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CORRECTIVE MEASURES OF THE RIVER BED PROTECTION DOWNSTREAM A DAM FOUNDED IN DEEP ALLUVIA. THE CASE OF CRESTUMA-LEVER DAM

JOSE F. MELO(1), JOSE DIAS DA SILVA(2), IRENE FERNANDES(3), LAURA CALDEIRA(4) & LUÍS MIRANDA(5)

(1) LNEC - National Laboratory of Civil Engineering, Portugal, jfmelo@lnec.pt
(2) EDP-Gestão da Produção de Energia, Portugal, josedias.silva@edp.pt
(3) EDP-Gestão da Produção de Energia, Portugal, irene.fernandes@edp.pt
(4) LNEC - National Laboratory of Civil Engineering, Portugal, jfmelo@lnec.pt
(5) LNEC - National Laboratory of Civil Engineering, Portugal, lmiranda@lnec.pt

Abstract

Crestuma-Lever dam, completed in 1985, is located in Douro River. A large design flood of 26,000 m^3/s involves 8 gated spillway bays with stilling basins directly founded on the alluvial river bed. Regular river bed surveillance downstream of the spillway evidenced unexpected progressive erosion of riprap.

Prototype data from dam operation evidenced a significant change of downstream rating curve. Subsequent hydraulic model tests confirmed it as being the main cause of riprap erosion.

Prototype observation data, invaluable physical modeling and interdisciplinary approach proved essential in confirming the causes of inadequate riprap behavior and in defining the corrective measures.

Keywords: Movable dam founded in alluvia bed; protective downstream riprap; scouring; rating curve.

1. Introduction

Crestuma-Lever dam is the most downstream hydropower scheme of a dam cascade system in the Douro catchment comprising several Spanish and Portuguese dams. In the Portuguese part of the catchment, there are presently eleven large hydropower schemes in operation (eight in the main course of Douro River and three in tributaries) and two schemes under construction (Figure 1).

Douro River is 927 km long, comprising a 597 km stretch in Spanish territory, 122 km defining the boundary between Portugal and Spain and a last 208 km stretch across Portuguese territory until the Atlantic Ocean. The catchment covers 97,603 km^2 (18,643 km^2 in Portugal) and includes some of the rainiest areas of the Iberian Peninsula.

Total installed hydropower capacity of Portuguese dams in Douro catchment exceeds 2 GW. Presently, it represents about 45% of the Portuguese hydropower installed capacity and an average of approximately 60% of the Portuguese yearly hydropower production. These numbers clearly evidence the relevance of the Douro hydropower schemes in the Portuguese hydropower system.

The five dams in the Portuguese stretch of the Douro River are basically low head schemes with very limited storage capacity.

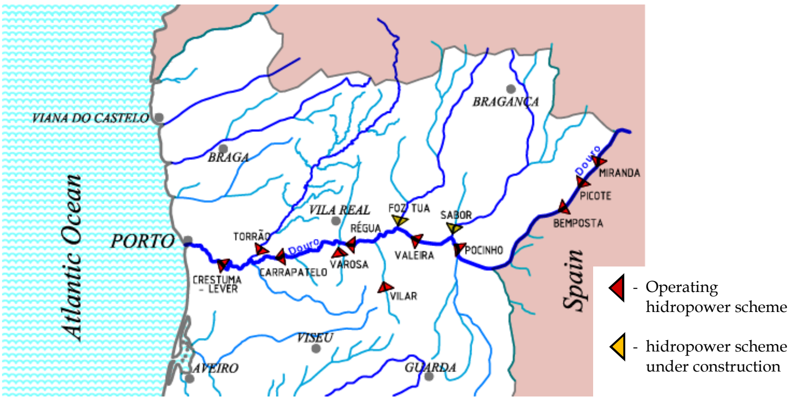


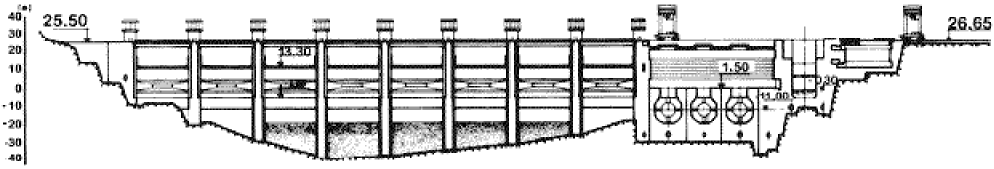
Figure 1. Location of major Portuguese hydropower schemes in Douro catchment.

