A new evolution on the wedge-shaped block for overtopping protection of embankment dams: the ACUÑA block

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Abstract

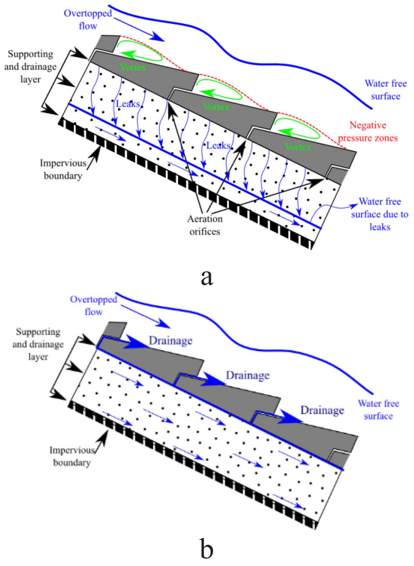
The article summarizes the research studies performed by the *Research Group on Dam Safety* (SERPA) of the Technical University of Madrid and the International Center for Numerical Methods in Engineering (CIMNE) in collaboration with the company PREHORQUISA. Such studies aim to deepen on the theoretical and practical understanding of wedge shaped blocks (WSB) technology. This research was funded by the Spanish Ministry of Economy and Competitiveness through the research projects called ACUÑA (IPT-2011-0997-020000) and DIABLO (RTC-2014-2081-5). One of the projects goals was to develop a new model of WSB looking for improving the performance of the existing ones. This research led to the new model of WSB called ACUÑA, proprietary in Spain since May 2017 (ES2595852). The paper presents a comparison between the behaviour of the new block with one of the existing models, specifically Armorwedge^{TM}. Such comparison has been made using physical and numerical modelling, studying the hydrodynamic pressures on the block and the leakage flow through the joints between blocks and the aeration vents.

1 Introduction and background

The hydraulic stability of wedge shaped blocks is based on the positive pressure of the water impacting on the upper face of each block, the overlapping, and the development of negative pressures on the block tread. Such stability is enhanced by the effect of the *vents* (also termed as "*air vents*" or "*holes*" in the bibliography) transmitting the suction generated on the block tread towards the block base when the drainage layer is not saturated (figure 1a). If the underlay is saturated, such suction may cause the return of a fraction of the drainage flow to the spillway chute, reducing the lift pressure under the blocks (figure 1b). WSBs have proven to be highly stable even in very unfavorable conditions (Hewlett et al., 1997).

The original concept of dam protections against overtopping by overlapping concrete blocks placed on the downstream shell of embankment dams arose from the work carried out by P.I. Gordienko, from Moscow Institute of Civil Engineering in the late 1960's (Hewlett et al., 1997).

Figure 1. Sketch of the hydraulic performance of a wedge-shaped blocks spillway (San Mauro et al., 2017).



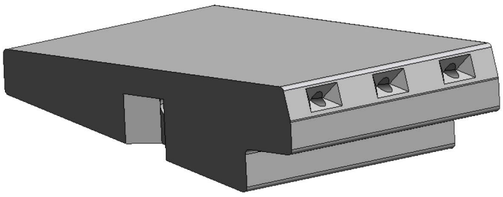
Initial works continued in the same organization by Pravdivets (Grinchuk, Pravdivets, and Shekhtman 1977; Pravdivets and Slissky, 1981). The research progressed along the next decades in countries such United Kingdom, USA, and Portugal, among others, and the construction in recent years of several dams in operation with this technology (Moran, 2017).

Since 2011, the Research Group on Dam Safety Research (SERPA) of the UPM, CIMNE and PREHORQUISA, with the support of the Center for Hydrographic Studies of CEDEX, have aimed to complement the theoretical and practical knowledge of the WSB technology (Caballero et al, 2015; Caballero et al. 2017, San Mauro et al. 2017).

2 ACUÑA block

The recent research made by the Spanish consortium concluded with the development of a new design of the block which was patented on May 8, 2017 (ES2595852, the ACUÑA block, Figure 2).

