ENERGY DISSIPATION OF HIGHLY CONVERGENT CHUTES IN STILLING BASINS OF CONCRETE DAMS

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Summary. This article presents the results of a combination of experimental and numerical research on the performance of stilling basins of spillways with highly convergent chutes (HCC). The comparison between the energy dissipation of the stilling basins with flat slab and baffle blocks shows that the latest are more efficient. Because of that, the cost savings of using such blocks can be significant. The results obtained could be applied in different cases such as increasing the capacity of existing spillways and protecting dams against overtopping. The application of HCC spillways in new dams could lead to a reduction in the cost of the stilling basin compared to conventional hydraulic jump energy dissipators.

1 INTRODUCTION

Highly Convergent Chutes (HCC) have been successfully used in spillways of gravity and arch-gravity dams in many countries, especially in Japan. This type of spillway is characterized by a concrete chute, usually placed on the downstream slope (also at the toe) of the dam, which changes the direction of the inlet flow and leads to a central area of the river valley (Figure 1). In plain view, the angle between the longitudinal axis of a typical HCC and the direction of the inlet flow differs greatly. This angle exceeds the usual design criteria for the maximum convergence of the sidewalls of spillway chutes (United States Bureau of Reclamation 1987).

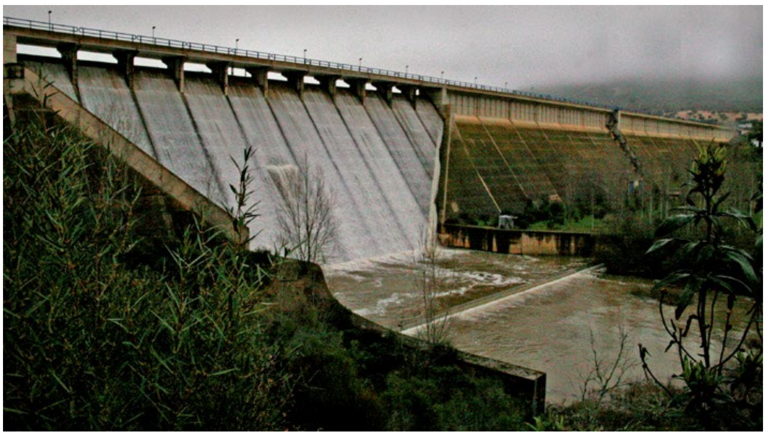


Figure 1. Spillway of the Torre de Abraham Dam (Spain) in operation.

However, the technical manual on dam protection against overtopping published by the FEMA of the United States of America (FEMA 2014) presented an alternative to protect the toe of the abutment of gravity and arch dams consisting of a concrete channel at the downstream toe. This protection was successfully applied (Figure 2) at the Tygart Dam (USA) and behaves hydraulically in a similar way to an HCC.

Figure 2. Overtopping protection of the right abutment of Tygart Dam (USA) (FEMA 2014).

In a similar way, most embankment dam overtopping protection systems usually need protection at the toe of the dam to avoid scour at that point, that could lead to the failure of the erosion protection system against overflowing. This need has led to several studies on the protection of the toe of the dam in overtopping protection systems using RCC and the hydraulics of stepped HCC (Hunt et al. 2012, Hunt 2008, Hunt et al. 2005).

The potential interest of HCC in increasing the capacity of existing spillways or protecting the toes of concrete and embankment dams led to new research effort to a better understanding of the energy dissipation at the stilling basins in the presence of converging flows proceeding from HCC. The research presented in this paper consists of two parts. First, a summary of the findings of a set of experimental tests on the dimensions required to dissipate energy in flat sill stilling basins subjected to the impingement of lateral jets from HCC (Moran et al. 2021). The second part presents a study on the effect of different deflector and baffle blocks on the reduction in the dimensions of the stilling basin compared to a flat slab. This part was performed by means of CFD numerical modeling, which was previously calibrated with laboratory experimental tests.

2 MECHANISMS OF ENERGY DISSIPATION

The main difference between the hydraulic performance of a conventional hydraulic stilling basin, with frontal discharge, and a HCC-type spillway dissipation basin is related to the way energy dissipation occurs. In the case of conventional basins, energy dissipation is produced by the formation of the hydraulic jump, and its overall behavior is markedly two-dimensional. On the contrary, the dissipation basins of the HCC type spillways dissipate a good part of the energy by the impingement produced between the side jets and the flow coming from the frontal discharge. The operation in this case is strongly three-dimensional, and the number of variables that characterize the phenomenon is greater.