Crestuma-Lever dam was designed, built and is owned and operated by EDP (Figure 2). This dam was completed in 1985 and, besides its use for hydropower purposes (3x39 MW), it also provides water supply to Oporto metropolitan area and plays a key role for the river navigation. The full operation of the scheme is therefore essential for its many beneficiaries and any major intervention in the dam will result in many direct and indirect negative impacts.

Design, construction and dam safety control has been since the earliest phases of the project followed-up closely by the owner EDP with technical support from LNEC. Several papers addressing the specificities of the river bed riprap protection have been published during its design, construction and the first years of operation (Ribeiro *et al.* 1973, 1976, 1979, 1982 and 1994). The observation of the riprap has been routinely carried out by EDP and analyzed by LNEC since it entered into service. Special attention has been paid to the behavior of the riprap protection downstream of the dam spillway, designed to accommodate a maximum flood discharge of 26,000 m^3/s.

In fact, the dam eight spillway bays have their concrete slabs directly founded on the alluvial river bed. This solution makes them particularly sensitive to any abnormal scouring of the river bed downstream that might induce high gradient seepage flows through the alluvial foundation, increasing the risk of piping erosion (Figure 3).

Figure 2. Crestuma-Lever dam aerial view.



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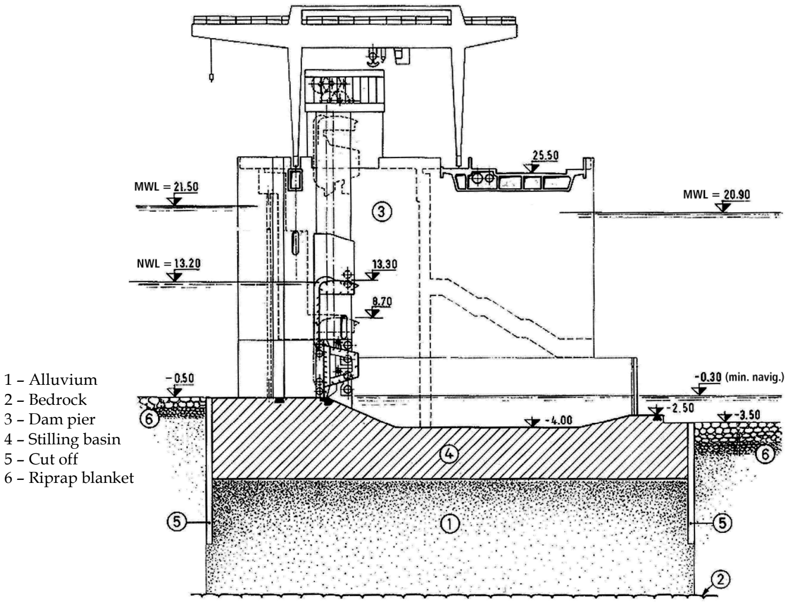

Cross Section

Figure 3. Spillway main features.

To prevent the development of river bed uncontrolled scouring, a heavy riprap protection was provided extending 60 m downstream of the spillway. The riprap was built on top of a two layer filter that stretches an additional 20 m downstream, totalizing 80 m of protected river bed (Figure 4).

2. Spillway operation

Deriving from its size, physiographic and hydrologic characteristics, the Douro catchment generates regular significant flows and frequent large floods. As the capacity of Crestuma-Lever reservoir to store flood inflows is limited, the dam spillway must operate under a wide range of flow discharges (up to 26,000 m^3/s) and must deal with a 20 m variation of downstream water depths (Figure 3).

To tackle these hydraulic constraints, a movable type of dam was considered, its body consisting mainly of a set of seven large piers, with the 28 m spans between them closed vertically by means of eight double leaf vertical lift gates (13.80 m high) and horizontally by means of eight 56 m long concrete stilling basins (Figures 3 and 4).