Figure 2. ACUÑA block (ES2595852).



The main difference of ACUÑA block with respect to the previous WSBs is the design of the aeration and drainage system, with the vents located in the upper area of the riser between consecutive rows. Additionally, a bevel has been placed in the contact area between the block tread and the riser, in order to increase the negative pressures in that area. This new layout allows reducing the leakage flow in the granular drainage layer. In addition, ACUÑA block has a transverse orifice that passes through its center of gravity and whose main objective is not only to transmit the negative pressures towards the base of the block by its sides, but also to facilitate the transportation tasks to the construction site by crane.

The new block is presented next, based on a brief description of the methodology followed for its definition and the main results obtained in the physical and numerical models.

2.1 Physical and numerical models. Research tests

2.1.1. Testing facility, measuring devices and data acquisition

The experimental set up, located in the Hydrographic Studies Center (CEH) of CEDEX (Madrid, Spain), includes a 0.50 m wide steel and methacrylate testing channel constructed on a 2H:1V slope, which provides a 4.7 m vertical drop (Figure 3a). Walls are 0.85 m high, measured normal to the base. A maximum flow rate of 0.24 m^2/s is available. A non-slip metallic grid allows the wedge-shaped blocks to stand 0.2 m over the channel bottom (Figure 3b) so that the pieces can be tested on different drainage conditions. The installation presents a total amount of 47 rows of WSBs with the size adopted for the WSB units.

Figure 3.Experimental facility up at CEDEX hydraulic laboratory (Madrid) (Caballero et al., 2017).

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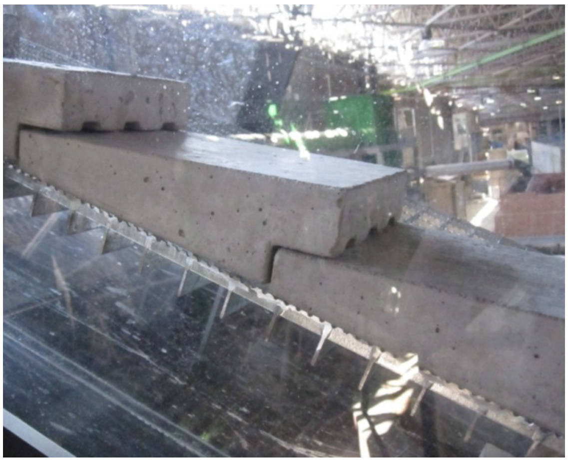

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The installed instrumentation allows to obtain measurements of water level; main flow and seepage flow discharges; pressures on different locations of the blocks by means of twelve pressure sensors (six on the block tread, three in the riser and three in the base of the block) and, finally, the air concentration of the flow.

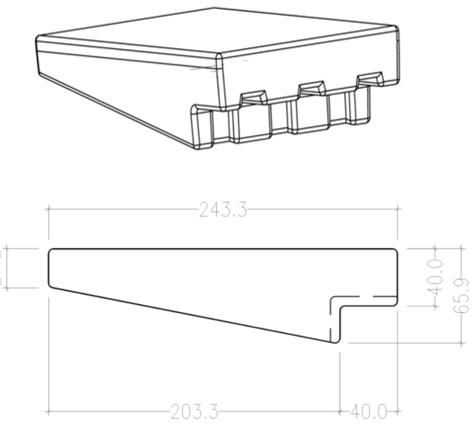
More details of the experimental facility and the instrumentation system can be consulted in previous references published at Protections 2014 and 2016 (Caballero et al., 2015; Caballero et al., 2017).

2.1.2. Physical tests

The tests have been grouped in several phases. In the first phase, the Armorwedge™ block (phase w1), scaled to one third of the unit installed at the spillway of Barriga dam (Morán and Toledo 2014; FEMA 2014), was used (figure 4a). Subsequently, the ACUÑA block was defined based on the results obtained in these very first tests. Next, new tests were made (phase w2, figure 4b) to evaluate the performance of the proposed design.

