dams of Riolunato and Lake Venina without any damage to the structures, and the bomb attack during the 2nd World War to S. Chiara d'Ula dam, completely repaired afterwards.

Figures 3, 4, 5, 6, 7 and 8 show most of the multiple arch dams built in Italy

Table 3. Characteristics of multiple arch dams in Italy.

Name	Reservoir Capacity (Mil. cu. m.)	Height (m)	Length (m)	Materials
Combamala	0.40	42.0	94	C
Riolunato	0.60	30.5	90	C/ M
S. Chiara	400.0	70.0	260	C/M
Pian Sapeio	0.20	17.5	120	C
Molato	13.0	55.3	180	C
Pavana	1.20	52.0	145	C
Lake Venina	11.30	49.5	175	C
Fontanaluccia	2.50	60.0	130	C/M
Ozola	61.50	27.5	96	C
Rutte	0.31	20.0	357	C

C = Reinforced Concrete; C/M = Arches in reinforced concrete and Buttresses in Masonry.

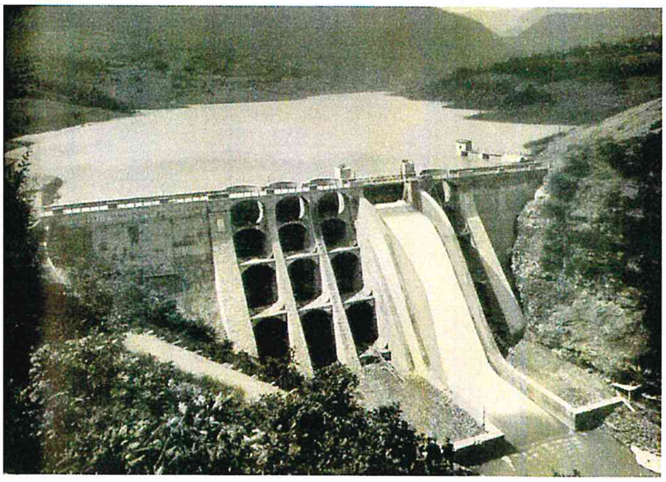

Figure 3. Downstream view of Fontanaluccia dam

Figure 4. View of Lake Venina dam from downstream left bank

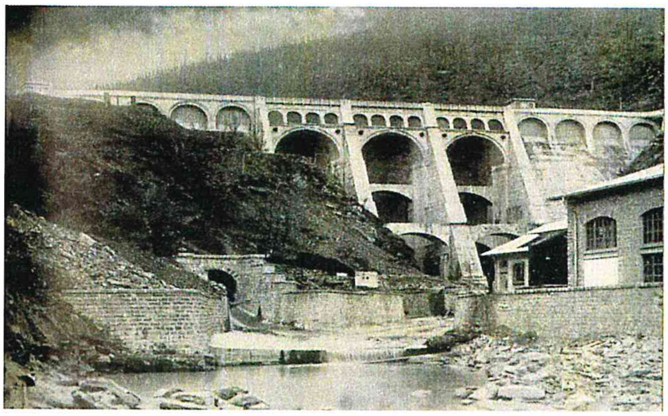

Figure 5. Downstream view of Pavana dam

Figure 6. Downstream view of Santa Chiara dam

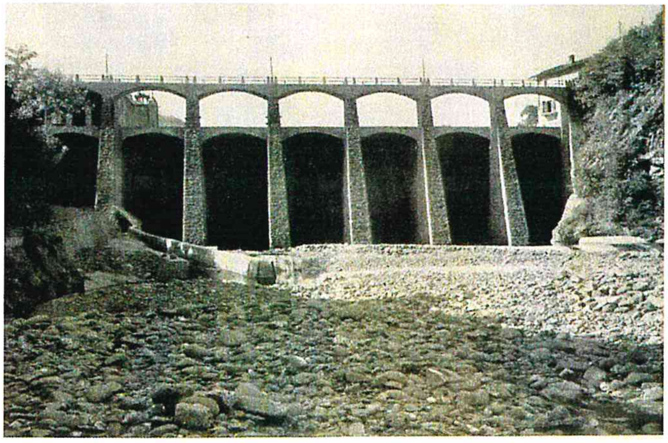

Figure 7. Downstream view of Riolunato dam

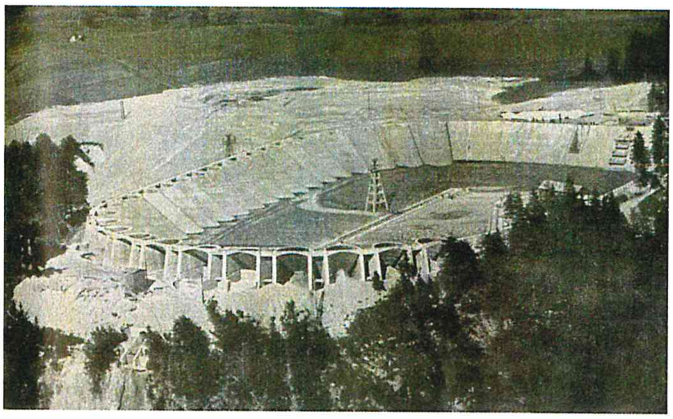

Figure 8. General view of Rutte dam

2 ENGINEERING PROBLEMS IN THE SAFETY REASSESSMENT OF MULTIPLE ARCH DAMS

On the basis of the professional experience of the Authors, the problems that the dam engineer has to tackle in the safety reassessment of dams, and in particular for multiple arch structures, are summarized here below.

a) Insufficiency of the outlets: this problem is generally due to the limited availability of hydrological data at the design stage and to the updated safety concepts imposed by the current Italian Standards. In fact, at the beginning of 1900, when most of the multiple arch dams have been built, the dimensioning of the outlets was based on designer evaluation of the precautionary analysis based on hydrological data. At present, the Hydrographic Italian Service expresses a binding opinion on the flood peak; this opinion is based on the past experiences and on statistic and probabilistic analyses. For this reason the actual dimensioning of the outlet works can become a very critical aspect that the dam engineer has to take into account in the safety reassessment.