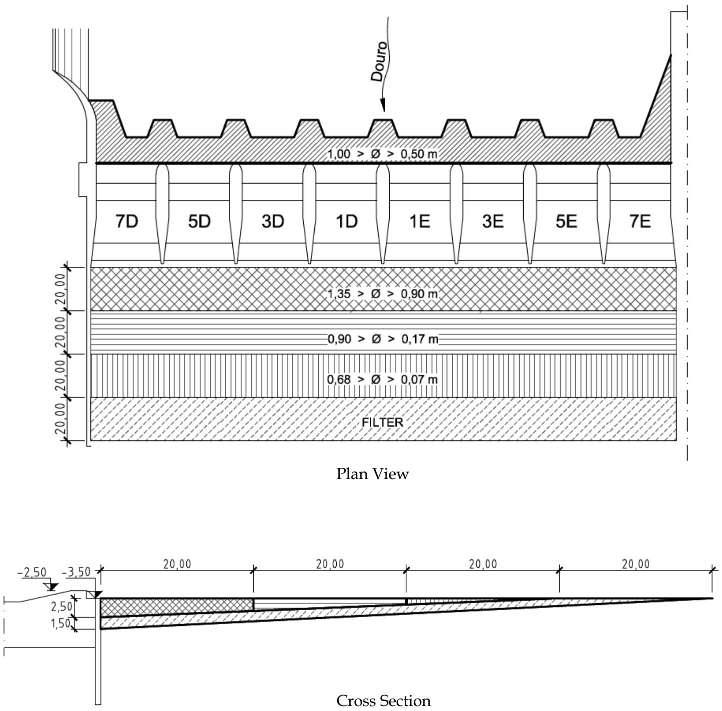

Figure 4. Riprap protection downstream of the spillway.

Under normal operation the "dam crest" is defined by having the top of the gates at elevation (13.30). Reservoir normal water level (*NWL*) is set at elevation (13.20), which shall be kept during low and intermediate floods by sequentially opening the gates. Only when all the gates reach their maximum allowable opening position of 7.00 m, the reservoir water level shall be allowed to go over *NWL*. Hydraulically speaking, for large floods the dam works as a local head loss due to the presence of the right abutment guiding wall, the power house on the left bank and spillway piers.

Under such design, the gates' operation rules can be synthesized in the following manner:

- *Low floods* - reservoir kept at *NWL* – sequential predefined steps lowering gates upper leaves and producing free falling napes that impinge directly into the stilling basins concrete slabs, resulting in an efficient energy dissipation mechanism;
- *Low-intermediate floods* - reservoir kept at *NWL* – sequential rising of gates lower leaves keeping upper leaves fully retracted, thus producing a cross flow inside the stilling basin. The high energy of the wall jets formed under the gates is mostly dissipated by intersection of horizontal jet flow and free falling nape. This cross-flows enhance the conditions for energy dissipation inside the stilling basin (Ramos 1979);

- *Intermediate-large floods* - reservoir to be kept at *NWL* – for openings under the gates between 4.5 and 7.0 m, energy shall be dissipated by means of an hydraulic jump formed inside each stilling basin. The natural rating curve of the river downstream must ensure subcritical conjugate depth at spillway end sections;
- *Large floods* - reservoir level between *NWL* and *MWL* – sequential full rising of the gates. When all eight gates are fully open, the head loss at the dam section associated to the flow conditions will define the upstream water level.