In addition, new tests are currently ongoing to simulate the conditions of a high permeability underlay (i.e. a downstream rockfill shell) and also a layout over a drainage layer on an impervious embankment dam. In the first case no drainage material was placed under the WSB (d1, free drainage) and, in the second, the blocks were placed over a 0.20 m thick of homogeneous gravel d_{85} = 13.6 mm layer, extended on the impervious bottom of the channel (d2, drainage layer).

Figure 4: WSBs tested during the experimental research. 3D view and longitudinal section. (a) WSB Armorwedge™: (b) WSB ACUÑA: (dimensions in mm., width of both block types: 165 mm)



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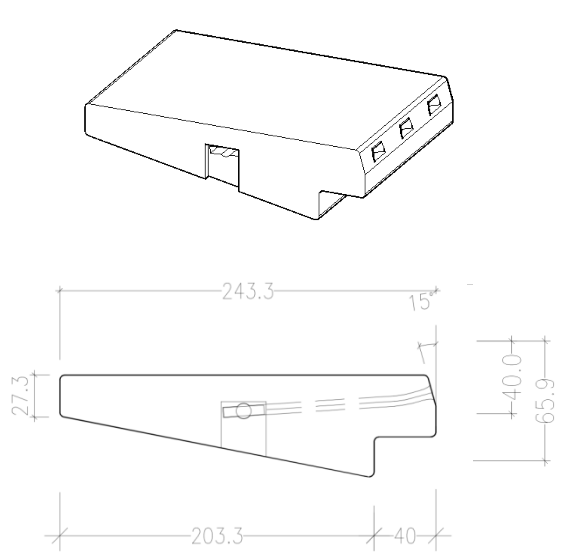


b

The leakage discharge through both the joints between the blocks and the vents was measured using a triangular, sharp crested weir, arranged for this purpose. Likewise, the leakage discharge was measured separately through the contact joints between the longitudinal, transverse blocks and the vents.

In addition, in order to compare the results of other authors, they were expressed in a dimensionless way (Figure 5 and table 1), following the criteria of Relvas and Pinheiro (2008-2011).

Figure 5: Geometric parameters of the block (Caballero et al., 2017).

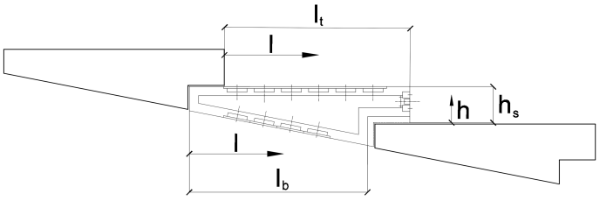


Table 1. Tested flow rates; h_c is the flume critical depth; h_s is the height of riser of the steps (see figure 4); q is the flow rate (Caballero et al., 2017).

$h' = h_c/h_s$	4.51	3.99	3.44	2.84	2.52	2.17	1.37
q (m^2/s)	0.24	0.20	0.16	0.12	0.10	0.08	0.04

2.1.3. Numerical tests

Two different numerical tools have been used to model the flow over the WSBs, which reproduce both the global behavior and the specific phenomena near the block surface, such as air-water interaction or vorticity. Both are based on the finite element method and the resolution of the Navier-Stokes 3D equations. However, one of them is based on a Lagrange formulation (the finite element particle method, PFEM) while the other uses an Eulerian formulation (Kratos Multi-physics open source software application). Both codes have already been applied in the various hydraulic problems in the field of dam hydraulics, among other engineering problems (Larese et al, 2008; Salazar et al. 2013; Salazar et al., 2016; San Mauro et al, 2016). Several numerical campaigns were carried out, with the objectives of characterizing the flow in the vicinity of the block and evaluating the effect produced by the riser orifices, for different positions and block shapes, modeling the water-air interaction.

