

# *State of Art in Block Ramp and Downstream Stilling Basin Design*

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## **ABSTRACT**

Block ramps are hydraulic structures which are commonly used in river restoration projects. Especially in the last few decades, the use of this type of structures have become more and more popular. They furnish a correct balance between the hydraulic functioning and the environmental care, as they minimize the impact on the environment in which they are located. In addition, they can be considered flexible structures, i.e. they can easily adapt to the in situ conditions and they can be easily built to re-convert traditional concrete structures. They can be built either by loose or fixed blocks, arranged on a sloped bed. However, a correct design of this structural typology has to take into consideration several aspects. In particular, the hydraulic functioning of a block ramp is assured when the structure remains stable, i.e. when the blocks are not removed from their original position. Thus, the first step in designing block ramps has to be the structural stability. Furthermore, the analysis has to focus also on the dissipative process occurring on them, in particular it has to consider the different flow regimes that can take place and the effect of the bed roughness on the energy dissipation. Another important aspect is the stilling basin design. In fact, a block ramp has not to be considered as an isolated element in the contest in which it is located. It is part of that contest and it contributes to modify it. Thus, it is extremely important to consider the scour process occurring downstream of the structure. In particular, the maximum scour depth and length have to be carefully estimated in order to avoid structural collapse of the ramp. The scour process occurring downstream of the structure is also extremely important in terms of energy dissipation. In fact, the global dissipative process is the result of two distinct processes: one occurring on the ramp and the other in the downstream stilling basin. Finally, the analysis has to take into consideration which are the global sediment transport conditions of the river in which the structure is located. Thus, it has to be conducted in both clear water and live-bed conditions. It appears evident that a correct design of this type of structures is a complex operation which requires a particular attention in order to avoid functioning problems.

## **Keywords**

Block ramps; Clear-water; Erosive processes; Hydraulics; Live-bed

## **1. Introduction**

The increasing environmental sensibility has forced scientific community to find solutions which could be, at the same time,

hydraulically functioning and allow a correct balance between technical necessities and environmental impact minimization on the natural contests. This necessity has become

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more and more prominent in the last few decades. The technical literature and the scientific research in the field of river restoration, using eco-friendly hydraulic structures, have been characterized by relevant results, especially in finding and proposing criteria for more traditional rock-made structures and in particular in proposing new solutions. Another aspect which has been relatively investigated in these last decades is the possibility of reconverting traditional concrete structure by using more flexible and low environment impact approach. The analysis of new structural typologies was conducted considering several aspects, including biological conservation of the in-situ conditions and preservation of optimal conditions for fish species. However, all hydraulic structures constitute a discontinuity in river morphology and their main hydraulic functioning is to regulate sediment transport. The correct conjugation of these necessities and the environmental care still requires a big effort. In particular, a correct balance and harmonization of the structure to the in situ conditions requires a deep and accurate analysis of the global conditions characterizing the river. Furthermore, the design approach has to take into consideration also the local conditions of the river area in which they are located. In this paper, the analysis of several aspects regarding a peculiar eco-friendly structural typology will be deepened. In particular, the analysis will be focused on the most recent development in block ramps design, taking into consideration both the hydraulics and the localized scour phenomena. Namely, regarding the hydraulics of the block ramps, the most recent literature achievements will

be presented, including the submerged configuration. This last configuration is particularly important as it is focusing on the entire dissipative process occurring in correspondence with the structure, i.e. both on the structure itself and in the stilling basing. Successively, the analysis will be focused on the erosive phenomena localized downstream of the structure. The erosive process will be described and several design criteria will be synthesized. In particular, the analysis will be focused on the estimation of the main geometric lengths of the scour hole and the effect of stilling basin geometry on them. Finally, the same analysis and literature review will be proposed for the case in which the erosive phenomenon is occurring in live-bed conditions, i.e. when an approaching sediment concentration is present. However, in this section a brief literature review will be reported in order to let the reader understand the research evolution process which led to the present knowledge regarding this type of hydraulic structures.

The first aspect which has to be deepened in order to assure hydraulic functionality of a block ramp is its stability. Namely, the rocks constituting the ramp have to remain stable in the position in which they are located during the designed flood event. This problem was analyzed by several authors who proposed numerous relationships, mostly empirical, valid for different ranges of parameters. In particular, Whittaker and Jäggi (1986) proposed guidelines in order to prevent block ramp failure on the basis of several model and fields experiments they conducted. Nevertheless, more recently, the stability design criteria was extended to wider range of configurations and the failure

mechanism was analyzed and deepened by also other authors, among whom Robinson et al. (1997), Pagliara and Chiavaccini (2003), Pagliara and Chiavaccini (2004) and Pagliara and Chiavaccini (2007), who conducted several experiments on block ramps, investigating also the effect of stabilizing elements on it, such as boulders located in different geometrical configurations. Just recently, Pagliara and Palermo (2011b) proposed a complete classification and a detailed analysis of all the failure mechanisms which can occur in the presence of a block ramp. In particular, Pagliara and Palermo (2011b) estimated the critical discharges which can lead to different failure steps, which were classified as follows: incipient motion, local failure, global failure and ultimate failure. They introduced a modified Froude number (the stone Froude number), and proposed four relationships corresponding to each failure phase. Namely, the incipient motion condition was assumed to occur when single rocks (generally ranging between 1 and 4) left their original positions and no localized scour could occur on the ramp itself. They stated that local failure occurs when more than one element left their positions simultaneously, producing a well-defined circular or semi-circular scour hole in the ramp surface and global failure is characterized by different and simultaneous processes of local failures. Finally, they defined as ultimate failure the phase in which the ramp completely changed its morphological configuration and a typical two-slopes geometry was obtained.

The hydraulic of block ramp is also an aspect which was deepened recently. The first studies analyzed the similarities of the dissipative process occurring on the block

ramps with that characterizing the concrete stepped chutes. In particular, it was clearly shown that the basic dissipative process is quite similar, resulting in an energy dissipation mechanism which is practically the same occurring in the case of skimming flow on stepped chutes (Chanson, 1994). Based on this observation, several experimental studies were conducted highlighting both the effect of geometric configuration and the effect of bed roughness (see for example Platzler (1983), Essery and Horner (1978), Chamani and Rajaratnam (1999a,b), Diez-Cascon et al. (1991), Peyras et al. (1992), Stephenson (1991), Christodoulou (1993), Armanini and Gregoretti (2005) and Pagliara and Palermo (2013)). Only recently, Pagliara and Chiavaccini (2006a,b) analyzed in details the effect of relative roughness and block ramp slope, concluding that these parameters are both strongly affecting the dissipative process. Furthermore, they analyzed also the effect of boulders location on base block ramp configurations in order to estimate the increase in the energy dissipation caused by them. A further and complete analysis conducted by Pagliara et al. (2008) took also into consideration the submerged ramp conditions and extended the study of the dissipative process also to the stilling basin. Finally, Pagliara et al (2009a) and Pagliara and Palermo (2012) included also the stilling basing geometry in the dissipative process analysis and Pagliara et al (2009b) explained the effect of ramp filling on the energy recovery process.

