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Pagliara, Stefano; Pelermo, Michele

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Scour at Foundations of Rock Made Low-Head Structures

S. Pagliara & M. Palermo
Department of Energy, Systems, Territory and Constructions Engineering (DESTEC), University of Pisa, Pisa, Italy

ABSTRACT: Low-head control structures are widely used for river restoration problems. Their main function is to control sediment transport. In the last decades, the increasing environmental sensibility has forced hydraulic engineers to find solutions which could be able to solve the cited problem and, at the same time, to assure a reduced environmental impact. Thus, several eco-friendly structural typologies were tested. Mainly, this type of structures are made of natural elements disposed in different configurations and geometries and are not rigid like classical transverse concrete check dams, i.e. they can easily adapt to the modified in situ conditions. Among these structure typologies, rock grade control structures and stepped gabion weirs, in different hydraulic and boundary configurations, were analyzed. As all other stream restoration structures, they have to be correctly designed in order to avoid structural problems and assure their hydraulic functioning. One of the main problem is the stability of the toe. Thus a detailed analysis was performed resulting in relationships by which it is possible to estimate the scour depth at the toe of tested structures which was found quite close to the maximum scour depth in the stilling basin.

Keywords: Erosion, Rock grade control structures, Stepped Gabion Weirs, Structural stability

1 INTRODUCTION

Low-head structures have been widely used for river restorations purposes. In particular, they have the function to regulate and control the sediment transport in natural rivers and, at the same time, they constitute a discontinuity in natural river morphology contributing to dissipate flow energy.

In the last decades, the increasing environmental sensibility forced hydraulic engineers to find solutions which could be suitable in terms of both hydraulic and structural efficiency and, at the same time, eco-friendly. Thus, the actual tendency is to find and build structures whose impact on the surrounding environmental contest is reduced. In particular, among this hydraulic structure typology, in the last decades "elastic" or "flexible" structures have assumed a great importance, i.e. structures which are characterized by the possibility to adapt to the in-situ conditions when changed. Generally, this type of structures are made of rocks of various dimensions which can be arranged either in loose configuration or in selected one and are also used to re-convert traditional concrete check dams. Block ramps, stepped gabion weirs, rock grade-control structures, block sills, etc., are typical examples of flexible rock made structures. Their advantage respect to traditional concrete structures is to be more easily adaptable to various contests, especially in mountain streams. In addition, the surface roughness, due to protruding elements, is a key peculiarity which contributes to make these structures more efficient in terms of energy dissipation. However, they present some peculiar and characteristic flow structures and their stability required a considerable attention in order to prevent collapse and assure hydraulic functionality. Thus, several studies dealing with hydraulic performances and scour mechanisms occurring in the downstream stilling basin were carried on. Nevertheless, despite the quite conspicuous technical literature present about block ramps (see for example Whittaker and Jäggi (1986), Pagliara and Palermo (2008), Pagliara et al. (2008), Pagliara et al. (2009), Pagliara and Palermo (2011) and Pagliara et al. (2011)), there is still a lack of knowledge about both the hydraulic and scour processes involving gabion stepped weirs and rock grade-control structures.

These two last structures present several similarities (in terms of flow characteristics on the structure itself) with stepped concrete chutes. Significant contribution are present in literature dealing with flow regimes occurring on stepped chutes. In particular, Chanson (1994) distinguished three different flow regimes: *Nappe Flow*, *Transition Flow* and *Skimming Flow*. Several Authors analyzed the transition between the different regimes and contributed to furnish a clear description of the parameters influencing the phenomenon in the presence of stepped chutes (among these Rajaratnam (1990), Essery and Horner (1978), Peyras et al. (1992), Chanson (1996), Othsu et al. (2000), Ohtsu et al. (2001), Boes and Hager (2003) and Ohtsu et al. (2004)). Whereas, relatively few studies are analysing the flow characteristics on the stepped gabion weirs and rock grade control structure (see for example Peyras et al. (1992), Chinnarasri et al. (2008) and Mohamed (2010)).

But, according to the Authors' knowledge, there are very few studies which take into consideration both the flow pattern (on the structure itself and in the stilling basin) in the presence of a downstream movable bed. Just recently, Pagliara and Palermo (2012) analysed both rock grade control structures and stepped gabion weirs, investigating both the flow characteristics on the structures and the hydraulic jump forming downstream of them. They conducted experiments in a large range of conditions testing different structure boundary configurations. In particular, they also analysed the scour process, proposing relationship by which, for each tested structure configuration, it is possible to estimate maximum scour depth and scour hole length. However, for practical purposes, another important parameter needs to be analysed: the scour depth at the toe of the structure. This parameter results to be very important in order to correctly design the structure. In fact, an excessive scour at the toe of the structure can lead to a structural collapse.

Thus, the aim of this paper is to analyse the scour at the toe of both rock grade control structures and stepped gabion weirs in different hydraulic conditions and for different boundary configurations of the structure. The analysis highlighted that there is a close relationship between the maximum scour depth and the scour at the toe of the structures. Simple relationships are proposed in order to estimate the maximum scour at the toe of the analysed structures, both in terms of maximum scour depth and in terms of non dimensional parameters.