Figure 3 illustrates the differences in energy dissipation between both mechanisms with similar boundary conditions, that is, the same inlet flow and tailwater depth in both cases. As can be seen, the length of the stilling basin required to hold the highly turbulent flow (white water) is shorter in the HCC (Figure 3, right) than in frontal inlet flow (Figure 3, left). This case shows the effect of energy dissipation due to the impingement of the jets and the potential interest of the HCC to reduce the cost of the stilling basin for a given inlet flow. Similarly, when HCCs are used to increase the capacity of an existing spillway, the cost of adapting the existing stilling basin could be lower due to the reduction of its length.

Figure 3. Side view of the performance of the stilling basin for an inlet discharge of 100 ls-1. Left: Hydraulic jump (tailwater depth 0.423 m) with frontal inlet flow. Right: Impingement of HCC jets with frontal flow (tailwater depth 0.417 m).

3 ADAPTATION OF TYPE I STILLING BASINS

As mentioned above, the research presented in this article was organized into two parts. The first (experimental) focused on studying the adaptation of the size of a Type I stilling basin for a given inlet discharge. The condition was to achieve a dissipation of the energy like the conventional hydraulic jump stilling basin for a given inlet discharge (Q). The adaptation was achieved by changing both the length (L*) and the required tailwater depth (d*) of the stilling basin, without adding elements such as deflector blocks. The second part consisted of an optimization of a single case study of HCC. In this case, a set of numerical models was performed to increase the reduction of L* and d* of the basin by adding baffles and deflector blocks to the original flat slab basin. In both parts, the goal is to demonstrate that the impact of the side jets can lead to a cost benefit of the stilling basin for a given inlet discharge (Q).

3.1 Basins with flat slab

The experimental research was developed at the facility shown in Figure 4. A more detailed description of the facility and the different configurations of the tests can be consulted in (Moran et al. 2021).

The tests were performed with symmetric flow along the longitudinal axis. The geometric configurations included tests with frontal flow (configuration *A*, used as the reference case with energy dissipation by hydraulic jump) and HCC flow (configurations *B, C, D,* simulating different convergence angles). The height of the inlet of the side jets in the basin (*P*) was also varied in the tests (0,10 and 20 cm). On the other hand, hydraulic loadings such as the flow distribution between frontal and side flows and tailwater depths were varied to obtain a more complete understanding of their effect on energy dissipation.

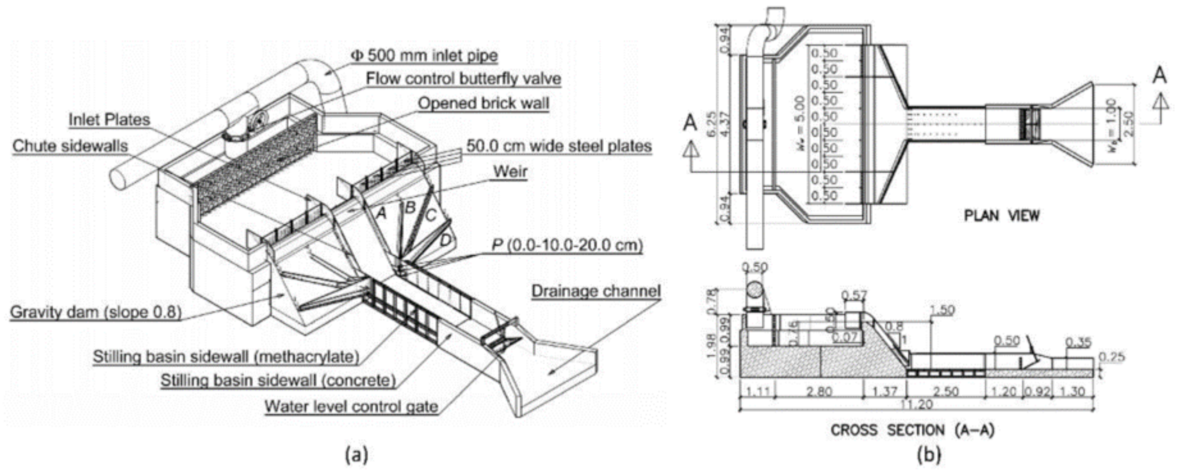


Figure 4. Experimental facility: (a) 3D scheme with the main parts and the setup configurations A, B, C, and D, and (b) plan view and longitudinal cross section (Moran et al. 2021).