But, a correct design of this type of studies cannot be done without taking into consideration the erosive process occurring downstream of them. As all other hydraulic

structure, even block ramps are characterized by erosive processes occurring downstream of them. This is one of the main topic for a hydraulic engineer, as also proven by the conspicuous technical literature. In particular, erosive phenomena are widely analyzed for clear water conditions and for several types of structures (see among others Sumer et al. (1993), Canepa and Hager (2003), Dey and Sarkar (2006), Ferro et al (2004), Veronese (1937), Hassan and Narayanan (1985), Farhodi and Smith (1985), Bormann and Julien (1991), D'Agostino and Ferro (2004), Breusers and Raudkivi (1991) and Hoffmans and Verheij (1997)). Generally, experimental tests led to the conclusion that the erosive phenomenon is characterized by several parameters, among which the most important are: the stilling basing granulometry, the jet characteristics, the stilling basin geometry, the hydraulic structure configuration and typology and the tailwater level downstream of the structure itself. Obviously, these can be considered just as general parameters affecting the phenomenon, but for each structure there are specific analyses which furnish more detailed clarifications of the independent governing variables. Regarding block ramps, the scour process occurring downstream of them has been extensively analyzed at the University of Pisa. In particular, for clear water conditions, Pagliara (2007) proposed the first systematic study on the topic, including the effect of hydraulic jump typology and non-uniformity of stilling basin material. Successively, Pagliara and Palermo (2008a,b) conducted a similar analysis including protection sills in the stilling basin. They furnished simple analytical relationships by which it is possible to estimate both the main lengths and the

morphological characteristics of the equilibrium configuration. Pagliara et al (2009a) and Pagliara and Palermo (2011a) analyzed the effect of symmetric expansion of the stilling basin on the erosive process concluding that, being constant all the other parameters, a lateral expansion of the basin increases the maximum scour depth. A detailed analysis of both tailwater effect and pile position at the toe of the ramp on the scour characteristics was performed by Pagliara and Palermo (2010), who furnished comprehensive relationships to evaluate the scour erosion downstream of block ramps, whose slope was up to 0.25. All previous cited studies are related to clear water conditions. Only very recently, two studies were performed for live-bed conditions, i.e., when sediments are continuously supplied and the equilibrium depth condition is reached when there is a balance between the sediment supply and sediment transported out of the hole. In particular, Pagliara et al (2011) analyzed the effect of both upstream sediment concentration and stilling basin geometry on the main characteristic of the hydraulic jump and scour morphology. Pagliara et al (2012) further developed this approach focusing on the effect of tailwater and inlet hydraulic conditions, concluding that the final dynamic equilibrium configuration is practically not dependent on the sediment load time history. Based on the mentioned literature, this paper aims to briefly describe the actual state of art on block ramp and stilling basin design. In the following pictures are reported examples illustrating the flow dynamic in a both longitudinally and transversally enlarged stilling basin downstream of a block ramp (Figure 1) and the final equilibrium scour configuration obtained for a test in live-bed condition (Figure 2).

## 2. Energy dissipation and hydraulics of block ramps

Block ramps are high-dissipative hydraulic structures. The dissipative process takes place both on the ramp itself and in the stilling basins downstream of them. In particular, according to the ramp geometry and different hydraulic flow regimes, several possible scenarios can occur: 1) the flow on the ramp is in supercritical conditions and downstream of it a hydraulic jump takes place; 2) the flow on the

ramp is in supercritical conditions in its upper part and the hydraulic jump occurs on the ramp itself; 3) the flow on the ramp is in subcritical conditions and no hydraulic jump takes place. The first two hydraulic conditions are the most realistic and interesting from an engineering point of view. Thus, in the following, an examination and a description of the dissipative process occurring in the first two cited configurations will be detailed. The hydraulic of block ramps appears quite similar to that characterizing stepped chutes.

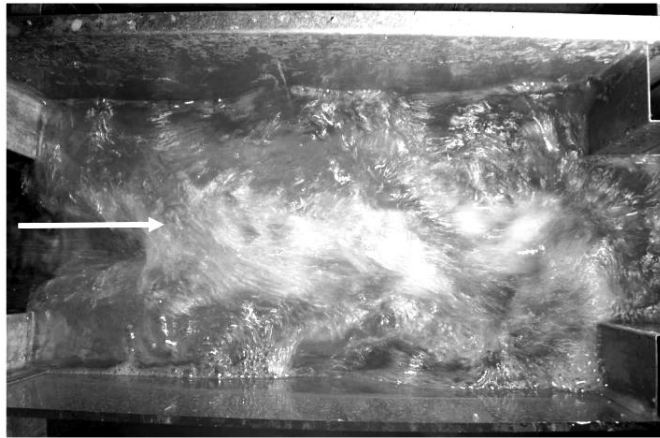


Fig. 1. Example of flow dynamic downstream of a block ramp in an enlarged stilling basin

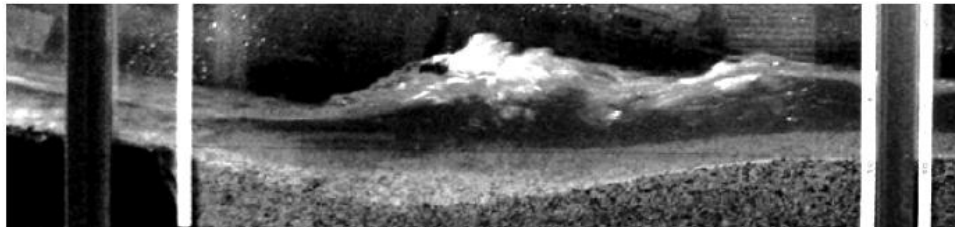


Fig. 2. Example of final scour configuration downstream of a block ramp in live-bed condition

The energy dissipation on the ramp is caused by the flow resistance due to the presence of unstable wakes beyond the gravel or micro vortexes formation. The dissipative process on the ramp itself is strongly influenced by the roughness of the bed material and in particular it depends on the relative roughness as specified also by Bathurst (1978) and Bathurst et al. (1981). The flowing

Figure 3 reports a sketch of a block ramp both in the case in which the hydraulic jump is entirely located in the stilling basin (Figure 3a) and in the case in which it partially submerges the ramp (Figure 3b).