Considering the described spillway operation, it is possible to infer that:

- *Low flood* discharges can be controlled independently of downstream water levels and ensuring adequate energy dissipation conditions. Hydrodynamic loads on the riprap are not severe;
- *Low-intermediate flood* discharges (above 4,350 m^3/s through the spillway) can be controlled by promoting cross flow energy dissipation inside the stilling basins. The efficiency of such dissipation mechanism depends on the downstream water levels, which must be high enough to force hydraulic energy dissipation to take place inside the stilling basin. These conditions being met, no excessive hydrodynamic loads will be applied to the riprap;
- *Intermediate-large flood* discharges are controlled exclusively through the openings under the gates (apertures from 4.5 to 7 m). Energy dissipation is achieved by means of hydraulic jumps inside the stilling basins, which require that downstream water level is higher than the subcritical conjugate depth downstream of each bay. If these conditions are met, the protective riprap downstream shall withstand the residual turbulence loads of stilling basins exiting flows;
- *Large flood* flows will involve operation with fully raised gates and, though involving very high water levels upstream and downstream of the dam, they are not particularly severe for the riprap in terms of energy dissipation, as velocities, turbulence and head loss associated are lower than in the operating conditions involving flow passing under the gates.

From the above it becomes relevant that the most severe energy dissipation conditions are those involving flow passing under the gates. This derives from the requirement of having river water levels downstream higher than the subcritical second conjugate depth. In fact, in case this condition is not met, the hydraulic jump is pushed downstream the stilling basin end sill, or even worse, it may not even form at all, the outflow being in essence a high energy horizontal jet. Any of these situations will put the riprap integrity at risk.

The details linked to the spillway gate operation rules were fine-tuned by means of hydraulic model tests carried out by LNEC in 1985 and the complex energy dissipation conditions were experimentally studied to a variety of flow conditions by Lopes *et al.*, 2004. The main concern of such tests and studies was to understand the conditions required to ensure riprap integrity for the whole range of spillway operation and define the gates operation rules.

3. Analysis of the riprap behavior (1985– 2010)

Regular surveying of the riprap stability has been performed since the dam entered into operation. Surveys were carried out with particular attention after the occurrence of significant flood discharges. Riprap surveys were made in 1985, 1987, 1988, 1990, 1998, 2001, 2007, 2010 and 2012. Major floods occurred in the winters of 1988/89 (13,000 m^3/s), 1995/96 (10,500 m^3/s), 2000/01 (10,000 m^3/s) and 2006/07 (9,400 m^3/s).

Until January 2007, surveys were made along a predefined number of longitudinal profiles aligned with the bays 7E, 3E, 1D and 5D central axis and extending 500 m downstream the spillway end sill. Transversal profiles were located respectively 5 m and 75 m downstream of the spillway end sill, thus covering the upstream and downstream zones of the 80 m long riprap protection. From October 2007 onwards, the detail of the surveys increased significantly, with the use of sonar and GPS equipment and allowing a three dimensional perception of the surface deformations of the riprap.

From 1985 until 1988 no significant movements were observed, no major floods having occurred in this period.

A survey made after the first significant floods of the 1989/90 winter evidenced already the development of an erosion cavity in the initial 10 to 20 m of the riprap and a bar reaching an elevation 1 to 2 m above the original riprap elevation some 30 m downstream of the spillway end sill in three of the eight bays.

A survey made in 1998, after the floods of the winter of 1995/96, evidenced some additional erosion in the vicinity of the spillway and after the floods of 2000/01 surveys evidenced the development of some erosion in the left side of the river and, more significantly, in the central part of it, whereas the right side didn't evidence much change. However, raising more immediate concerns, the transversal profile closer to the spillway evidenced that the previously observed erosion near the spillway was developing further upstream, exposing the spillway downstream cutoff wall. The erosion near the cutoff wall presented an average 4 m depth.

The survey made after the 2006/07 floods revealed that, despite some deviations from previous survey, the overall pattern of the river bed downstream of the spillway was kept, although closer to the dam the erosion of the riprap increased 1m to 2 m downstream of bays 3E, 1D and 5D, and decreased 1.5 m downstream of bay 7E.

The tridimensional bathymetry surveys performed from October 2007 onwards allowed the confirmation of general erosion near the spillway given by the previous partial and more limited survey information.

EDP decided to initiate studies to determine the likely causes of the erosions observed in the river bed downstream of the dam and to assess its safety in case of riprap complete failure near the spillway. In the scope of these studies, additional surveys were made in 2010 and 2012, the most recent survey being depicted in Figure 5.

