Ageing process and rehabilitation works at Riolunato dam (Italy)

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ABSTRACT: The Riulonato dam, built in 1918-20, was the first multiple arch dam in Italy. Although regular maintenance works have been carried out, the more than 80 years old structure is presently no longer in condition to fulfil the current Italian dam regulation. After the description of the dam and of the observed ageing process as well as the analysis for the dam rehabilitation, the paper discusses the main features of the proposed rehabilitation design, showing the main project features.

1 INTRODUCTION

The Riolunato dam, built in 1918-20, is located in the province of Modena, near the same named town. The dam is located on the Scoltenna river, a left bank tributary of the Panaro river, providing a small storage volume to supply the downstream located Strettara power plant.
Although the existing multiple arch dam does not show any major sign of deterioration or indication of an insufficient stability, the dam is no longer in condition to fulfil the current Italian dam regulation as will be shown. The present dam owner, Enel Green Power S.p.A., thus decided in 2001 to evaluate various options for the dam rehabilitation.
The paper summarizes the various design constraints leading finally to the selected rehabilitation project. It first reviews the main features of the Strettara power plant, describing the present dam layout and operative conditions.
It should be mentioned that presently, the final design of the rehabilitation is still ongoing, in order that some of the constructive details and figures presented hereafter are necessarily based on the preliminary design and might be partially revised and adapted in the future.

2 MAIN FEATURES OF THE POWER PLANT

The 30.5 m high Riolunato dam, designed by Eng. Gaetano Ganassini, was the first multiple arch dam in Italy. The dam includes 7 buttresses spaced at 9.5 m with a 2.5 m thickness at the base and 1.5 m at the crest. The buttresses are made of sandstone masonry reinforced with 0.60 m thick concrete strands spaced at 2.0 m vertical distance. The buttresses support 8 reinforced concrete arches with a slope of the upstream face of 1:0.79. The thickness of the arches varies between 1.00 m at the base and 0.40 m at the top.
In 1925 the space between the right abutment and the first buttress on the right bank has been plugged with masonry.
The inclined arches are connected to the horizontal vaults at an elevation of 657.24 m a.s.l., supporting the free overflow spillway crest. According the present dam configuration the spillway is subdivided into six chutes on the left dam side, each 8.0 m wide, with a total maximum flow capacity of 529 m^3/s.

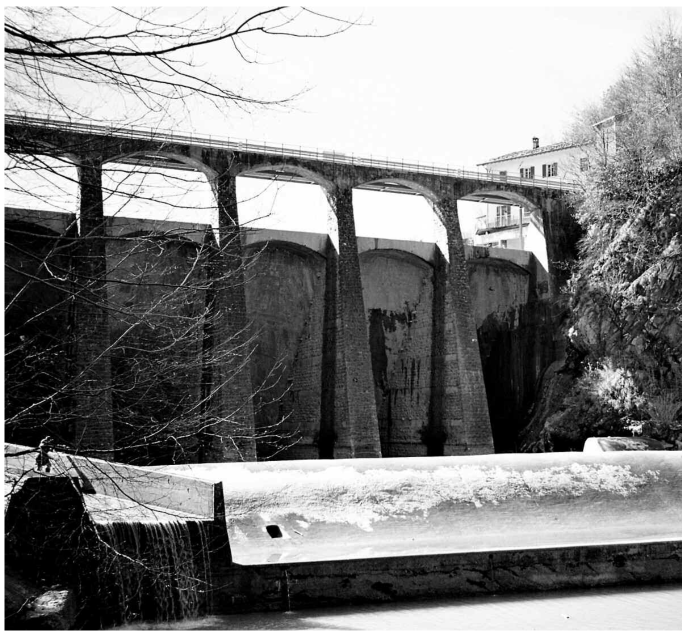

Figure 1. Downstream view of the Riolunato dam with in front the overflow sill of the stilling basin.