Note that, in the previous figure,  $k$  is the critical depth,  $H$  the ramp height,  $h_1$  is the water depth at the ramp toe,  $Q$  is the inflow discharge,  $q$  the discharge per unit width,  $g$  the

acceleration due to gravity,  $h_2$  the tail water depth,  $L$  the horizontal distance of the beginning of the jump from the ramp toe,  $L_T$  the horizontal length of the ramp,  $z_m$  the measured medium cross-sectional scour depth in the section of maximum scour and  $l_0$  the scour length. A detailed analysis of the dissi-

pative process on block ramp was conducted by Pagliara and Chiavaccini (2006a) who stated that, for a base ramp, the relative energy dissipation  $\Delta E_{r1}$  depends on the ramp slope, the relative critical depth  $k/H$  and the relative roughness  $k/d_{50}$ , in which  $d_{50}$  is the mean size of the material constituting the ramp.

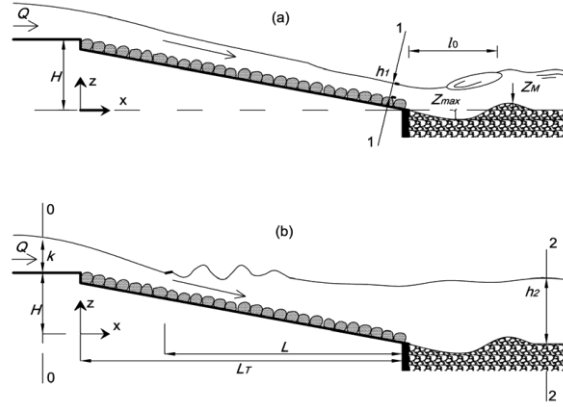


Fig. 3. Longitudinal profile of a block ramp and the downstream stilling basin with the indication of the main parameters for (a)  $L/L_T=0$  (free jump) and (b) and for  $L/L_T>0$  (submerged jump)

The authors analyzed the dissipative phenomenon occurring on a block ramp in two case: base configuration and reinforced configuration of the ramp bed (presence of protruding boulders). In the case of base configuration, Pagliara and Chiavaccini (2006a) proposed the following relationship to estimate the relative energy loss:

$$\Delta E_{r1} = \frac{\Delta E_1}{E_0} = A + (1 - A) e^{(B+CS)(k/H)} \quad (1)$$

Where  $\Delta E_1 = E_0 - E_1$ , in which  $E_0 = H + 1.5k$  is the total upstream energy with  $E_1 = h_1 + q^2 / (2gh_1^2)$ ;  $A$ ,  $B$  and  $C$  are variables depending on the relative roughness;  $S$  is the ramp slope. Furthermore, Pagliara and Chiavaccini (2006a) distinguished three relative roughness conditions: large scale roughness condition (LR) for  $k/d_{50} < 2.5$ , intermediate scale roughness (IR) for

$2.5 < k/d_{50} < 6.6$  and small scale roughness (SR) for  $6.6 < k/d_{50} < 42$ . According to the different scale roughness, they suggested the following values for coefficients  $A$ ,  $B$ ,  $C$  of Eq. (1):  $A$  is equal to 0.33, 0.25, 0.15 if the roughness condition is LR, IR, SR, respectively;  $B$  is equal to -1.3, -1.2, -1.0 if the roughness condition is LR, IR, SR, respectively;  $C$  is equal to -14.5, -12.0, -11.5 if the roughness condition is LR, IR, SR, respectively. If boulders are located on the ramp, the flow structure is essentially modified and the dissipative process is strongly affected. Moreover, even the configuration in which the boulders are located on the base ramp is a factor which can modify the flow structure and consequently the energy dissipation. The main effect of protruding boulders is to disturb the flow reducing the shear stress.

Thus, the presence of the boulders causes an increase of ramp stability. It means that a larger discharge is required to generate failure mechanisms on the ramp. Pagliara and Chiavaccini (2006b) analyzed the effect of boulders concentration  $\Gamma$  on base configurations and modified Eq. (1) in order to take into account their presence in the dissipative process. They stated that the relative energy loss can be estimated as follows:

$$\Delta E_{r1} = \frac{\Delta E_1}{E_0} = \left[ A + (1-A)e^{(B+CS)(k/H)} \right] \left( 1 + \frac{\Gamma}{E+FG} \right) \quad (2)$$

where  $E$  and  $F$  are two coefficients depending on the boulders' arrangements (for random disposition and rounded boulders  $E=0.6$  and  $F=13.3$ ; for row disposition and rounded boulders  $E=0.55$  and  $F=10.5$ ; for random disposition and crushed boulders  $E=0.55$  and  $F=9.1$ ; and for row disposition and crushed boulders  $E=0.4$  and  $F=7.7$ ). As specified, the dissipative process cannot just be limited to the ramp but it is a process which regards also the eventual hydraulic jump forming downstream of the ramp or on the ramp itself. For this reason, Pagliara et al (2008) deepened the global dissipation occurring in the presence of a block ramp considering also the downstream movable stilling basin and analyzing different jump configurations. Namely, they studied the energy dissipation occurring between the entrance of the ramp (section 0-0) and the section 2-2, downstream of the jump, with different ramp submergence conditions (see Figure 3a-b). In particular, they conducted experiments in three different submergence configurations: 1) hydraulic jump located at the toe of the ramp (free jump,  $L/L_T=0$ ) and

at 1/3 or 2/3 of the ramp length, i.e. submerged jump with  $L/L_T=1/3$  and submerged jump with  $L/L_T=2/3$ , respectively. Pagliara et al (2008) conducted experiments both in presence and absence of scour downstream of the ramp and compared the relative energy loss occurring in the respective configurations. They noted that no significant differences can be estimated. Moreover, in the tested range of parameters, the relative energy loss  $\Delta E_{r2} = \Delta E_2/E_0$ , where  $\Delta E_2 = E_0 - E_2$  in which  $E_2 = h_2 + q_2 / (2gh_2^2)$ , was found to be function of the parameters  $k/H$  and the scale roughness. In fact, in the case of submerged hydraulic jump, the dissipative process mainly occurs on the ramp and the scour presence does not significantly affect it. In addition, they experimentally proved that the relative energy dissipation is an increasing monotonic function of the roughness condition, confirming the findings of Pagliara and Chiavaccini (2006a), and for ramp slope varying between 0.125 and 0.25, the effect of the parameter  $S$  on  $\Delta E_{r2}$  is negligible. Based on this observations, Pagliara et al (2008) proposed the following relationship to estimate  $\Delta E_{r2}$ :