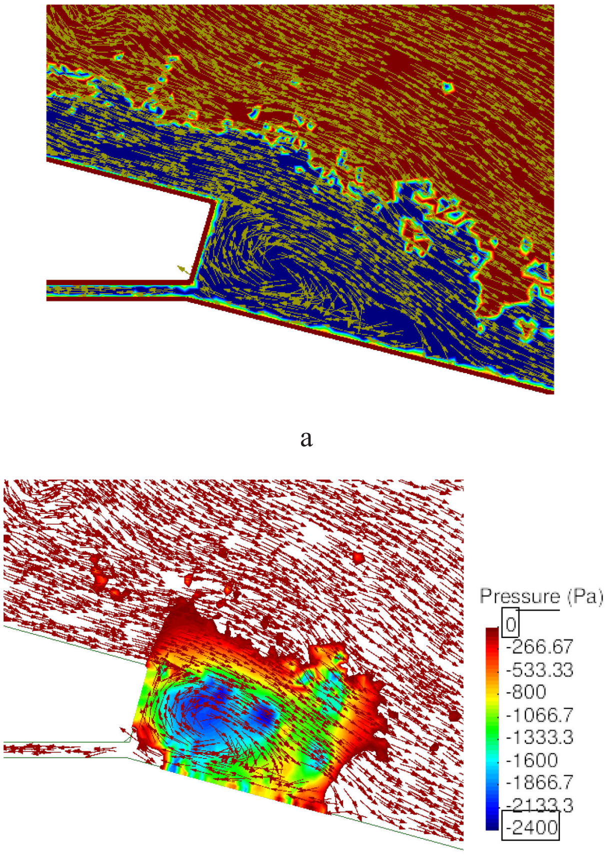
2.2 Some results. Why the ACUÑA block

The numerical simulations allowed obtaining the field of velocities and pressures in the whole calculation domain. The observed behavior consisted in the formation of a vortex near the concave junction of the block tread and the riser, with slight spatial oscillations throughout the simulation (Figure 6a). This vortex generates a zone of negative pressure on the surface of the riser, with minimum values in the upper third of it (Figure 6b). The characteristics of the vortex will determine the pressure distributions in the tread and riser of the block, as well as the operating conditions of the vents.

Figure 7a shows some of the results obtained in phase d1 (free drainage). The maximum average pressures recorded in the sensors located in the block tread of row 25 of the physical model for flow rates between 0.04 to 0.24 m^2/s in the studies carried out in the ACUÑA project were compared with the results obtained by other authors (Bramley and Baker, 1989; Bramley and Baker, 1991; Slovensky, 1993; Relvas, 2008; Relvas and Pinheiro, 2011) for an equivalent uniform flow regime (Caballero et al., 2017).

Previous studies showed the general agreement between the results and those obtained by other authors. They are also in accordance with the previous numerical models carried out during the project to characterize the flow in the vicinity of the blocks, being able to establish the limit between the negative and positive pressure on the block tread between 30-40% of his length, approximately. Besides, the maximum positive pressures are recorded systematically between 52-67% of the footprint length (Caballero et al. 2017).

Figure 6: a. Flow pattern with velocity vectors for discharge with Froude number equals to 3 and slope 2H:1V. Blue color represents water and red, air. b. The colored area represents the distribution of negative pressures, where it is observed that they are essentially associated to the vorticity.



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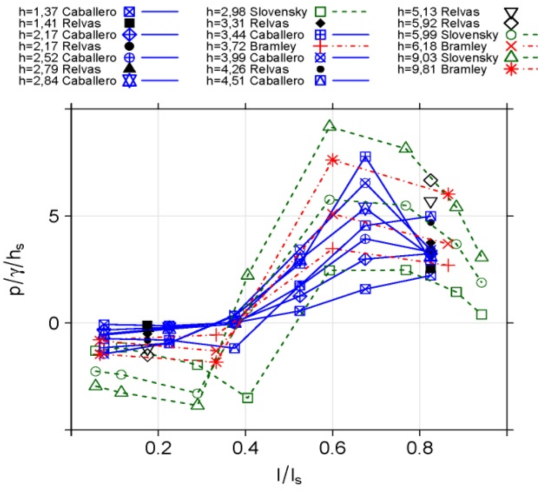
Three sensors were placed within the measurement blocks in order to experimentally characterize the distribution of the maximum average pressures in the riser. As expected, the pressures were negative or close to zero in that area, with a higher value of the suction at the top of it (Figure 6b).