From the overflow sill, the free-falling jet is entering into the stilling basin at the downstream toe of the dam.
A 2.0 m large reinforced concrete footbridge crosses the dam at the elevation 662.74 m a.s.l, that is 5.50 m above the spillway crest. In 1995 an additional steel footbridge has been installed upstream of the existing one, in order to provide the required accessibility to some additional monitoring instrumentation installed at the dam crest.
The 1.25 m diameter bottom outlets located on both sides of the second buttress on the right flank includes a 2.2 m long steel pipe. The flows are regulated with a sluice gates placed in front of each pipe inlet and operated from a tower structure to be accessed from the dam crest.
The initially available 400’000 m^3 storage capacity of the Riolunato reservoir decreased progressively due to the relatively significant sediment transport. After 80 years of operation the present live storage capacity is approx. 95’000 m^3, with at some locations the sediments reaching the reservoir surface.
The water intake located on the left dam abutment with a capacity of 7 m^3/s is diverting the flow in a 5’555 m long headrace tunnel. The tunnel which includes three canal bridges has a section of 4 m^2 supplying at its downstream end the 4’000 m^3 capacity head pond. A 453 m long penstock of 1.55 m diameter and a gross head of 112 m is finally feeding the two units of the above ground powerhouse.
The main features of the Riolunato dam according to its present layout may thus be summarized as follows:

Direct catchment's area	*149 km^2*
Initial storage capacity	*400’000 m^3*
Present active storage capacity	*95’000 m^3*
Normal water level	*657.24 m a.s.l.*
Maximum water level	*660.74 m a.s.l.*
Crest elevation	*662.74 m a.s.l.*
Height above lowest foundation	*30.50 m*
Crest length	*90 m*
Maximum spillway capacity	*529 m^3/s*
Maximum bottom outlet capacity	*30 m^3/s*

3 EVALUATION OF THE AGEING PROCESS

3.1 *Dam behaviour*

The dam has shown a satisfactory behaviour, confirmed by the monitoring results and the reduced leakages through the arches. Furthermore, it overcame without major damages a severe earthquake occurring in 1920 shortly after the structure was set into operation. However the dam shows presently some conceptual limits mainly related to insufficient design experience and a progressive evolution of the Italian dam regulation. The main aspects to be improved concern the structural behaviour under seismic loads and the spillway capacity which has to be significantly increased.
The monitoring data collected during more than 30 years confirm the elastic behaviour of the dam, with generally reversible deformations, to be associated with the seasonal temperature variations.
The vertical crest displacements vary between 1 and 4 mm, depending from the considered dam section. A crest raising of some 0.2 - 0.3 mm/year seems to be confirmed by topographic surveys. In the upstream-downstream direction the horizontal displacements are completely elastic although only a short measurement period is available.
The leakages through the dam are generally smaller than 1 - 1.5 l/s, without any relevant variation during the years.