$$\Delta E_{r2} = A + (1-A)e^{(B)k/H} \quad (3)$$

Valid for  $0 < L/L_T < 0.7$  in which

$$A = 0.239 e^{-2.323 \frac{L}{L_T}} \quad (4)$$

$$B = - \left( 10.7 \frac{L}{L_T} + 1.729 \right) \quad (5)$$

for SR roughness condition;

$$A = 0.249 e^{-1.618 \frac{L}{L_T}} \quad (6)$$

$$B = -\left(9.95 \frac{L}{L_T} + 1.863\right) \quad (7)$$

for IR roughness condition;

$$A = 0.256 e^{-1.245 \frac{L}{L_T}} \quad (8)$$

$$B = -\left(8.475 \frac{L}{L_T} + 1.931\right) \quad (9)$$

for LR roughness condition. The hydraulic of a block ramp is strictly connected to the hydraulic jump occurring downstream of it. In particular, the dissipative process has to take into account also the amount of energy dissipated in the hydraulic jump. In the case of a free jump occurring downstream of the ramp (and entirely located in the stilling basin), mainly two different typologies can be distinguished when the width of the stilling basin is the same of the ramp:  $F_{MB}$  type and  $S_{MB}$  type. In particular,  $F_{MB}$  type is characterized by a clock wise flow (see Figure 4b). For this typology, the flow does not tend to submerge the ramp toe and the sediment transport in the stilling basin in correspondence with the jump is occurring both downstream and upstream. It means that the sediment are transported both downstream and upstream of the scour hole. For  $S_{MB}$  type, the flow circulation is counter clock-wise, as shown in Figure 4a. The jump tends to submerge the ramp toe and the direction of the sediment transport is unique, i.e. the sediment are transported just downstream of the scour hole. The two jump typologies occur for different geometric and hydraulic conditions. In particular, Palermo et al (2008) specified the range of variation of the ramp slope  $S$  and the densimetric particle Froude number  $F_{d90} = V_1 / (g' d_{90})^{1/2}$  for which the two different jumps take place. Note that  $V_1$  is the approaching flow velocity at the ramp toe,  $g' = g(\rho_s - \rho) / \rho$

with  $\rho_s$  and  $\rho$  particle and water densities, respectively, and  $d_{90}$  is the size of the bed material for which 90% in weight is finer. In the case of an abrupt prismatic expansion downstream of the ramp, the hydraulic jump structure is essentially three-dimensional.

The hydraulic jump structure becomes much more complicate than that described in the previous case. In particular, in this case, three main parameters are affecting the jump: 1) the expansion ratio, i.e. the ratio between stilling basin width and ramp width; 2) the downstream water level  $h_2$ ; and 3) the inlet conditions, that are depending on both ramp configuration (slope) and discharge. In particular, in the case of an enlarged stilling basin, mainly four hydraulic jump typologies can be distinguished, according to Pagliara et al (2009a).

- Repelled Symmetric jump (R-S): this hydraulic jump is characterized by a 3D scour hole. The exiting flow is deflected axially by the re-circulation occurring in the lateral zones downstream of the ramp. The re-circulation structure is symmetric and the jump appears undular with evident superficial shock waves (Figure 5a).
- Repelled Oscillatory jump (R-O): this hydraulic jump is characterized by a flow periodically deflected laterally, towards both the side of the basin and eventually impacting on them. Evident oscillations are present on the water surface and the scour hole appears less 3D than the case illustrated above (Figure 5b).
- Toe Symmetric jump (T-S): this hydraulic jump is generally occurring for higher ramp slopes and a prominent ridge forms downstream of the scour hole, strongly affecting both the lateral re-circulations and the flow pattern in the stilling basin.



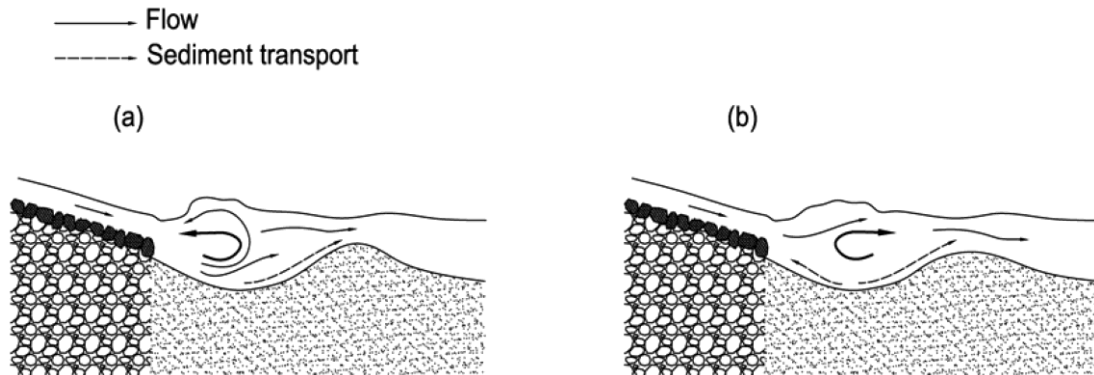


Fig. 4. Hydraulic jump typologies: (a)  $S_{MB}$ ; (b)  $F_{MB}$

In this case, the jump takes place just downstream of the ramp toe. The superficial flow structure appears symmetric and the scour hole is deep and tends to be 2D. The hydraulic jump mainly occurs in the centre of the basin (Figure 5c).

- Toe Oscillatory jump (T-O): this hydraulic jump appears similar to the T-S jump type, but it occurs for higher  $F_{d90}$  values. The superficial flow structure appears not symmetric and it is characterized by asymmetric periodic deflections. The scour hole morphology is almost 2D, and the ridge appears wider and flatter respect to the previous case (Figure 5d).

Pagliara et al. (2009a) found that a basin expansion causes a larger energy dissipation. Moreover, they experimentally proved that this effect is mainly due to the formation of the scour hole, which is generally deeper than the case in which no enlargement is present, being constant all the other parameters.