b) Ageing/deterioration of the materials: in the chapter 1 it has been already emphasized how the environmental conditions have caused serious problems to the structures and in several cases it has been necessary to carry out remedial works. It has to be put into evidence that usually the problems are mainly related to the reinforced concrete elements of the structure while the masonry elements have shown better performances. This was mainly caused by the technological limits related to the cement quality and to the casting of the concrete at the construction stage. Some other problems (e.g. alkali aggregate reaction, corrosion of the steel bars, etc.) have also been experienced during reassessment activities carried out for the dams examined in the present paper.

c) Seismic behaviour of multiple arch dams: seismic aspects have been firstly introduced into the Italian Standards issued in 1959 and updated in 1982. For this reason, and considering the low seismic level of the zones where these dams have been built (see Table 1) none of the 10 multiple arch dams before mentioned has been designed taking into account seismic loads. However, the policy of the Dam Italian Service is oriented to request to the owner to take into account seismic loads independently from the location of the dam when a safety reassessment or a rehabilitation design is carried out. As a general consideration, it is worthwhile mentioning the positive role played by the reinforced concrete transversal beams (or arches) of which most of these dams (except Riolunato and Rutte dams) are provided, thanks to the caution and the engineering sensitiveness of the designers.

d) Observance of Italian Standards in the frame of structural safety reassessment of dams: Italian Standards (last time updated in 1982) comply with well defined stress limit values and safety factors linked to the dam typology under analysis. These aspects are obviously valid for a new design, but they are also requested by the Authorities when "major" safety reassessment and rehabilitation designs are carried out (even if there is a certain level of controversy in the interpretation of the Standards with reference to their retroactivity to existing dams). This interpretation can require a very difficult job to the owner not only for the aspects above mentioned - point a) insufficiency of the outlets, point c) seismic loads - but also because the methods to carry out nowadays the analyses (e.g. finite elements models) could be very different from those adopted at the design stage and this aspect can give rise to controversial interpretations of the results.