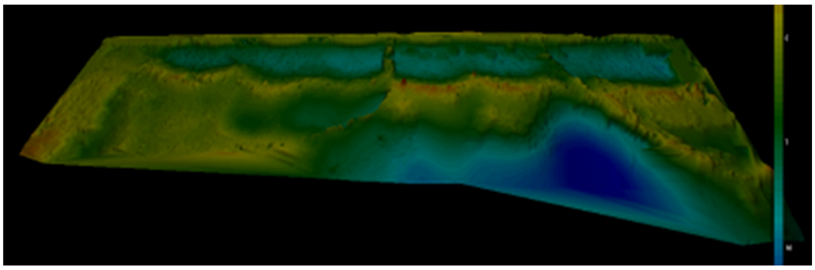

Figure 5. Riprap erosion downstream of the spillway in July 2012 (looking upstream).

Underwater inspections with divers were carried out to assess what type of material covered the scoured zone. Special attention was given to the interface between the spillway downstream cutoff wall and the river bed. Visual inspections evidenced that most material in the scour hole was formed by sediments, the protective riprap and underneath filter layers having been damaged across most of the spillway width in the immediate vicinity of its downstream cutoff wall.

After 27 years of systematical observation of the riprap and assessment of need of corrective interventions, a decision was taken in 2011 to replace the damaged riprap. The correction measures involved:

- detailed analysis of the causes for the unexpected riprap scour;
- assessment of the hydraulic gradients through the alluvia foundation and risk of piping;
- hydraulic model studies of corrective solutions capable of resisting the hydrodynamic actions due to spillway operation;
- the planning of the works in order to avoid interference with the hydropower, navigation, water supply and flood control aspects of the Douro system.

4. Study of cause of the scour and corrective solution

4.1 Approaches

The following approaches were considered to analyze the riprap damage causes, to assess the need for repair and to design a corrective solution:

- study of the seepage flow through the spillway alluvia foundation by means of a 2D numerical model and assessment of risk of piping erosion;
- analysis of the field data regarding spillway operation and riprap surveillance between 1987 and 2010;
- hydraulic model of the dam spillway at a scale 1/80 to assess probable causes for scouring and study the corrective solution;
- follow-up of the works of removal of the existing riprap material and the construction of the new reinforced riprap.

4.2 Seepage through spillway foundation

A study of the seepage flow through the foundation of the spillway was performed by LNEC. For that purpose a 2D numerical model was developed using the PlaxisFlow 1.1 software. The main goals of the model were: i) assessing the conditions for development of internal erosion ii) checking the advisability of refilling the scour cavity that developed downstream of the spillway.

The model allowed: i) a comparison of foundation behavior regarding hydraulic heave and local or global internal erosion considering project design and different scenarios of conditions observed 2010; ii) to recommend the key aspects to be corrected allowing to comply with the safety regarding these two ultimate limit states and provide technical specifications.

Geotechnical investigation data dating back to May 1972 was used to estimate the foundation permeability coefficients. Data from prototype piezometers readings provided information on foundation pore pressures to calibrate the main parameters of the model.

The geometry of the slab and concrete cutoff walls was reproduced in the finite element model. The river bed was modeled considering an alluvial layer 32.5 m thick, over a 4.0 m thick layer of slightly weathered and fractured rock on top of moderately weathered rock (Figure 6). This model, with some adjustments, was used in a more specific scenario regarding basins 1E and 3E, for which an upstream and a downstream constructive plastic curtains were placed for the basins construction. As the corrective solution found to address this specific problem was independent of the downstream riprap protection, its description is not considered in this paper.

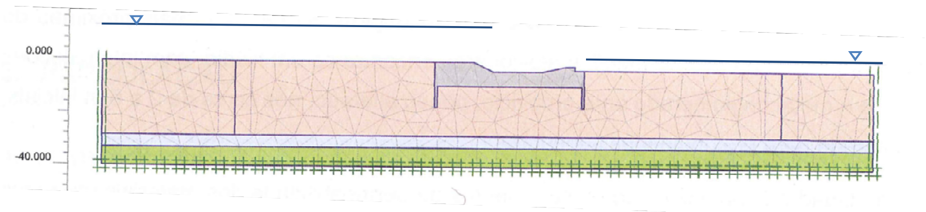

Figure 6. Stilling basins foundation 2D model - finite element mesh.