### 3. Scour hole lengths in clear water conditions

To assure hydraulic functioning of a block ramp, one essential requirement is that the ramp has to be stable. The stability

of the ramp has to be assured both in terms of stability of the rocks constituting the ramp and in terms of toe stability. This last aspect requires a detailed analysis of the scour process occurring in the stilling basin. In particular, the analysis has to be focused on the influencing parameters and their effect on the erosive process. Pagliara and Palermo (2010) proposed a detailed study in which they analysed the scour morphology occurring in the stilling basin, when it has the same width of the ramp, i.e. the case of a prismatic channel whose expansion ratio ( $B/b$ ) is equal to 1, where  $B$  is the stilling basin width and  $b$  is the ramp width. They found that the non-dimensional parameter  $(z_{max}+h_2)/h_1$  for  $B/b=1$  can be expressed as function of the following parameters, in the case of uniform stilling basin material:

$$\frac{z_{max} + h_2}{h_1} = f(F_{dxx}, S) \quad (10)$$

In which  $F_{dxx} = V_1/(g'd_{xx})^{1/2}$  is the densimetric Froude number relative to the diameter  $d_{xx}$  for which  $xx\%$  of sediment is finer.  $z_{max}$  is the maximum scour depth,  $h_2$  the downstream tailwater depth,  $h_1$  the approaching flow depth at the ramp toe and  $S$  the ramp slope (see Figure 6a-b).

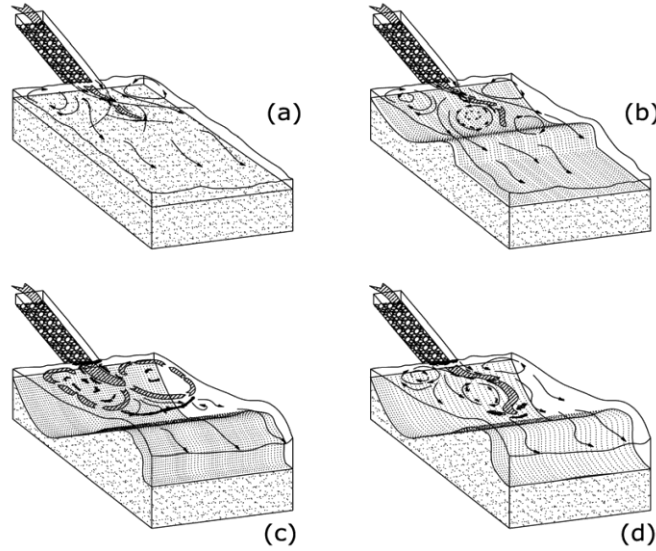


Fig. 5. Sketches of flow patterns for hydraulic jump a) R-S, b) R-O, c) T-S, and d) T-O

Furthermore, Pagliara et al. (2009a) extended the analysis conducted by Pagliara and Palermo (2010) to the cases in which an abrupt expansion of the stilling basin is present downstream of the block ramp. In particular, they analysed two prismatic expansions whose  $B/b$  was 1.8 and 2.8, respectively (see Figure 6c and 6d), using also non-uniform bed materials.

They concluded that the previous functional relationship expressed by Eq. (10), has to be rearranged in the following:

$$\frac{z_{max} + h_2}{h_1} = f(F_{dx}, S, B/b) \quad (11)$$

Note that in the previous functional relationship, the material non-uniformity does not appear. In fact, it was experimentally proven that it has a negligible effect on the non-dimensional dependent variable  $(z_{max} + h_2)/h_1$ . In the tested ranges of parameters ( $B/b=1$ ,  $0.083 \leq S \leq 0.25$  and  $F_{d90} < 4$ ) Pagliara and Palermo (2010) furnished a simple analytical expression to

foresee the maximum scour depth:

$$\frac{z_{max} + h_2}{h_1} = (11.64S + 0.7) \exp[-(0.64S + 0.17)F_{d90}] \quad (12)$$

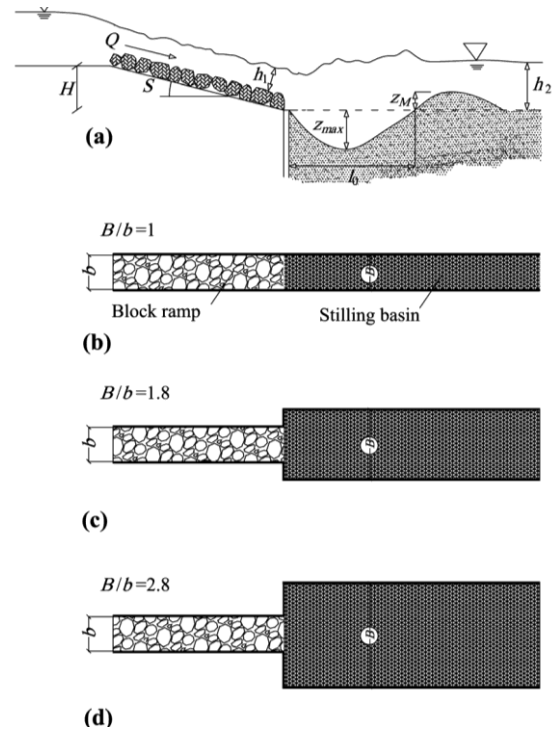


Fig. 6. (a) Definition sketch and plan views for  $B/b=(b) 1$ , (c) 1.8, and (d) 2.8

From the previous equation, it can be easily deduced that the non-dimensional dependent variable (in the tested ranges of parameters) is an increasing monotonic function of the ramp slope  $S$ , such as of the densimetric Froude number. In addition, it is evident that if the tailwater level increases, being constant all the other parameters, the maximum scour depth reduces. This is also confirmed by other experiences conducted by Hoffmans (1998). An increase of the tailwater depth determines an increase of the diffusion length of the jet exiting from the ramp and entering the stilling basin. Thus, it partially loses its erosive capacity before reaching the stilling basin bed.

The previous analysis was extended to abruptly expanded channels. Namely, as mentioned above, experiments, were conducted for two expansion ratios  $B/b=1.8$  and  $B/b=2.8$ . The effect of the expansion is to increase the non-dimensional dependent variable  $(z_{max}+h_2)/h_1$ . This occurrence is due to the fact that, as illustrated above for 3D hydraulic jumps dynamic, a strong later flow re-circulation is occurring just downstream of the ramp toe. This effect is amplified when the expansion ratio increases and the flow exiting from the ramp is deflected and axially concentrated. Thus, the maximum scour depth increases considerably. This occurrence is also confirmed by the tests conducted by Veronese (1937), who analysed the scour process occurring in an abrupt expansion with an horizontal upstream channel. Based on these observations, Pagliara et al (2009a) introduced a modified (equivalent) densimetric Froude number  $\tilde{F}_{d90}$  defined as follows:

$$\tilde{F}_{d90} = F_{d90} (B/b)^{(150.5S^2 - 43.8S + 3.8)} \quad (13)$$

Note that the previous equivalent densimetric Froude number has the following

peculiarities: it is equal to  $F_{d90}$  in the case in which  $B/b=1$  and it is an increasing monotonic function of the expansion ratio. The introduction of the previous densimetric Froude number allowed to preserve the analytical expression (Eq. 12) derived by Pagliara and Palermo (2010), just substituting  $F_{d90}$  with  $\tilde{F}_{d90}$ . Thus, the following equation (Pagliara et al (2009a)) was found able to predict the generality of case, including the scour depth in an enlarged stilling basin with non-uniform bed materials:

$$\frac{z_{max} + h_2}{h_1} = (11.64S + 0.7) \exp[(-0.64S + 0.17)\tilde{F}_{d90}] \quad (14)$$