3 THE MOLATO DAM CASE-STUDY

As a meaningful example of safety reassessment and rehabilitation design of a multiple arch dam, the case-study of Molato dam is presented in this chapter.

3.1 *General information on Molato dam*

Molato dam, which main general original data are synthetically reported in Tables 1, 2, and 3, is a structure with a central part consisting of 17 reinforced concrete arches which rest upon 16 intermediate reinforced concrete buttresses and 2 solid lateral gravity shoulders (see Figs. 9, 10, 11, 12, and 13). Seven series of reinforced concrete T-section arches, arranged horizontally at different elevation, form the bracing between the buttresses.

The design calculation did not take into account the uplift pressures (not important in the original design, but significant with reference to the changes in the dam foundation construction) and, as above said, the seismic loads.

The arches have been calculated by the cylinder formula as elastic rings fixed at the abutments.

The central section of the dam crest is shaped as a spillway (discharge capacity 500 m^3/sec), consisting of 3 sluices controlled each by automatic balanced sector gates with additional electric or hand-operation from the overlying control cabin.

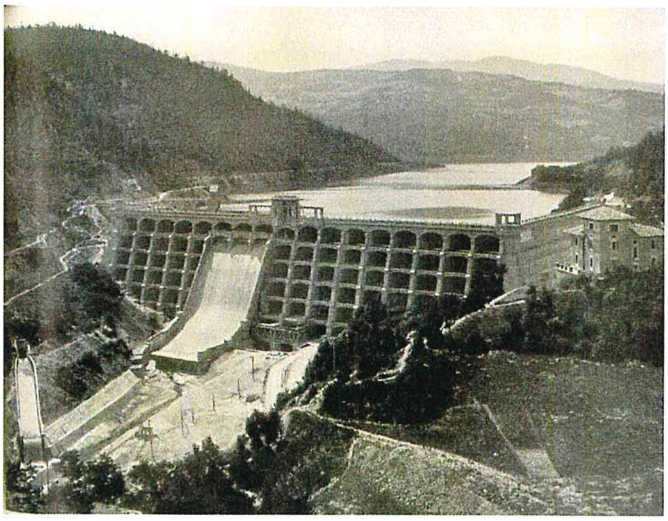

Figure 9. Downstream view of Molato dam

The dam is also provided with an intermediate outlet with a discharge capacity 50 m^3/s, consisting of a tunnel located in the right bank and controlled by a sluice gate.

Moreover, the dam is provided with a bottom outlet with a discharge capacity 30 m^3/s, consisting of two steel pipes embedded in the concrete platform and controlled by a butterfly valve upstream and a needle valve downstream.

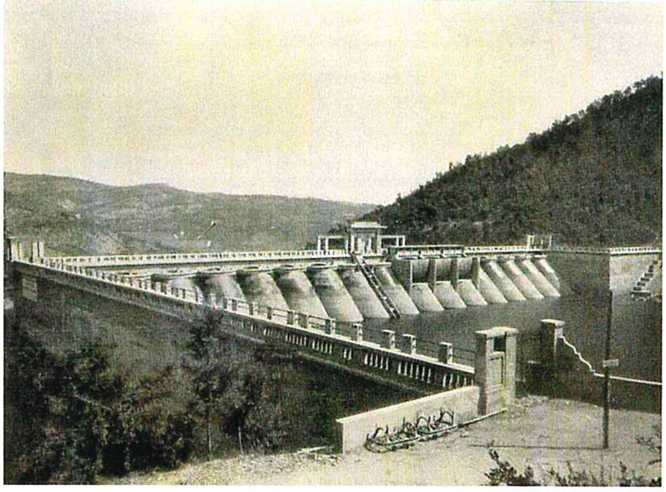

Figure 10. Upstream view of the dam showing the 17 reinforced concrete arches and the left gravity shoulder