The main conclusions presented in (Moran et al. 2021) showed that *'the use of HCC spillways with symmetric side jet inlets can effectively dissipate flow energy in the stilling basins of gravity dams, with a likely reduction in the size of the corresponding Type I basin. This is particularly interesting in cases where the outflow capacity of an existing well needs to be increased and the stilling basin has already been built. It can also be applied in cases where it is intended to protect the downstream toe of the dam against erosion due to overtopping'.*

The results of the tests led to average reductions in the length of the basin (L^*) from 23% to 35%, compared to the Type I basin operating with conventional frontal flow (for the same total discharge). However, the results of the required tailwater depths (d^*) were closer to those needed by Type I basins, which means that the height of the side walls of the basin would be similar in both cases (that is, frontal flow and symmetric HCC flow).

Apparently, tests with the inlet of the HCC at the bottom of the basin (P=0) presented a more effective dissipation. Under these conditions (P = 0), greater reductions in L^* and d^* were achieved when the direction of the side jets caused a more direct impingement between them, and the water discharge from the HCC side jets was higher compared to the frontal discharge.

Finally, flow patterns in the HCC basins shown that operation in submergence conditions was preferable in comparison with lower tailwater depths due to the formation of side waves along the basin and flow concentrations in some areas of the transversal cross section.

3.2 Basins with baffles and impact blocks

This section aims to evaluate the effect on the reduction of required dimensions (L^*, d^*) of a stilling basin by installing impact or baffle blocks. In some real cases, the installation of such blocks has been carried out as a successful way to reduce the length (that is, the cost) of the stilling basin (Figure 5).

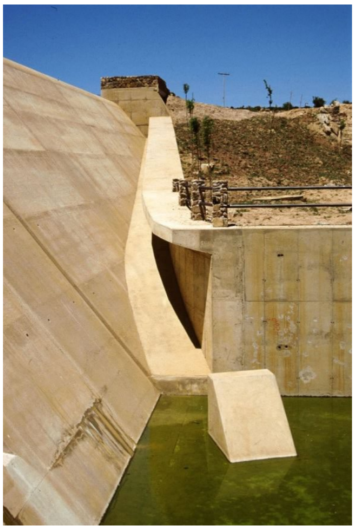


Figure 5. Picture of an impact block in the HCC spillway in Zapardiel de la Cañada Dam (Spain).

3.2.1 Methodology

The research of the influence of baffle blocks in the stilling basin has been studied by numerical modelling with the CALA software, developed by CIMNE specifically to build hydraulic 3D models of HCC spillways. The CALA program integrates into the graphic interface of the GiD processor and allows the numerical simulation of this type of spillways (Peraita et al. 2019).

The investigation was developed according to the following strategy: first, a specific case of study about an HCC spillway with a clearly defined geometry was established. Then the dimensions of the stilling basin with flat slab (reference case) were defined. Subsequently, different designs for the deflection or impact blocks and their position in the stilling basin were studied. After the results obtained from each model were evaluated, another configuration of the baffle blocks was analyzed later, and the investigation continued adding new variants that may improve energy dissipation, always trying to reduce as much as possible the required dimensions of the basin.

As was said, the study case is based on a spillway with HCC with a defined design. This geometry is characterized by a fixed distribution of the frontal (37,5%) and lateral discharge (62,50 %, 31,25% from each side). Furthermore, the angle from the bottom of the HCC to the horizontal plane was 47º. Obviously, the conclusions of the research presented in this article are limited to this case study (reference case) of the HCC spillway.

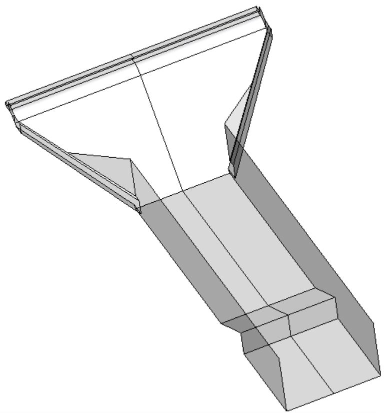


Figure 6. 3D view of the stilling basin of the flat slab (reference case).