It is easy to observe that Eq. (14) coincides with Eq. (12) for  $B/b=1$  and it furnished higher  $(z_{max}+h_2)/h_1$  values when  $1 < B/b < 2.8$ . Another important parameter which was analysed by Pagliara et al (2009a) was the non-dimensional scour hole length  $L_0=l_0/h_1$ . Based on the observations of Breusers (1966) and Breusers and Raudkivi (1991), Pagliara et al (2009a) extended the findings of Pagliara and Palermo (2010) relative to  $B/b=1$  and proposed the following general relationship by which it is possible to foresee the scour hole length:

$$L_0 = 7.42 \exp(0.37\tilde{Z}_{max}) \quad (15)$$

The variable  $\tilde{Z}_{max}$  was evaluated as follows:

$$\tilde{Z}_{max} = Z_{max\ calc} (B/b)^{-0.25} \quad (16)$$

Where

$$Z_{max\ calc} = \left( \frac{z_{max} + h_2}{h_1} \right)_{calcEq(14)} - \frac{h_2}{h_1^*} \quad (17)$$

In which  $[(z_{max}+h_2)/h_1]_{calcEq(14)}$  is given by Eq. (14) and  $h_1^*$  is the ramp flow depth estimated with Manning's equation in which the coefficient  $n$  is estimated according to Pagliara and Chiavaccini (2006a) with the following equation:

$$n = 0.064(D_{50}S)^{0.11} \quad (18)$$

in which  $D_{50}$  is the mean ramp material diameter. The previous equations are valid in the tested range of parameters specified in Pagliara et al (2009a).

#### 4. Scour hole lengths in live-bed conditions

The analysis of clear water scour process allowed to deduce relationships by which it is possible to foresee the main morphologic parameters in a wide range of hydraulic and geometric conditions. However, in practical applications, it can very often occur that clear water conditions are not obtained, meaning that in correspondence with the structure sediment are also supplied by the approaching flow and transported into the downstream stilling basin. Namely, the scour process results to be extremely affected not only by the erosive capacity of the flow itself, but also by the concentration of sediment in it. A live-bed conditions occurs when the scour hole is continuously fed with the sediment by the approaching stream. Thus, the concept of equilibrium configuration of the scour hole is extremely different from that discussed for the clear water conditions. In fact, the equilibrium configuration of the stilling basin morphology is reached after a certain time, when the rate of removal of sediment out of the scour hole equals the rate of supply of sediment into the scour hole.

Pagliara et al. (2012) conducted a detailed study on live-bed scour mechanism downstream of a block ramp. Namely, the authors tested a wide range of experimental conditions, introducing a sediment concentration in the approaching flow. They obtained the dynamic equilibrium of the scour hole when the inlet sediment load  $Q_{s-in}$  (supplied at the entering

ramp section) became equal to the outlet sediment load  $Q_{s-out}$  (collected in a sediment trap downstream of the scour hole). In particular, they tested several inlet sediment concentrations  $C\%_o = (Q_{s-in}/Q) \cdot 1000$ , where  $Q$  is the water discharge, and analysed the behaviour of the scour formation mechanism. They simulated the live bed conditions adopting a model whose diagram sketch (including the main geometric and hydraulic parameters tested) is reported in Figure 7. The authors conducted experimental tests introducing a known quantity of sediments in the upstream flow, i.e. a known concentration of inlet sediment. Then, they collected the outlet sediment using a trap opportunely shaped and located downstream of the scoured zone in order to avoid backwater effects.

In the previous figure,  $z_m$  is the maximum averaged scour hole depth, which was evaluated in the transversal section where the maximum scour hole depth occurs. The analysis was also focused on the temporal evolution of the sediment dynamic. One example is reported in Figure 8.

Previous figure illustrates the dynamic of the sediment load. In particular, this figure refers to a test with a ramp slope  $S=0.071$  and inlet densimetric Froude number  $F_{d90}=4.35$ . The test was repeated in the same hydraulic and geometric configurations for three different inlet sediment loads, namely for  $C\%_o=0.14$ ,  $C\%_o=0.4$  and  $C\%_o=0.74$ . The data were plotted in a graph  $Q_{s-out}/Q_{s-in}$  versus  $T=[(g'd_{50})^{0.5}/h_1]t$ , i.e., the non-dimensional temporal parameter, in which  $t$  is the time from the beginning of the test and  $d_{50}$  the mean diameter of the stilling basin material (i.e. the same of the sediment present in the approaching flow).

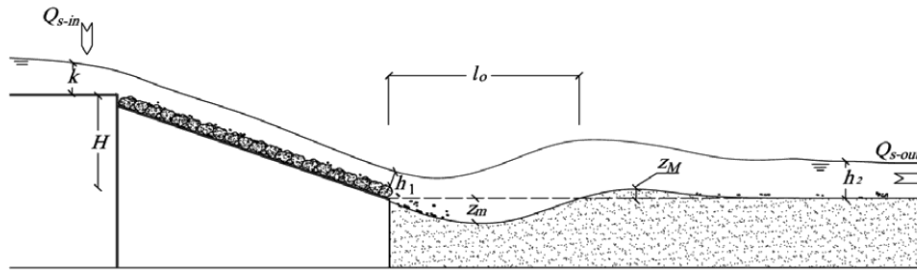


Fig. 7. Diagram sketch of the experimental apparatus

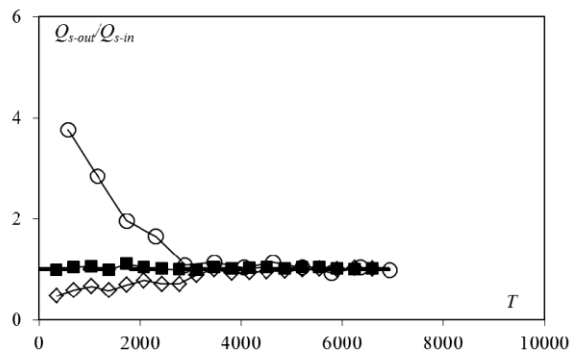


Fig. 8.  $Q_{s-out}/Q_{s-in}$  versus  $T$  for  $C\%_o = 0.14$  (A),  $C\%_o = 0.40$  (J),  $C\%_o = 0.74$  (D).