The numerical modeling of the foundation stability provided helpful information regarding its safety and the effect of the erosion of bed material immediately downstream of the spillway cutoff wall. It evidenced that any further development of the erosion would result in the reduction of foundation safety comparing to the designed solution, namely if erosion would go below elevation (-8.00) near the downstream basins cutoff walls.

4.3 Hydraulic model Studies

The hydraulic model studies of Crestuma-Lever dam spillway were performed by LNEC between 2011 and 2012. For that purpose, a model explored according to Froude similarity law was built at a non-distorted geometrical scale 1/80 (Figure 7).

The model reproduces the Douro River full width, 300 m upstream of the dam section and 560 m downstream of it.

Figure 7. Hydraulic physical model – general view.

The spillway eight bays were reproduced using cement mortar and the eight vertical double leaf gates were reproduced at a detail that allowed the simulation of the whole range of positions of each gate.

Concerning the riprap, selected gravel to comply with prototype block size was used to reproduce the initial 60 m of the riprap, as the last 20 m correspond to gravel in the prototype, which in the model was not possible to reproduce adequately. As the damaged area of the riprap corresponds essentially to the first 40 m, this area of smaller particle size at its downstream end was not critical for the problem being analyzed in the physical model tests.

The test planning was established having in mind the priority of assessing the riprap erosion main causes and then to allow the definition of the block size required for the riprap reinforcement. Therefore, the first phase involved the reproduction of the riprap according to the original design block sizes. Based on the information that was possible to gather regarding the dam construction, it was considered adequate to assume that the riprap met the design criteria. The model tests of the existing riprap in accordance with project specifications evidenced that, if the gate operation rules are followed, no erosion of the riprap was observed. Additionally, for operation conditions in which the gate operations rules somewhat deviated from the established operation rules, no major effect was observed in the riprap either.

As adequate performance of the original riprap design observed in the model tests were in contradiction with the generalized erosion observed in the prototype, it was then admitted that some sort of deviation must have taken place from the project assumptions or requirements. Among the many causes, the two main probable ones were:

- Douro River natural rating curve changed unfavorably over time producing lower water levels downstream of the dam;
- Riprap placed downstream of the spillway didn’t comply with the designed block size.

Some research on both topics made it more likely that the cause of erosion would derive from changes of the natural rating curve mostly because:

- bathymetry data from 1985 to 2010 evidenced an average lowering of river bed of 4 m downstream of the dam;
- sand mining and navigation channel dredging took place since the dam entered into service;
- operation data regarding the downstream water level and corresponding flow discharges evidenced a deviation from design rating curve.

Tests were made in the model imposing a revised and conservative rating curve, based essentially in the lower boundary of the operation data points, as depicted in Figure 8. Tests were run for the most conditioning range of gate positions in terms of energy dissipation, i.e., considering openings under the gates between 1 and 3 m.

After a simulating two days of continuous operation (prototype), riprap developed an erosion pattern in accordance with the prototype observed pattern of erosion (Figure 9). This indicated that the unfavorable evolution of the river natural rating curve was a major factor leading to the observed erosion.

Tests with riprap involving larger mean block sizes were then carried out to assess adequate size capable of withstanding the hydrodynamic actions of the flood discharges considering the revised downstream rating curve of the river.

The tests carried out in the model evidenced that a considerable increase of blocks diameter was necessary, the mean size having increased from a range of 0.9 to 1.35 m considered in the project to a range of 1.0 to 2.2 m.