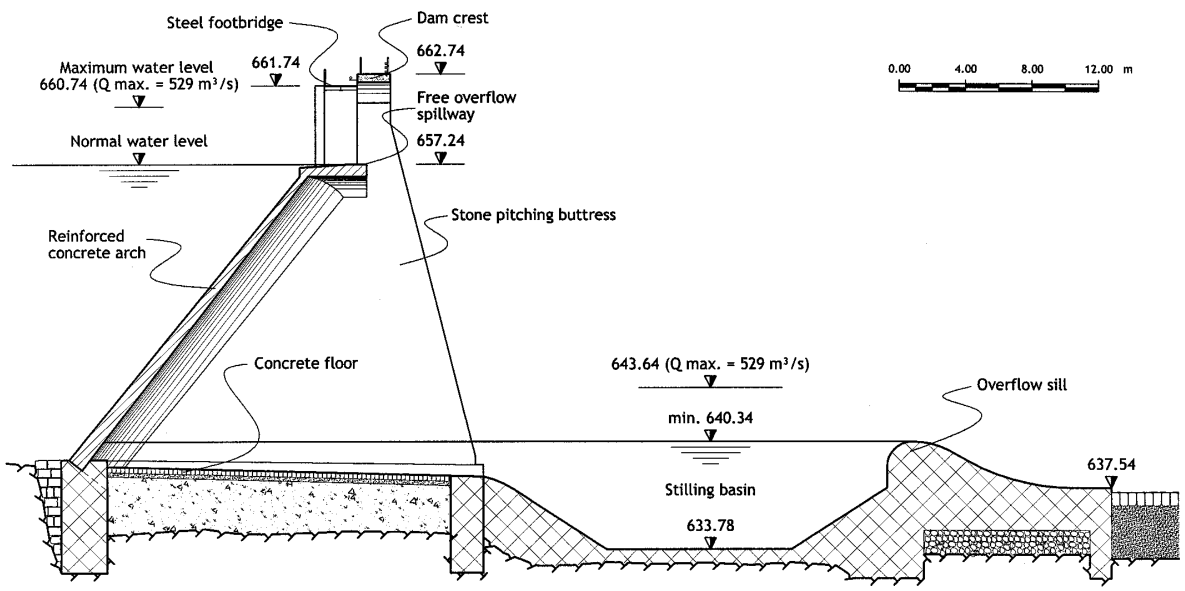

Figure 2. Typical cross section of the existing dam and the stilling basin.

As regards the dam abutments, a slow creep movement has been observed since several years on the right abutment representing a specific issue of the rehabilitation project. Various geological investigations have been carried out in the past on this flank constituted of fair marly sandstone. Accurate monitoring including topographic surveys, inclinometers and piezometers have progressively completed the available information on the flank movements.

The measured displacements are mainly towards the reservoir and the upstream direction, showing a maximal speed of 3 - 4 mm/year at the surface. The inclinometric measures confirm that the movement involves the rock down to a certain depth. Although some areas with higher deformability are observed, a definite sliding surface can however not be recognized, excluding the risk of a sudden large slope failure.

Based on the presently available data it can be concluded that the dam displacements are presently not influenced by the creep movement of the right abutment although an influence cannot be excluded in future.

3.2 *Maintenance works*

Disregarding the current rehabilitation, the dam has been partially adapted several times during its operation period with however only limited documentation available for most of the works carried out. In recent years a partial dam rehabilitation was carried out in 1970-1971 with the purpose to reduce the leakages of the dam and its foundations. The sediments in the basin were removed down to the top of the upstream cut-off wall. Consolidation grouting of the dam foundation were then carried out from the upstream dam base. The extrados of the concrete arches was completely renewed by the application of a 10 cm thick reinforced concrete layer completed with a 5 cm thick reinforced gunite layer. The spillway crest was also completely reshaped after removing of the superficial concrete layer. In addition, the buttresses bases were reinforced with ϕ 32 mm grouted bars anchored into the rock foundation.

Additional major rehabilitation works were done in 1977-1978, with the reinforcement of the buttresses. All joints between the sandstone blocks were refilled with mortar, and grouted bars were placed in the masonry.

Finally, in 2000-2001 a waterproofing layer protected by a geomembrane was applied on the upper section of the upstream dam face, between elevation 654.24 m a.s.l. and 657.24 m a.s.l. significantly reducing the leakages of the arches.

3.3 *Present condition of the dam*

Although the safety of the 80 years old structure, both from the structural and hydraulic points of view, is not source of major concerns, some improvements of the present dam configuration are needed.

The Italian Superior Council for Public Works required in March 2001 a rehabilitation of the whole structure in order to fulfil the current dam regulations. Based on this decision, the owner was asked in May 2001 by the Italian National Dam Agency to present a rehabilitation project, addressing following specific issues:

- structural reinforcement of the dam, including a seismic analyses for a 3^{th} class structure according to the Italian regulation,
- capacity increase of the free flow spillway, from the present capacity corresponding to a flood of 100 years return period, to a flood of 1000 year return period;
- increase of the bottom outlets capacity, in order to improve the sediment management in the reservoir and preventing a possible clogging of the existing outlets;
- modification of the spillways to avoid free falling jets between the buttresses for multiple arch dams despite an adequate stilling basin is provided, and
- evaluation of the stability conditions of the right abutment with stabilisation measures, if required.