The equilibrium condition ( $Q_{s-in} \approx Q_{s-out}$ ) is clearly reached in different ways according to the inlet concentration  $C\%_o$ . In particular, for low inlet concentration, initially there is a high outlet sediment load, whereas the opposite occurs for high inlet sediment concentration.

A detailed analysis of the scour hole morphology evolution showed that the dynamic equilibrium scour hole shape does not depend on the sediment load time history. In fact, experiments were conducted extending the test duration and it was observed that even for very long durations, once the dynamic equilibrium condition is reached, there is no more variation in scour hole profiles. Furthermore, the equilibrium condition is also independent from the time in which the inlet sediment concentration is supplied. It means that, having fixed water discharge and ramp configuration, the final

dynamic equilibrium of the scour hole does not depend on the instant in which a certain inlet sediment concentration is supplied. In fact, Pagliara et al (2012) proved that the scour hole profiles were practically identical if the same inlet concentration was supplied either at the test beginning or after some time from the test beginning. It is obvious that even if the final equilibrium profiles are practically the same, the evolution of the scour hole morphology is different according to methodology of supplying the inlet sediment load. Another important aspect which has to be taken into consideration for live-bed tests is that generally several profile typologies can occur, according to the rate of inlet sediment load, different tested values of the ramp slope and hydraulic conditions. Namely, Pagliara et al (2012) distinguished four main scour hole profiles at the equilibrium configuration: scour profile with

downstream bed degradation ( $D_{LB}$ , Figure 9a); scour profile with downstream bed at the same level of the original bed ( $E_{LB}$ , Figure 9c), scour profile with downstream bed aggradation ( $A_{LB}$ , Figure 9d), and absence of scour hole and with bed aggradation ( $NS_{LB}$ , Figure 9b). In addition, the authors furnished a classification of the scour hole profiles, by which, knowing the relative tailwater depth, the densimetric Froude number and the inlet concentration, one is able to foresee which profile typology will occur. Figure 10 shows a typical  $A_{LB}$  scour profile, whereas Figure 11 shows a  $D_{LB}$  scour profile. Figure 12 illustrates the effect of inlet sediment concentration  $C\%$  on non-dimensional scour profiles for a test in which  $F_{d90}=3.88$  and  $S=0.071$ . Note that in Figure 12,  $z$  is the vertical coordinate,  $x$  is the longitudinal coordinate and  $l_s$  distance of the transversal section from the ramp toe in which the maximum scour hole depth occurs.

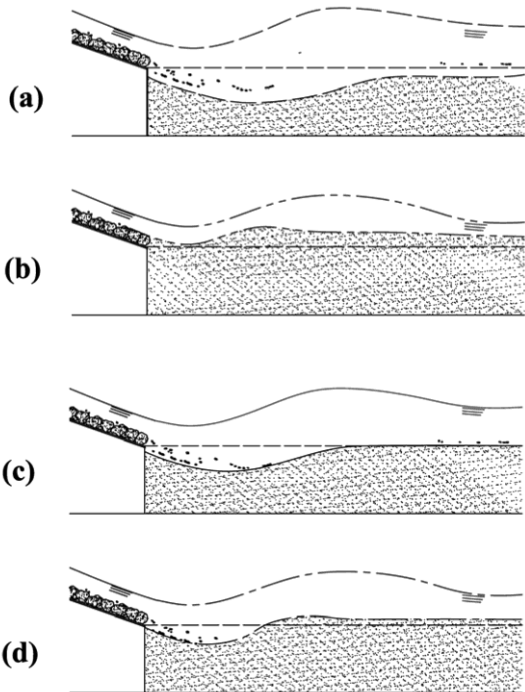


Fig. 9. Sediment patterns for different sediment concentration: (a)  $D_{LB}$ , (b)  $NS_{LB}$ , (c)  $E_{LB}$  and (d)  $A_{LB}$

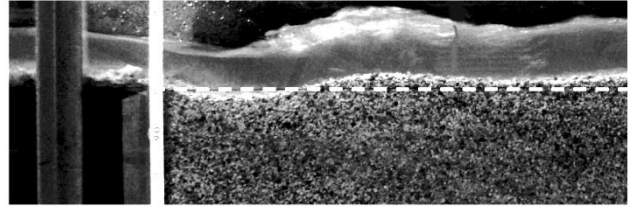


Fig. 10. Scour profile  $A_{LB}$

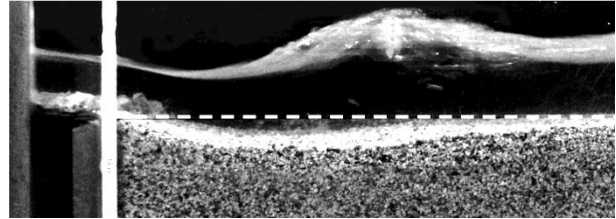


Fig. 11. Scour profile  $D_{LB}$

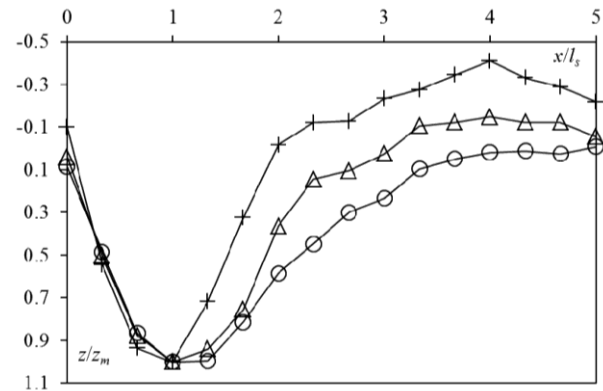


Fig. 12. Effect of inlet sediment concentration on non-dimensional profiles in the test in which  $F_{d90}=3.88$  and  $S=0.071$ : (+) is for  $C\%_o=0.517$ ; (C) is for  $C\%_o=0.332$ ; and (A) is for  $C\%_o=0.148$