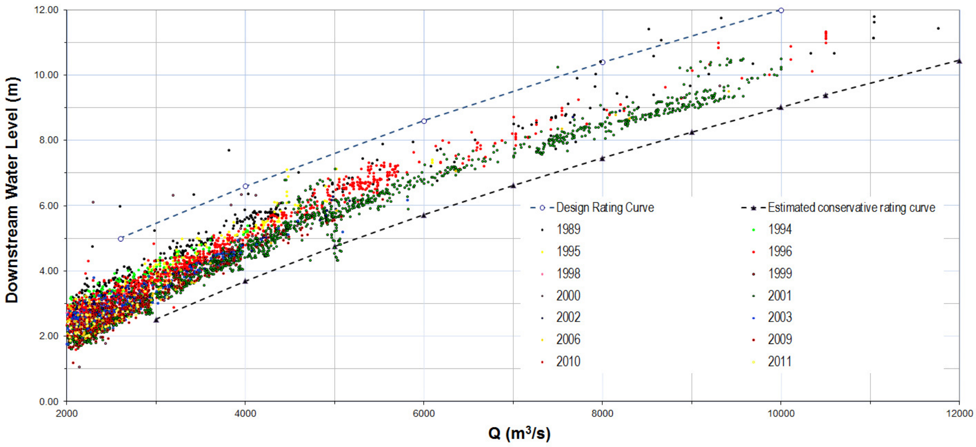

Figure 8. Downstream design and estimated corrected rating curves, and operation observed points.

Figure 9. Riprap erosion reproduced in model assuming a revised downstream rating curve.

5. Corrective measures, surveillance and monitoring

In order to ensure the global homogenous behavior of the new riprap protection, it was carried out the demolition of the damaged riprap, extending from the spillway end sill until the existing bar formed approximately 40 m downstream. Excavation near the cut off wall of the stilling basin was foreseen until the original river bed was attained and down to elevation -8.00 m, allowing the required thickness to place the first and second layers of filters and the riprap itself (Figures 10 and 11).

Based on hydraulic tests results and recommendations of geotechnical nature, a revision of the particle size was recommended for riprap and underlying filter layers (Figure 11).

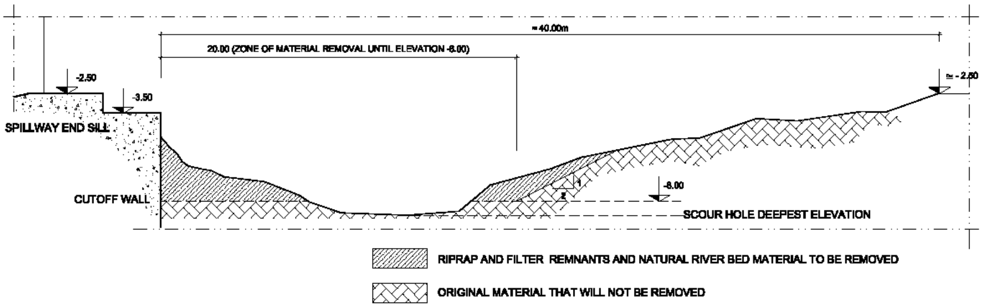

Figure 10. Schematic representation of removal of remnant material from riprap scour hole.

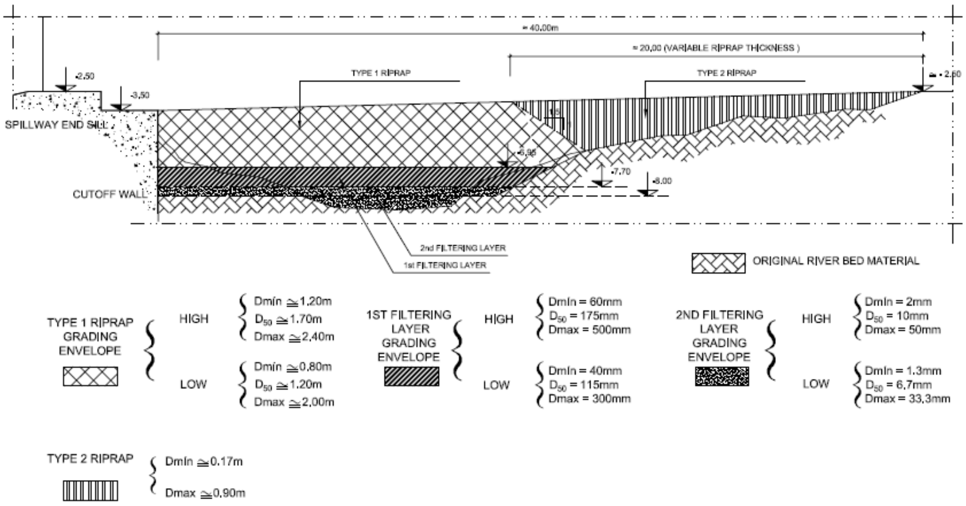

Figure 11. Schematic representation of replacement of riprap and filters for repair of damaged zone.