Since the vents of the Armorwedge^{TM} block (phase w1 of the tests) are located at the base of the riser, a small but positive pressure is developed in that area. This could cause a flow circulation towards the drainage layer through the vents, as it is showed in Figure 6b, in the case of the block located in row 25 for a flow rate of 0.16 m^2/s.

Figure 7. a. Mean pressures on the tread of the block at row 25 for flow rates from 0.04 to 0.24 m^2/s and those reported by

different authors (h´= hc/hs). b. Pressures on the block rise at row 25: q_1=0.16 m^2/s; q_3=0.20 m^2/s. (Caballero et al., 2017)



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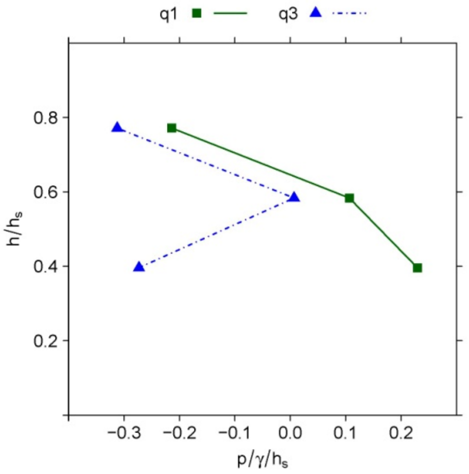

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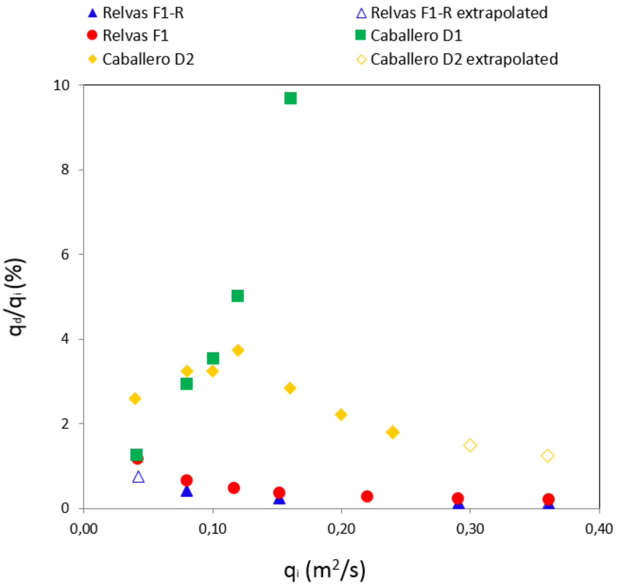
The suitability of modifying the position of the vents of the new design (ACUÑA block) to the upper part of the riser was proposed before doing the experimental research. This proposal was made foreseeing a possible reduction of leaks in the new block with respect to existing ones in the traditional models, with the vents in the lower area of the riser.

Relvas and Pinheiro reported results about drainage flow for different flow rates (Relvas, 2008; Relvas and Pinheiro, 2010). As mentioned in Caballero et al. 2017, a clear reduction in the percentage of drainage flow is observed as the discharge rate of the main flow becomes higher, due to the fact that the drainage layer under the WSB is saturated, and a fraction of the drainage flow is sucked towards the main flow area due to the negative pressure in the vents at the base of the riser.

Unlike the results reported by Relvas and Pinheiro, an increase in the percentage of drainage flow is observed as the main discharge flow rate becomes higher during phase d1 (free drainage) of the tests (figure 8). As previously indicated, during phase d1, a free space of 0.20 m under the blocks was available. Therefore, that space could not become saturated, and the return of the leakage flows to the channel was not possible, reaching values up to 10% (figure 8) for the higher flow rates tested (0.24 m^2/s).

However, during phase d2 (drainage layer), it was observed a different behavior of the drainage unit flow, which was coincident with the evolution described by Relvas and Pinheiro (figure 8). There was a difference between the leakage rates (q_d/q_i) which could be explained by the differences of the granulometry used in the drainage layers in both researches.