4 PURPOSES OF THE DAM REHABILITATION

4.1 *Evaluation of the present dam safety*

As mentioned above, the monitoring records as well as visual inspections of the downstream dam faces do not reveal any anomalous behaviour of the dam. All deformations are generally reversible, depending from the seasonal temperature variations.

From the hydraulic point of view the main concern is given by the insufficient spillway capacity of only some 530 m^3/s, corresponding to a flood of approximately 100 years return period. It should be mentioned that in November 2000 the water level exceeded by 5 cm the maximum water level, corresponding to a discharged flow of 550 m^3/s.

A second important issue is the relevant reservoir siltation of which the available live capacity is now less than half of the initial one. Additional sediment deposits in the reservoir may produce a complete clogging of the existing bottom outlets, no further allowing the emptying of the reservoir. The management of the sediment load and of the already deposited sediments represents a serious safety concern.

4.2 *Creep movement on the right dam abutment*

Since 1979 a specific monitoring program has been implemented for the surveillance of the creep movements on the right slope, successively completed in 1985 and 2001. The monitoring measure-

ments confirm that the movement involves the slope down to a certain depth, reaching however the maximal speed of approximately 3 mm/year at the surface. The sliding speed is rather constant during the year.
A definite sliding surface can not be identified, although at depths of 9 and 11 m two soil layers of higher deformability have been observed.
In spite of the very low longitudinal rigidity of the dam given only by thin concrete arches, the creep movements do not seem to having affected the dam. In particular no vertical cracks in the arches or in the spillway vaults have been observed. A cracking has probably been prevented by the filling with conventional masonry of the zone between the right abutment and the first buttress in 1925, only 5 years after the completion of the dam.
One can suppose that the engineers of that time, although not disposing of accurate monitoring devices, evaluated correctly the instability on the right abutment, providing an adequate strengthening of the structure.

4.3 *General requirements of the rehabilitation project*

In addition to the specific issues presented in section 3.3, additional general requirements were considered by the dam owner for the design of the dam rehabilitation. In particular the following aspects had to be taken into consideration:
- preservation as far as possible of the present dam layout;
- use, as far as possible, of simple statical models;
- adequate consideration of the difficult access conditions;
- development of solutions requiring minimum maintenance works after rehabilitation and with a minimum environmental impact.

5 RESULTS OF THE DESIGN BIDDING

5.1 *Generalities*

Considering the challenging issues to be dealt with Enel Green Power S.p.A. carried out a public bidding for the rehabilitation design, in order to dispose of various proposals before having to select the most appropriate solution.
The design competition required the presentation of a feasibility study for the rehabilitation, including an evaluation of the construction costs and works schedule.

5.2 *Criteria for the selection of the best design*

In addition to the engineering costs for the development of the various design steps, a number of aspects were taken into account in selecting the best project, and in particular:
- total cost of the rehabilitation works;
- duration of the power plant shutdown;
- development of the specific issues in the feasibility study;
- quality of the presented documentation.

5.3 *Presented design proposals*

The presented studies showed very different approaches to the specific rehabilitation requirements. In some cases the proposals included specific measures in order to fulfil all the single requirements, however without a general approach to the various problems. In particular these included the reinforcement of the concrete arches, the design of a specific structure to support the nappe plunging into the stilling basin, the increase of the spillway capacity by lowering of its crest (in some cases with the installation of new gates), the construction of a new larger bottom outlet, and the installation of rock anchors and drainage holes in the right bank slope.
On the contrary, other projects showed a global approach to the dam problem, thus suggesting remedial works solving at the same time more than one single issue.
This kind of approach resulted in this case in a more systematic and economic rehabilitation project. The selected proposal presented in detail hereafter, has been evaluated as the best one satisfying all the above listed criteria.