Once the geometry of the spillway of the study case was defined, an acceptance criterion was established for the energy dissipation to analyze the behavior of the stilling basin. Following the methodology proposed in (Moran et al. 2021), the index selected for the acceptance criteria was the coefficient of variation (*Cv*) of the pressure, which was obtained registering the dynamic pressures along the central longitudinal axis of the basin as a way to characterize the degree of turbulence at the end of the basin. The *Cv* index was compared with the established acceptance criteria for energy dissipation *Cvf*, which at the research was set at 3,0%. When the index of pressure *Cv* coincided with *Cvf*, it meant that the required length of the stilling basin was achieved to correctly dissipate the energy (L^*). Meanwhile, the downstream water level (d^*) was established at the end of the stilling basin as a boundary condition. In summary, applying this methodology proposed by (Moran et al. 2021), a pair of values (L^*, d^*) was obtained that determined the needed size of the stilling basin to dissipate the energy with a set discharge.

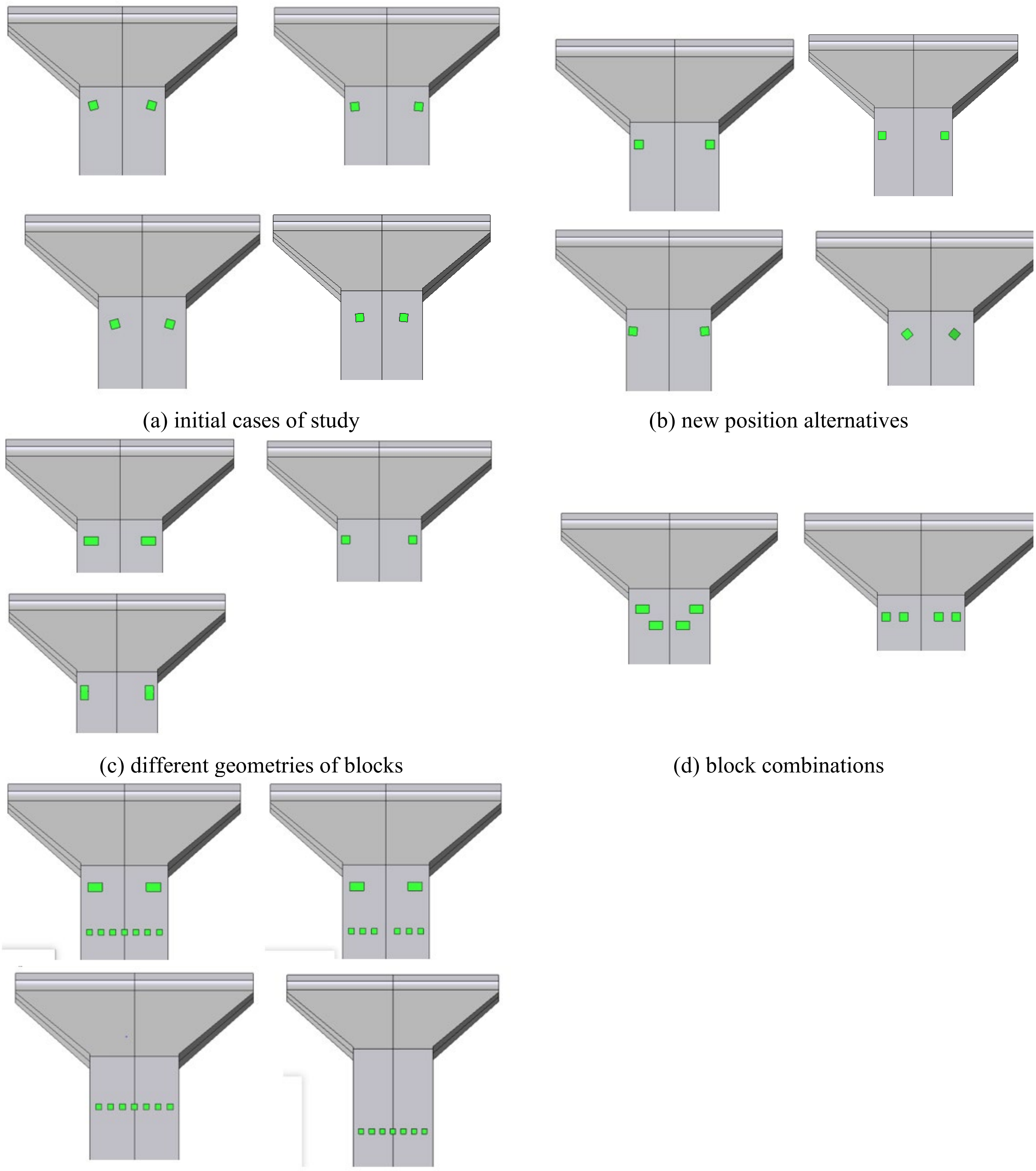
3.2.2 Results and Discussion

Initially, the L^*, d^* parameters were determined in the reference case with flat slab (i.e., without blocks). Subsequently, additional cases with impact blocks were defined using configurations with baffle blocks slightly turned with respect to the downstream slope at the beginning (that is, the blocks are facing more directly to the frontal spillway chute than to the HCCs). Therefore, the objective was to reorient the flow direction rather than provoking a direct impingement with de blocks. This configuration tried to achieve better energy dissipation by the impact of the side jets between them.

The result of this initial arrangement (Figure 7a) showed a relevant influence of the angle between the block and the longitudinal axis of the stilling basin, being more effective in the cases with lower angle (i.e., a more tangential impingement of the flow in the block surface) to facilitate collision of the lateral discharges. Furthermore, it was observed that the cases where blocks were located in positions in the vicinity of the center axis of the basin resulted in a worse performance because of the difficulty of reorienting the side flows to cause a more direct impingement between them.

After the analysis of the initial results, new alternatives were studied without any turning of the baffle blocks (i.e., frontal face of the block perpendicular to the longitudinal axis of the stilling basin) or with a small angle in the direction of the stilling basin (Figure 7b). All of them were defined to facilitate the change of direction of the lateral flows to a more direct impingement. In addition, new configurations were modeled to place the impact blocks heading on the HCCs, to evaluate if a straight impact with de blocks could be more effective than reorienting the side jets to impinge between them. The results evidenced that the configurations without