But, the most important parameters for engineering applications are the scour hole depth and the scour hole length. Pagliara et al (2012) proved that, in the case of live-bed conditions, the main lengths depend on the following parameters: densimetric Froude number, block ramp slope and inlet sediment concentration. Moreover, also tailwater plays a fundamental role. Based on experimental tests results, the authors proposed the following relationship by which one can easily foresee the value of the non-dimensional parameter  $(z_m+h_2)/h_1$ :

$$\frac{z_m + h_2}{h_1} = (2.6S + 1.47) \exp \left[ (0.28S + 0.07)F_{d90} + (2.33S - 0.96)C_{\%o} \right] \quad (19)$$

It was experimentally proved that if  $C_{\%o}$  is constant, the variable  $(z_m + h_2)/h_1$  is a monotonic increasing function of both  $S$  and  $F_{d90}$ . It means that for the same ramp configuration, an increase in discharge causes an increase in scour depth. In addition, for the same hydraulic conditions and geometric configuration, the effect of an increase of the inlet sediment concentration is to reduce the scour hole depth. This occurrence is clearly visible from the analytical structure of the Eq. (19). In fact, it is a monotonic decreasing function of  $C_{\%o}$ . Moreover, as shown in the previous figure, there is also a limiting condition for  $C_{\%o}$ . In fact, if the inlet sediment concentration is too high the scour does not even form. Based on the findings of Breusers (1966) and Breusers and Raudkivi (1991), Pagliara et al (2012) proved that the non-dimensional scour length  $L_0 = l_0/h_1$  can be expressed as function of the non-dimensional maximum scour depth  $Z_m = z_m/h_1$ . Namely, they noted that there is a satisfactorily correlation between the following non dimensional groups:  $L_0S/(h_2/h_1)$  and  $Z_m = z_m/h_1$ , proposing the following relationship:

$$L_0S/(h_2/h_1) = 1.266Z_m \quad (20)$$

By which one can derive the value of the parameter  $L_0$ . The previous equations are valid in the tested range of parameters specified in Pagliara et al (2012).

## 5. Conclusions

The present paper deals with the most recent achievements in the block ramp and the

downstream stilling basin design. In particular, the attention was focused on the hydraulics of the block ramp and the analysis of the dissipative mechanisms occurring both on it and in the downstream stilling basin. Namely, the hydraulic jump types occurring in different geometric configurations of the stilling basin were discussed and analysed. Successively, the analysis was focused on the evaluation of the main scour hole lengths, both in clear water and live-bed conditions. Even if the technical literature has been substantially enriched in the last few decades, there are still many aspects which needs to be further developed, especially in the optimization of the design. Furthermore, the complexity of the global phenomena occurring in correspondence of these structures, up to now, did not allow to establish a global theory valid for the generalities of the cases. Another aspect which needs further analysis is the confirmation of the proposed design equations with real applications.

## Nomenclature

$A$	coefficient
$B$	coefficient, stilling basin width
$b$	ramp width (m)
$C$	coefficient
$C_{\%o}$	inlet sediment concentration
$D$	coefficient
$D_{50}$	mean ramp material diameter (m)
$d_{xx}$	diameter for which xx% of sediment is finer (m)
$E$	coefficient
$E_0$	total upstream energy (m)
$E_1$	total energy at section 1-1 (m)
$E_2$	total energy at section 2-2 (m)
$F$	coefficient
$F_{d90}$	densimetric particle Froude number
$k$	critical depth (m)

$g$	acceleration due to gravity ( $\text{m/s}^2$ )	flow condition. <i>Water resources research</i> , 41:1-8.
$g'$	reduced acceleration due to gravity ( $\text{m/s}^2$ )	
$H$	ramp height (m)	Bathurst JC (1978) Flow resistance of large-scale roughness. <i>Journal of Hydraulic Division</i> , ASCE 104(12):1587–1603.
$h_1^*$	estimated ramp flow depth (m)	Bathurst JC, Simons DB, Li RM (1981) Resistance equation for large-scale roughness. <i>Journal of Hydraulic Division</i> , ASCE 107(12):1593–1613.
$h_1$	water depth at the ramp toe (m)	
$h_2$	tailwater depth (m)	
$L$	horizontal distance of the beginning of the jump from the ramp toe (m)	
$L_T$	the horizontal length of the ramp (m)	
$L_0$	non-dimensional scour length	Bormann E, Julien PY (1991) Scour downstream of grade control structures. <i>Journal of Hydraulic Engineering</i> , ASCE 117(5):579-594.
$l_0$	scour length (m)	
$l_s$	distance of the transversal section from the ramp toe in which the maximum scour depth occurs (m)	Breusers HNC, Raudkivi AJ (1991) IAHR Hydraulic structures design manual. Balkema, Rotterdam, The Netherlands.
$Q$	inflow discharge ( $\text{m}^3/\text{s}$ )	Canepa S, Hager WH (2003) Effect of air jet content on plunge pool scour. <i>Journal of Hydraulic Engineering</i> , ASCE 128(5): 358-365.
$Q_{s-in}$	inlet sediment load ( $\text{m}^3/\text{s}$ )	
$Q_{s-out}$	outlet sediment load ( $\text{m}^3/\text{s}$ )	Chamani MR, Rajaratnam N (1999a) Characteristics of skimming flow over stepped spillways. <i>Journal of Hydraulic Engineering</i> , ASCE 125(4):361–368.
$q$	discharge per unit width ( $\text{m}^2/\text{s}$ )	Chamani MR, Rajaratnam N (1999b) Onset of skimming flow on stepped spillways. <i>Journal of Hydraulic Engineering</i> , ASCE 125(9):969–971.
$S$	ramp slope	Chanson H (1994) Hydraulic design of stepped cascades, channels, weirs and spillways, Pergamon, Oxford, U.K.
$t$	time (s)	Christodoulou GC (1993) Energy dissipation on stepped spillways. <i>Journal of Hydraulic Engineering</i> , ASCE 119(5): 644–650.
$T$	non-dimensional temporal parameter	D'Agostino V, Ferro V (2004) Scour on alluvional bed downstream of grade-control structures. <i>Journal of Hydraulic Engineering</i> , ASCE 130(1): 1-14.
$V_1$	approaching flow velocity at the ramp toe (m/s)	Dey S, Sarkar A (2006) Scour downstream of an apron due to submerged horizontal jets.
$x$	longitudinal coordinate	
$z$	vertical coordinate	
$z_m$	medium cross-sectional scour depth (m)	
$z_{max}$	maximum scour depth (m)	
$\Delta E_{r1}$	relative energy dissipation (section 0-0 – section 1-1)	
$\Delta E_{r2}$	relative energy dissipation (section 0-0 - section 2-2)	
$\Gamma$	boulders concentration	
$\rho$	water density ( $\text{kg/m}^3$ )	
$\rho_s$	sediment density ( $\text{kg/m}^3$ )	

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