6 SELECTED DESIGN FOR THE REHABILITATION WORKS

6.1 *General design concept*

After examination of several possible options, the proposed rehabilitation design includes following works:
- filling of all the spaces in between the buttresses with unreinforced concrete, in order to transform the multiple arch dam in a conventional gravity structure;
- construction of a new bottom outlet of large capacity on the left dam abutment, promoting the scouring in the area of the existing intake structure;
- increase of the free overflow spillway capacity, by lowering the concrete sill, improving its hydraulic efficiency and providing an additional chute on the right side of the dam;
- modification of the existing bottom outlets and its integration in the new structure.

In order to reduce the uplift pressures on the dam foundation a drainage gallery along the whole dam is foreseen, with 200 mm diameter boreholes every

2.5 m. The gallery will also be used to access to the various equipments inside the dam structure (outlet valves, monitoring instrumentation, ecc.).

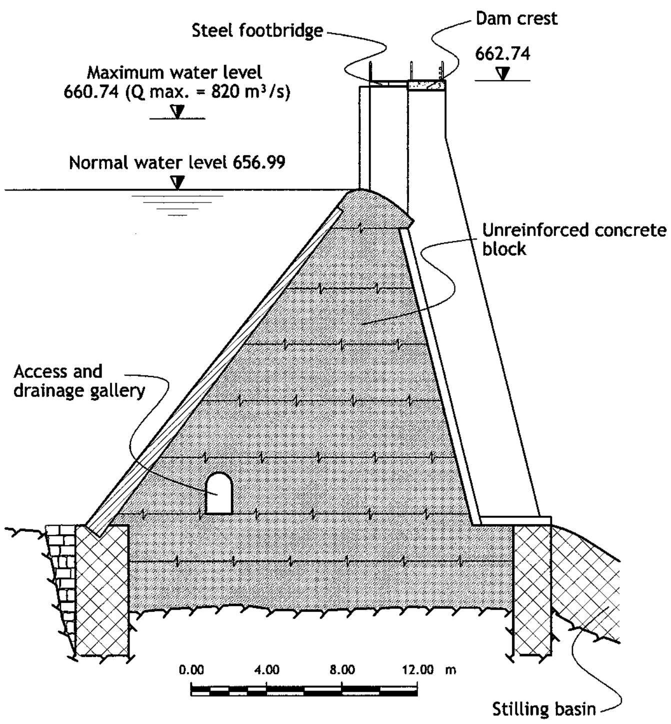

Figure 3. Typical cross section of the dam after rehabilitation.

The design includes various additional works, as for example a modification to the stilling basin, the heightening of the steel footbridge on the dam crest, and the extension of the monitoring instrumentation.
The rehabilitation and integration of the existing bottom outlets in the rehabilitated structure is based on the wish to improve the hydraulic safety in case of a reservoir emptying as well as to promote the sediment management in the reservoir.

6.2 *Evaluation of the proposed rehabilitation*

Although the proposed rehabilitation involves a relatively large amount of concrete (approx. 16'000 m^3), the proposed alternative is offering the following main advantages:

- the dam might be considered as a conventional gravity structure, thus simplifying significantly the static and dynamic analyses. In addition, the rehabilitated dam satisfies easily the stability requirements both under static and dynamic loads;
- the dam type allows an easy integration of the new discharge structures;
- since the works are mainly carried out from the downstream dam side, the mechanical removal of the sediments in the reservoir in not necessary. Only in the area close to the intake of the new bottom outlet the sediments have to be removed;
- the works can be performed mostly with a full reservoir, in order that the plant shutdown is limited to a short period;
- the relevant rigidity of the new structure, both in longitudinal and in transversal directions, reduces the sensibility of the dam to the creep movement of the right abutment. Extensive stabilisation works of the right abutment are thus not felt necessary;
- the rehabilitation has a minor visual impact on the dam, since the design basically preserves the present layout.