any turning in the blocks, i.e., means placed heading on to the frontal chute, were more effective than the other ones. In other words, these models showed that the energy dissipation achieved by the baffle blocks was more effective due to the change of the direction of the side jets to impact between them, instead of causing a straight collision between the jet and the block. In addition, it was observed that the configurations with baffle blocks close to the inlet of the side jets to the basin apparently improved the influence to change of direction of the side jets, making the collision between them.

The next step was to evaluate the effect of the baffle block on the flow patterns. The width (in the direction along the dam axis), the length (orthogonal direction to the dam axis), and the height (vertical direction) were varied (Figure 7c). The location and orientation of the block were kept constant, with the baffle blocks heading toward the frontal chute, placing them close to the arrival of the highly converging chutes to the basin. Initially, the tested configurations seemed to indicate that a larger size of the baffle block was beneficial in changing the direction of the side jets as a matter of the larger surface of impact.



(a) initial cases of study

(b) new position alternatives

(c) different geometries of blocks

(d) block combinations

(e) Configurations with intermediate blocks

Figure 7. Plan view of the configuration of baffles and impact blocks in the modeled basins.

Evaluating each dimension separately, it was observed that wider blocks achieved an improvement in the energy dissipation in the stilling basin, reducing the required length and height. The consequence of widening the baffles was a reduction of the required length of the basin in a 27.4%. However, these alternatives usually generated a concentration of the flow stream in the middle of the stilling basing after overtaking the blocks. Consequently, the flow was not uniformly distributed throughout the width of the basin. Moreover, it was observed that excessive width of the baffle blocks produced a negative result on the flow pattern because of the generation of a barrier effect. In this situation, with an extremely wide block, the flow stream was unable to find an outcome, and appears to tend to overflow the block, instead of redirecting in the way of a straight collision between the side jets.

Finally, different block combinations were investigated, setting more than one baffle block per model. The combination of several blocks led to the best options to reduce the basin (Figure 7d). Thus, it was noted that the location of several deflection blocks on each side increased the options to more precisely the side jets. Furthermore, using these configurations was helpful in homogenizing the stream flow in the basin in addition to the benefit in energy dissipation. However, the effect of placing the blocks in the intermediate part of the stilling basin (Figure 7e) did not produce suitable solutions compared to the placement of the blocks on both sides of the basin.