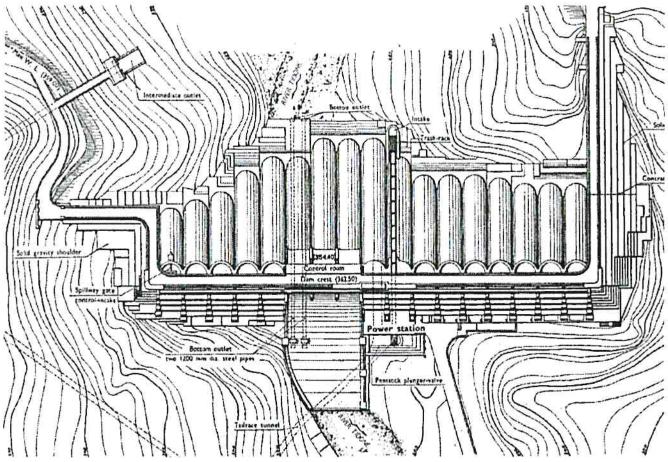

Figure 11. Plan of Molato dam.

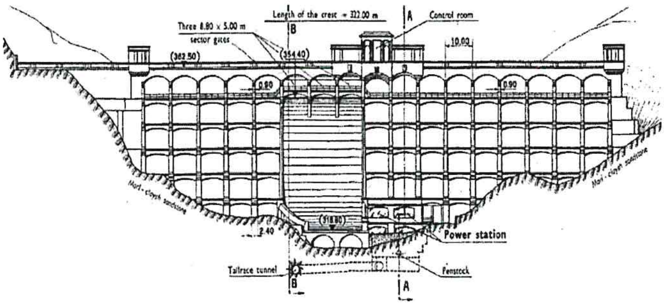

Figure 12. Downstream elevation of the dam

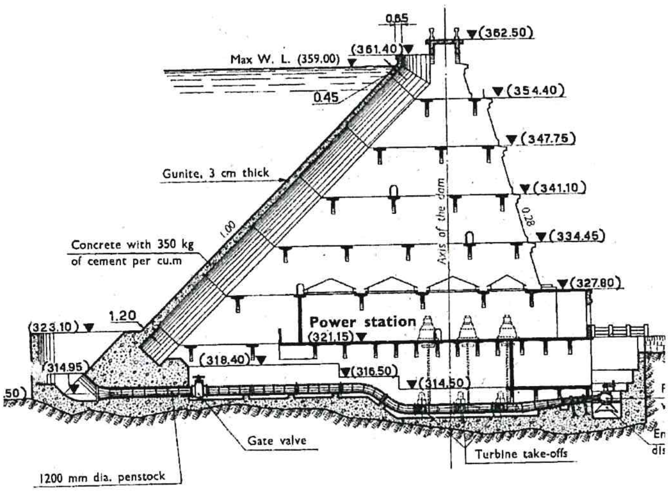

Figure 13. Cross section of Molato dam

3.2 *Present state of the dam*

The dam operation has been restricted by the Dam Italian Service by reducing the retention water level of the reservoir, essentially for three reasons:

- the low sliding stability;
- the insufficient discharge capability of the outlets;
- the low resistance of the structure with reference to seismic loads mainly in the transversal direction.

In the present case the limited sliding resistance is connected to the original building characteristics which have caused the complete covering of the buttress spans with large concrete slabs casted on the rock and the consequent possible rising of uplift pressures on the contact slab-rock.

The purpose of this solution adopted during the construction of the dam was addressed to protect the foundation rock (sandstone-marl flysh) from the negative effects possibly caused by atmospheric agents on the marly part.

During the eighty years of operation, these large slabs were frequently drilled in different locations to reduce the uplift pressures.