Figure 8. Unit flow rate through the drainage layer (qd), expressed as a percentage of the flow rate, (qi), for different qi.



Besides, the origin of the leakage flow between the blocks was analyzed, trying to discriminate among the leaks through the contact joints between the blocks: longitudinal, transverse at the overlapping area and also at the vents. Such analysis was made both in the Armorwedge^{TM} as in the ACUÑA unit.

The results of this study reflect a predominance of the drainage flow through the longitudinal joints at the contact surfaces between blocks. Thus, in both units, the longitudinal joints generate between 55 and 80% of the total drainage flow, increasing with lower flow rates, while the rest of the leakage is produced by both the transverse joints between the blocks and the vents.

It should be noted that the leakage through the vents is negligible in the case of the ACUÑA unit for flow rates below 0.1 m^2/s. Besides, for such unit, the leakage flow rate is in a range of between 1 and 2% of the total leakage for flow rates up those indicated until to 0.24 m^2/s. These results suppose a reduction on the total leakage flow with respect to the Armorwedge^{TM} block of 12-15% for flow rates between 0.1 and 0.24 m^2/s.

2.3 Mechanical tests and research on new materials to increase the impact resistance of WSBs

A number of impact tests have been carried out in order to evaluate and compare the resistance of WSBs with different reinforcements of the mass concrete. To do so, a new test methodology was proposed which involved the makeup of a new device to do the experiments. Such device was designed to release a steel sphere of 38 kg with a diameter of 210 mm from an average height of 1.37 m, impacting the tested blocks in a preselected location. (Figure 9). The criterion of failure was established by the crack opening and was considered as total failure when such opening was higher than 2 mm.

The reference tests were those performed in the blocks made of mass concrete without reinforcement. These units broke at the first impact with a total failure (crack opening over 2 mm).

The use of conventional steel mesh in the upper surface (i.e. the face of impact) of the block was first evaluated to improve the resistance of the WSBs. Thus, with a reinforcement of a mesh of 150 mm opening and diameter 5 mm placed on the upper face, there was an improvement in the behavior given that, although there was also breakage in the first beating, the 2 mm separation between the broken pieces was not reached. This kind of damage is considered slight because it allows an onsite repair in a quick and simple way with mortar or pitch with no need of replacement of the entire block in the stepped channel.

The next tested reinforcement was the addition of plastic (FIBRAFLEX) and metal fibers (DRAMIX) to the fresh concrete. To do so, different proportions of fibers were added during the concrete mixture prior to pouring it into the molds.

Figure 9. Above WSBs for impact tests and impact testing instrumentation. Below, WSB mass concrete pattern and views of metal fibers DRAMIX type in broken WSB

The results of the tests with fibers showed an important improvement in comparison with both the mass concrete and the armed units in all the cases. So, the best result of the trials was obtained with the addition of DRAMIX metallic fibers. This reinforcement required up to 9 impacts to cause the total failure of the block.

Different rates of DRAMIX fibers were used (between 40 and 80 kg/m^3) but it was observed that there was not a proportion between the increase of the rates and the number of impacts needed to break the blocks, so it was considered that the use of the lowest rate was enough to significantly increase the impact resistance of the WSB.

However, for practical purposes it should be noted that addition of fibers may increase the manufacturing costs, produces a reduction of the workability of the fresh concrete and, in some cases, a risk for the workers may appear due to potential fiber impacts during the mash tasks.

3 Conclusions

New research has been carried out during last years in Spain to deepen the knowledge about the performance of WSBs. Such research has resulted in a new block design: the ACUÑA block. The results of the experimental and numerical research showed a significant reduction of the leakage flow towards the drainage layer. Such reduction contributes to improve the hydraulic stability of the block.

Likewise, the promising results obtained in the addition of fibers in the mass concrete of WSB must be highlighted, given that they significantly increase the resistance of these blocks against impacts. This fact is important because it may reduce the possible damages caused by the flow debris or vandalism.

4 Acknowledgement

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