The best solution among all the cases, selected as the adopted solution of the investigation, was achieved with a configuration of four deflector blocks, heading in the frontal chute and located in the same row, two in each side, and located in the inlet of the side jets into the stilling basin. The selected alternative significantly improved the energy dissipation as a matter of the deflection of the side jets, reaching a straight impact between them. This arrangement allowed the combination of blocks to behave as a group, deflecting the flow as a wider block, and, in addition, the water can pass through the baffle blocks. The generated flow pattern also contributed to a uniform distribution of flow in the basin. In summary, a reduction in the length required in the basin to dissipate the energy of 34% was achieved, in addition to a reduction in the depths of the water (that is, the height of the side walls of the basin) of 9%, compared to the reference case.

4 COST BENEFITS OF HCC AND APPLICATIONS ON NEW PROJECTS

The cost benefits of the HCC are related to the reduction in the costs of the stilling basin for a certain discharge flow. In projects aimed to increase the capacity of existing spillways or protect dams against overtopping of gravity dams, benefits can arise due to the possibility of taking maximum advantage of the use of the existing stilling basin with minor adaptations, depending on the importance of the additional discharge to be managed. Of course, HCCs include new costs that must be considered, such as side chutes and the possible construction of baffles, downstream sill, or other elements. The studies presented in this document focus on the required dimensions of flat slab and those that can include baffles or impact blocks, and the results seem promising for cost savings in the construction.

An evaluation of the costs and benefits of HCC with baffle blocks was carried out by comparing the best solution of the study cases with blocks, with the reference case without geometry blocks defined in the research. This circumstance indicates that the cost-benefit estimate only applies when comparing a particular case of the HCC spillway with and without blocks, and it did not evaluate the impact on a traditional spillway with frontal discharge. It should be noted that the reference case possibly has a cost savings compared to the traditional solution of frontal flow with dissipation by the formation of a hydraulic jump formation, but this saving was not evaluated in this work.

The reduction in the dimensions of the required stilling basin makes sense if it translates into an economical saving. Economic evaluation was carried out by applying homogeneous criteria, valuing the most relevant elements of basin construction in each study case. Consequently, the aim was to verify whether the adopted solution (i.e., the best among the stilling basin with baffles made in this study) with blocks significantly improved the cost savings compared to the reference case with flat slab configuration.

The cost estimate considered the costs of the concrete, the required amount of reinforcement, the required formwork, the tasks to establish the base of the block, including the work on the surface of the slab of the basin, the execution of the anchors and sealing works. The reduction in the required size of the stilling basin due to the use of baffle blocks turned into a 36% of reduction in the cost needed to construct the basin compared to the reference case. The cost of the basin structure decreased by almost 40%, though it was slightly balanced by the cost of setting up the blocks. This cost was 5% of the total amount.

In conclusion, the economical estimate showed that it is possible to significantly reduce the cost of construction of the stilling basin for a HCC spillway by improving its energy dissipation performance, considering baffle blocks in the design. However, it is necessary to keep in mind that this conclusion is applicable for the specific geometry of an HCC spillway of this case study, and more general conclusions should be verified in future research with a wider scope.

5 CONCLUSIONS

The results of this research showed that HCC spillways are promising alternatives to increase the capacity of outlet works and an effective way to protect gravity (or arch-gravity) dams against overtopping. Furthermore, the effect of impingement of the side jets on frontal flow causes an increase in energy dissipation that leads to a reduction of the size of the stilling basin compared to conventional hydraulic jump basins.

In addition, the research conducted for a particular case study of HCC concluded that baffle blocks can improve the hydraulic performance in the flat slab HCC still basin, reducing its required dimensions to dissipate the energy, particularly in a reduction of the basin length. In terms of side walls, the required height did not vary considerably between the different study cases, although it was usually reduced in the same configurations that the length of the basin did. Energy dissipation was achieved more efficiently with a straight collision of the side jets under submergence conditions. This flow pattern seems to be facilitated when the baffle blocks are placed heading on the frontal discharge chute and located close to the inlet of the HCC into the basin, where the blocks improve their influence on deflecting the lateral discharges.

The increase in energy dissipation leads to a reduction in the required size of the stilling basin with flat slab configurations. The case study presented in this article showed that the use of baffle blocks can obtain additional cost reductions, up to 36% from a reference case with a flat slab HCC still basin.

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