In order to carry out the dam safety reassessment, with reference to the three main aspects above described (the improvement of the seismic behaviour of the structure with particular attention to the transversal dynamic loads, the sliding assessment taking into account the uplift pressures not considered at the design stage, the insufficient discharge capacity of the outlets), several finite element models (using ABAQUS code, 2001), with different levels of detail, have been realized by means of which thermal and static analyses of the present dam state have been performed.

On the basis of laboratory investigations carried out on core samples of the concrete and on the steel reinforcing bars, it has been found the rather good performance of the materials with respect to the stress state, computed with the above said models.

Only in the lower part of the buttresses high stress values have been found. On the other hand, the sliding assessment keeping into account uplift pressures has shown that for the highest buttresses the limits imposed by the Italian Standards are not fulfilled.

3.3 *The design for dam rehabilitation*

The preliminary design stage was devoted to find the optimal rehabilitation solution.

In this phase, the behavior of new concrete reinforcement structures – which aim was to partially bear the hydrostatic loads and to make stiffer the whole structure – was considered.

The results, also based on additional laboratory investigations carried out on a set of mixes for new concrete, have shown that, in spite of the expedients possibly adopted to reduce creep and thermal effects, shear stresses between the old structural elements and the new ones, remained rather high.

For these reasons, and with reference to the results related to the present dam state, the designer has chosen the solution shown in Figure 14.

The solution is represented by the partial filling with concrete of the lower part of the spans between the buttresses and the arches.

The building of these reinforcements allows to reduce the stresses in the lower part of the buttresses and to accomplish with the limits imposed by the Italian Standards for sliding.

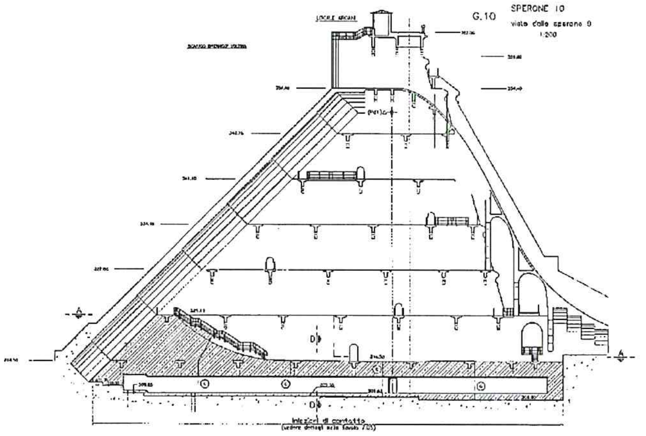

Figure 14. Partial filling with concrete designed for the rehabilitation of the dam

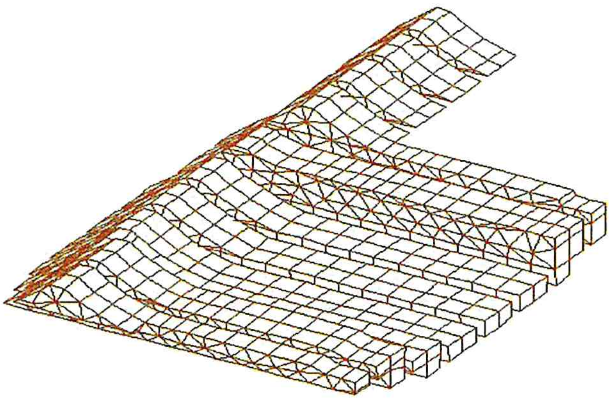

Figure 15. Numerical model of the partial filling for the rehabilitation of the dam.

In Figure 15 the numerical model of the partial filling with concrete of the lower part of the dam is shown.

With reference to seismic aspects, the analysis carried out with the model of Figure 16 has shown that the dam as it is at present is not able to withstand the seismic transversal loads mainly because of the limited strength of the reinforced concrete T-arches which connect the buttresses.

For this reason it has been designed a suitable reinforcement and replacement of the T-arches and their beneficial effect has been assessed making reference to a fully dynamic (response spectrum) analysis which takes into account the fluid-structure interaction (Bolognini et al., 1995). A typical modal shape computed to carried out the dynamic analysis is shown in Figure 17.