6.3 *Discharge structures*

6.3.1 *Capacity increase of the surface spillway*

The hydrological analysis showed that the flood with a 1000 years return period has a peak inflow of some 820 m^3/s. Since the limited storage capacity of the reservoir is not providing any relevant retention capacity, the new spillway will be designed to evacuate the 1000 years flood at the present maximum water level located at elevation 660.74 m a.s.l. without the operation of the bottom outlets.
The proposed design consists in a free overflow spillway, with the crest at elevation 656.99 m a.s.l., thus 25 cm below the present crest.
In addition, the removal of the concrete plug of the arch between the first and the second buttress on the right dam side is considered, in order that the new spillway will include 7 openings, each 8.0 m large, resulting in a total overflow length of 56.0 m.
The shape of the new spillway has been designed in order to offer the maximum hydraulic efficiency.
The existing stilling basin downstream of the dam provides an adequate energy dissipation of the plunging water jets. It is worth noting that at present the hydraulic behaviour of the basin is satisfactory, without any visible sign of erosion or deterioration.
A lateral basin will collect the flow from the 7th opening at the dam base diverting the water into the main stilling basin using an overflow sill located at elevation 645.50 m a.s.l.
Finally it has to be mentioned that five 1.5 m large trenches will be provided in the existing sill of the main stilling basin, in order to reduce the downstream water level and the uplift pressures under normal operating conditions.

6.3.2 *New bottom outlet on the left dam side*

The new bottom outlet, having a maximum capacity of 75 m^3/s, is located in the concrete block between the first and the second buttress near the left dam abutment. The new outlet includes a concrete intake structure at elevation 643.24 m a.s.l., designed to reduce the head losses. Downstream of the intake, a 9 m long rectangular shaped section 2.0 m wide and 2.5 m high is followed by the guard and the service sluice gates.
Downstream of the second gate the canal height is increased in order to assure an adequate flow aera-

tion. Upstream of the gates a complete steel liner is foreseen, whereas on the downstream section a steel liner will be provided only at the bottom and at the sidewalls, up to a height of 2.0 m.

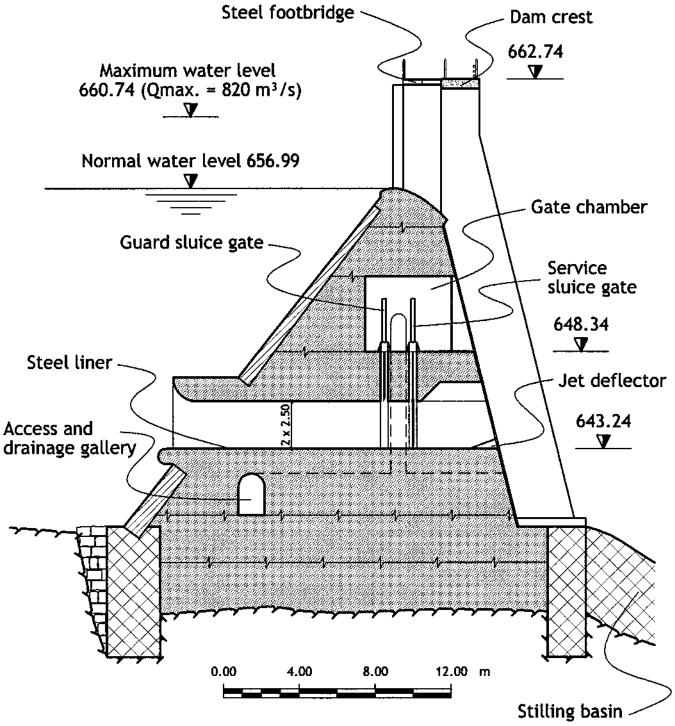

Figure 4. Typical cross section of the new bottom outlet on the left dam side.