To allow adequate quality control of the riprap repair works, several measures were considered, namely:

- detailed bathymetric 3D surveys prior to the initiation of the works and, at least, at the end of the removal of the remnant material from the scour whole, after the completion of placement of each filtering layer, after the placement of riprap Type 1 and Type 2 materials (Figure 11) and when particular unexpected situations occurred, such as existence of large blocks in the intervention area or operation of spillway to pass flood waters;
- visual inspections with divers prior, during and at the end of the works to confirm its correct execution or to visually confirm atypical situations;

- *in situ* and laboratory controls and tests concerning the filter and riprap material to ensure adequate mechanical, chemical and geometrical characteristics.

Similarly to what was performed before the repair works, a program for systematic observation of riprap will be set up and implemented, taking as reference the situation evidenced in the most recent bathymetry detailed survey. This bathymetry was made upon the conclusion of the repair works downstream of the dam spillway in September 2013 (Figure 12). The extension of riprap on the right side of the river (left side of figure) resulted from a local additional reinforcement of riprap downstream of bay 3D (refer to Figure 4 for bay identification).

Additional control measures are being considered, namely concerning the identification of a suitable river cross sections downstream to be instrumented for monitoring of river rating curve evolution.

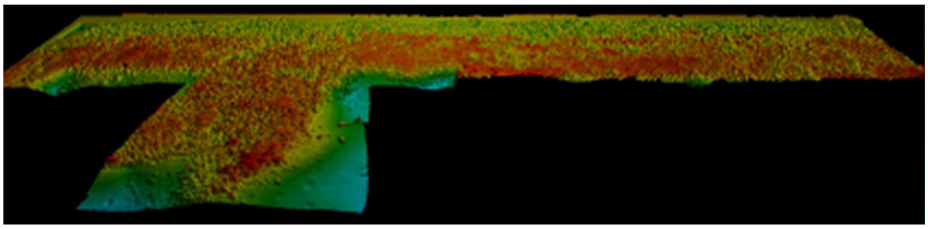

Figure 12. Riprap downstream of spillway after completion of works in Sept. 2013 (looking upstream).

6. Conclusions

Regular observation and survey data analysis are key for safety control procedures, allowing to effectively manage situations in which actual behavior presents deviations from expected. Observed deteriorations may derive from a number of causes, its assessment sometimes requiring additional and multidisciplinary studies to identify the main causes.

The abnormal riprap erosion downstream of Crestuma-Lever spillway confirms the advantages of regular monitoring and safety control procedures. Multidisciplinary approach was considered to understanding riprap erosion causes, involving the development of a spillway foundation seepage flow numerical model, construction of a physical model to reproduce riprap hydraulic behavior and in-depth project, construction and operation data analysis to assess actual conditions in which the spillway operated.

These studies pointed out as main cause of the erosion the significant deviation between the assumptions regarding the river natural rating curve in design phase and the rating curve actually occurring since the dam entered into service in 1985. This deviation was most likely caused by exogenous factors such as sand mining or navigation channel dredging. Regardless of what caused the deviation, it resulted in an important shift of some key hydraulic parameters and led to inadequate flood flow energy dissipation, most particularly in the range of the more frequent floods.

Hydraulic model tests and geotechnical analysis allowed the definition of corrective measures of the scoured riprap. These measures involved the definition of larger riprap blocks mean size, the redesign of grading curves for riprap and filters, the project of a new geometry of the reinforced riprap and an increase of thickness of the different involved layers.

EDP will put in place a revised dam monitoring plan in order to include the recent repair works of the riprap blanket as well as the evolution of the river natural rating curve, thus allowing an assessment of the behavior of the implemented repair and reinforcement works.

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