Among the additional structural analyses it is worth mentioning the sliding assessment carried out for the solid lateral gravity shoulders and the analyses for the evaluation of thermal stresses (caused by the hydration phenomena due to the casting of the new concrete) performed to consider the effects of the concrete filling, shown in Figures 14 and 15, on the lower part of the dam.

From the hydraulic point of view, the interventions were directed:

- to discharge a flood peak value of 940 m^3/s (against an original discharge capability of 500 m^3/s);
- to renew the existent bottom and intermediate outlets to ensure the best operation conditions.

The considerable increase of the flood peak discharge has asked for the realization of an additional spillway, in tunnel on the right bank.

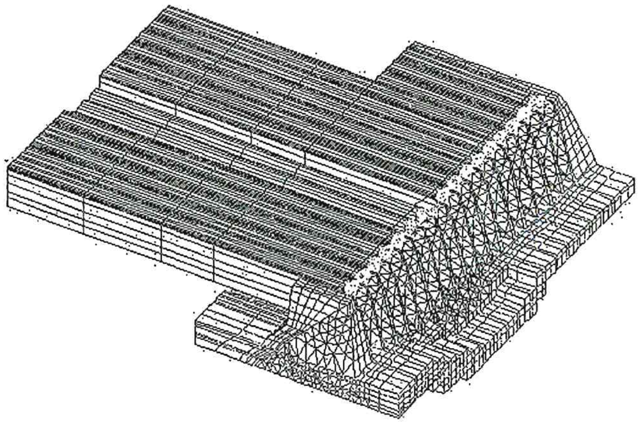

Figure 16. Finite element model adopted for numerical analyses.

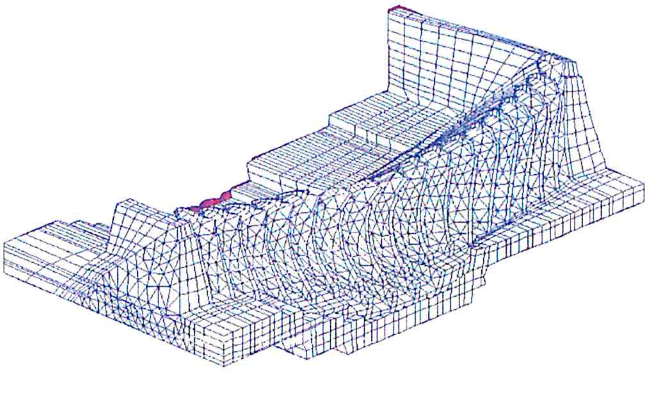

Figure 17. A typical modal shape computed to carry out the dynamic analysis.

The inlet work with three gates (two lateral free spillways and the central one controlled by an automatic flap gate) was built so as to allow the operation of the reservoir at an intermediate elevation, with the possibility to up-rise its position when the overall reservoir level will be authorized (presumably when the structural works will be over).

4 CONCLUSIONS

On the basis of the large and complex experimental as well as numerical activities, it was possible to define the optimal rehabilitation design.

The rehabilitation works are divided into two operative phases, the first of which has been completed and the second one is at present in progress.

In particular, in the first stage the following works have been carried out:

- an auxiliary free spillway built in a tunnel on the right bank with a discharge capacity of 400 m^3/s;
- a waterproof curtain located at the upstream toe of the dam and the complementary drainage system;
- the rehabilitation of the bottom and intermediate outlets;
- the waterproofing of the upstream face of both the multiple arches of the dam and of gravity concrete shoulders.

For the second stage the following works have been planned:

- the partial filling with concrete of the lower part of the dam;
- the strengthening of the T-arches which connect the buttresses with reference to seismic loads;
- the rehabilitation of the surface spillway in the dam body;
- the rendering of all surfaces exposed to environmental conditions;
- the uprising of the auxiliary free spillway built during the first stage.

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