The purpose of the steel liner is to prevent possible erosions of the sediment loaded flows.

In order to promote the energy dissipation, the final section of the bottom outlet is equipped with two deflectors, spreading the flow and increasing the jet aeration.

Hydraulic servomotors located in the valve chamber above the bottom outlet will be used for the gates operation. For the permanent access to the gates chamber, the drainage gallery will be used whereas an additional access of larger dimensions is foreseen above the bottom outlet for maintenance purposes.

6.3.3 *Rehabilitation of the existing bottom outlet on the right dam side*

Although the new bottom outlet has a large capacity, it was preferred to maintain the existing outlets on the right side in operation and to include their rehabilitation in the project.

Considering the difficulties associated with the rehabilitation of the 80 years old hydromechanical equipments, it was decided to replace the existing gates and steel linings with new equipments. It is thus planned to introduce two 5 m long steel pipes with a diameter of 110 cm in the existing conduits, to be equipped with a service sluice gate at their downstream end. The water is then discharged in the existing channels. The existing gates at the upstream end of the pipes will be used as guard valves, for maintenance purposes only.

The new valves are operated by hydraulic servomotors lodged in the valve chambers above the downstream end of the steel pipes. For the access to the valve chambers, the drainage gallery is available.

6.4 *Results of the static analyses*

According to the requirements of the Italian dam regulation, the structural analyses shall include stability and stress analyses on typical horizontal dam sections.

Since the static system of the dam will be completely modified within the rehabilitation works in comparison to the existing structure, no static analysis of the latter have been carried out.

As part of the preliminary structural analyses, three horizontal sections have been considered: the dam foundation (at elevation 635.24 m a.s.l.), the buttress basis (at elevation 639.24 m a.s.l.) and a construction joint at half height of the new blocks (at elevation 646.24 m a.s.l.).

For each section, the forces resulting from the following load combinations have been taken into account:

1. Maximum water level. This combination considers, beside the dam weight, the hydrostatic pressure of water and the sediment load in the reservoir and in the stilling basin and the uplift pressures for the 1000 years flood (820 m^3/s). The water level in the stilling basin is thereby assumed at elevation 644.79 m a.s.l.
2. The seismic loads. In addition to the above mentioned forces, the seismic loads due to the weight of the structure and to the impounded water, evaluated according to a pseudo-static model (the inertia forces are assumed as external static loads proportional to their mass), are taken into account. The water levels in the reservoir and in the stilling basin correspond to a flood equal to half the hydraulic head of the design flood.

According to the Italian dam regulation the sliding safety is usually satisfied if the ratio between the sum of the horizontal forces and the sum of the vertical ones do not exceed 0.75. This limit can be extended up to 0.80 in the horizontal sections in-between the dam crest and 15 m below it, in case the value of 0.75 is only exceeded under seismic loads. In the present case the maximum ratio, calculated for the foundation section at el. 635.24 m a.s.l., is 0.71. The preliminary stress analysis showed a maximal tensile stress of some –140 kPa at the upstream boundary of the dam foundation, whereas the maximal compressive stress is 550 kPa on the downstream boundary of the buttress basis. Both values are small and below the upper limits of the regulation. It should be mentioned that the present preliminary analyses will be completed with a more accurate one taking into account the interaction between the existing and the new structures as well as the influence of the reservoir level and the temperatures on the stress distributions.

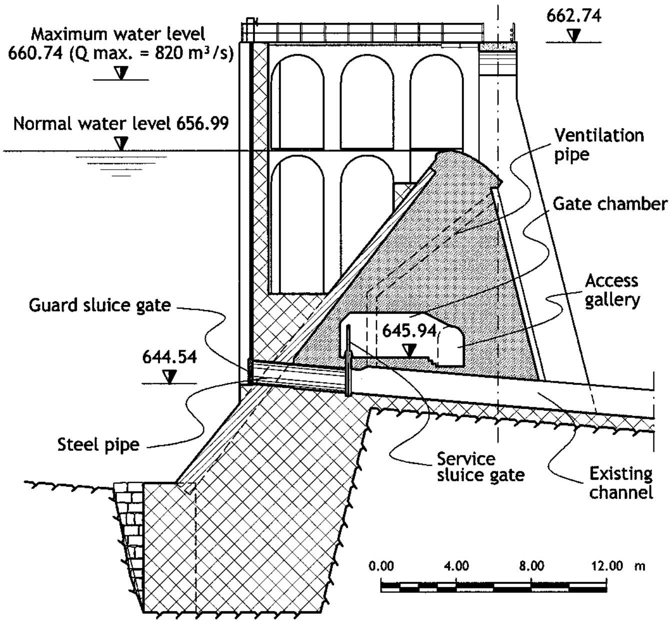

Figure 5. Typical cross section of the existing bottom outlet on the right dam side after rehabilitation.

6.5 *Monitoring program*

6.5.1 *Existing instrumentation for the dam monitoring*

The first monitoring instrumentation was installed on the dam in 1970, then stepwise improved and extended. The following measurements are presently available for the analysis of the dam behaviour:

- leakages at the dam and the abutments, measured at the outlet of the stilling basin;
- horizontal displacements of the dam crest in transversal and longitudinal direction, measured with two inverted pendulums installed in two central buttresses. In addition, a collimator installed on the steel footbridge measures the relative displacements of each buttress. The relative values are then transformed in absolute displacements by referring to the pendulums measurements;
- vertical displacements of the dam crest, measured with two 50 m long vertical borehole extensometers anchored into the rock, installed in the same buttresses as the pendulums. Furthermore, eight survey points are periodically measured on the dam crest using as reference the above mentioned extensometers.

6.5.2 *Existing instrumentation for the right slope monitoring*

A specific monitoring instrumentation of the right slope creep was first installed in 1979, and completed with new survey points and additional devices in 1995 and 2001 respectively. The present system includes:

- geodetic measures with a high precision theodolite and distometer, consisting in a reference point on the left abutment and 15 survey points on the right slope;
- inclinometric measures with 4 boreholes of 23, 29, 36 and 70 m length, respectively;
- measurement of the horizontal displacements in direction of the creep movement, by means of a multi-rod borehole extensometer (anchored points at 18, 28 and 51 m depth) at the basis of the second buttress toward the right abutment;
- measurement of the horizontal displacements by means of a multi-rod borehole extensometer (anchored points at 6, 26 and 50 m depth) installed close to the dam crest;
- measurement of the water table elevation with 3 standpipe piezometers installed at different depths in the same borehole.

6.5.3 *Extension of the monitoring program*

In order to acquire accurate information of the dam behaviour after rehabilitation, the design includes the following extension of the monitoring installation:

- thermometers in a central concrete block, i.e. in proximity of the inverted pendulums and the vertical extensometers in order to determine the thermal conditions of the dam;
- piezometers in the drainage gallery one in each concrete block, for the evaluation of the uplift pressure on the dam foundation;
- measurement of water seepages in some characteristic sections of the drainage gallery.

7 FINAL REMARKS

The present contribution describes the design principles of the Riolunato dam rehabilitation.

Although the stability of the dam itself is not source of any concern, the existing configuration is no longer in condition to fulfill the current Italian dam regulation.

While the proposed solution is not challenging from a structural point of view, the simplicity of the proposed configuration involves a number of relevant advantages, having a decisive role for the selection of the presented design.

Starting from the main issues identified by the owner for the dam rehabilitation and concluding with specific features of the rehabilitation project, the article describes the main steps leading to the selection of the final works layout.

Finally we would like to extend our congratulations to the original designer of the Riolunato dam for the innovative and outstanding engineering achievement. The elegant multiple arch dam has been in operation for more than 80 years, never suffering any mayor damage. Regular maintenance works carried out by the owner have obviously positively to the control of the ageing process.