2 EXPERIMENTAL SET-UP

Two series of experiments were conducted at PITLAB, the hydraulic laboratory of the University of Pisa. Experiments were carried out using two different models and, for each model, different boundary structure conditions were tested. Models were located in a channel 0.30 m wide, 0.60 m deep and 6 m long.

The first series of experiments was conducted using a model simulating a rock grade control structure. The model was built using uniform crushed rocks whose average diameter was D_{50}=7 cm. Several rock layers were located in the channel in such a way that the downstream face of the structure was characterized by a 45° slope. In addition, the rock layers were linked together using a silicon glue, thus the resulting permeability of the structure is practically negligible. In order to test structure height effect on both flow pattern and scour process, two different structure heights H were tested. The height of the structure was measured from the original initial bed level. The two grade control structures tested were termed $B1$ and $B2$, and their height was 10.3 and 13.7 cm, respectively. Nevertheless, the analysis was conducted varying both hydraulic parameters and boundary structure configuration. In particular, a filtering layer made by the same material constituting the stilling basin (trapped in an opportunely shaped 2x2 mm squared holes iron net) was located upstream of the structure. The filtering layer had the same height of the tested structure and the granulometric characteristics of the material by which it was filled were: d_{50}=4.78 mm, d_{90}=5.7 mm, where d_{xx} is the granular material diameter for which xx% is finer, non uniformity coefficient $\sigma=(d_{84}/d_{16})^{0.5}$=1.2 and density ρ=2645 kg/m^3. In the presence of the filtering layer, two different structure boundary conditions were tested, i.e. B_f and $B_{f\text{-}imp}$, respectively, where the subscript f indicates the presence of a filtering layer upstream of the structure and the subscript imp means that an impermeable covering was adopted to make the filtering layer impermeable. Thus, in synthesis the following grade control structure configurations were tested: $B1$ and $B2$, i.e. grade control structure with different height but without any filtering layer upstream of them; B_f, i.e. grade control structure and upstream filtering layer; $B_{f\text{-}imp}$ grade control structure and upstream impermeable filtering layer. Figure 1a illustrates the tested configurations and reports the main hydraulic and geometric parameters. Namely, H is both the structure and filtering layer height (when present), h the upstream water depth (measured from the horizontal plane passing through the top of the structure), h_0 the downstream water depth, z_{max} the maximum scour hole depth, and z_f the scour depth at the structure toe.

The second series of experiments were conducted in the presence of a stepped gabion weir. Two base stepped gabion weirs were tested and termed GW_0 and GW_{imp}. They were both simulated using superimposed layers of squared holes 1 cm x 1cm prismatic gabions, located in such a way that the downstream pseudo bottom of the structure had a slope equal to 45° (see Figure 1b). The height of the structure measured from the original bed level was H=15.4 cm. The prismatic gabions were filled using rounded uniform stones whose average diameter was d_{50}=1.2 cm. In addition, the steps were shaped in such a way that their length (w_s) and height (h_s) was both equal to 5.13 cm. The main difference between the base structure configurations tested is constituted by the presence of an impermeable covering (opportunely shaped) on the upstream part of the structure. In fact, the structure GW_0 was a simple gabion stepped weir, in which the upstream flow could filter inside the structure also from the upstream side, whereas the structure GW_{imp} had an impermeable steel covering on its upstream part, thus water filtration could not occur from the upstream side.

Also in this case, a filtering layer with the same structure height and containing the same stilling basin material (as specified above) was used in order to simulate different boundary conditions. In particular, in the presence of the base configuration GW_0, a permeable filtering layer was adopted, thus obtaining the configuration termed (GW_f). Whereas, for the base configuration GW_{imp}, the filtering layer adopted had an impermeable covering in order to not allow water filtering inside the structure from the upstream. In synthesis, the tested structure configuration characteristics are the following: gabion stepped weir GW_0, i.e. base configuration with no impermeable covering on the upstream part of the structure; gabion stepped weir GW_{imp}, i.e. base configuration characterized by the presence of impermeable covering on the upstream part of the structure; gabion stepped weir GW_f, i.e. configuration characterized by the presence of an upstream filtering layer, but no impermeable coverings are present, neither on the upstream part of the structure nor on the filtering layer; gabion stepped weir $GW_{f\text{-}imp}$, i.e. configuration characterized by the presence of an upstream filtering layer, with impermeable coverings both on the upstream part of the structure and on the filtering layer.

For the present experiments, the discharge Q ranged between 4 l/s and 11 l/s. Tests were conducted varying the downstream water level h_0 in the range $0.25<h_0/H<0.82$ and they lasted up to 120 minutes in order to reach the equilibrium scour configuration. The hydraulic parameters were selected in order to avoid live-bed conditions, i.e. a ridge was always present downstream of the scour hole. Both the water depths and the scour lengths were measured using a point gauge 0.1 mm precise. In Figure 2a-b two pictures are reported, showing a rock grade control structure and a stepped gabion weir, respectively.

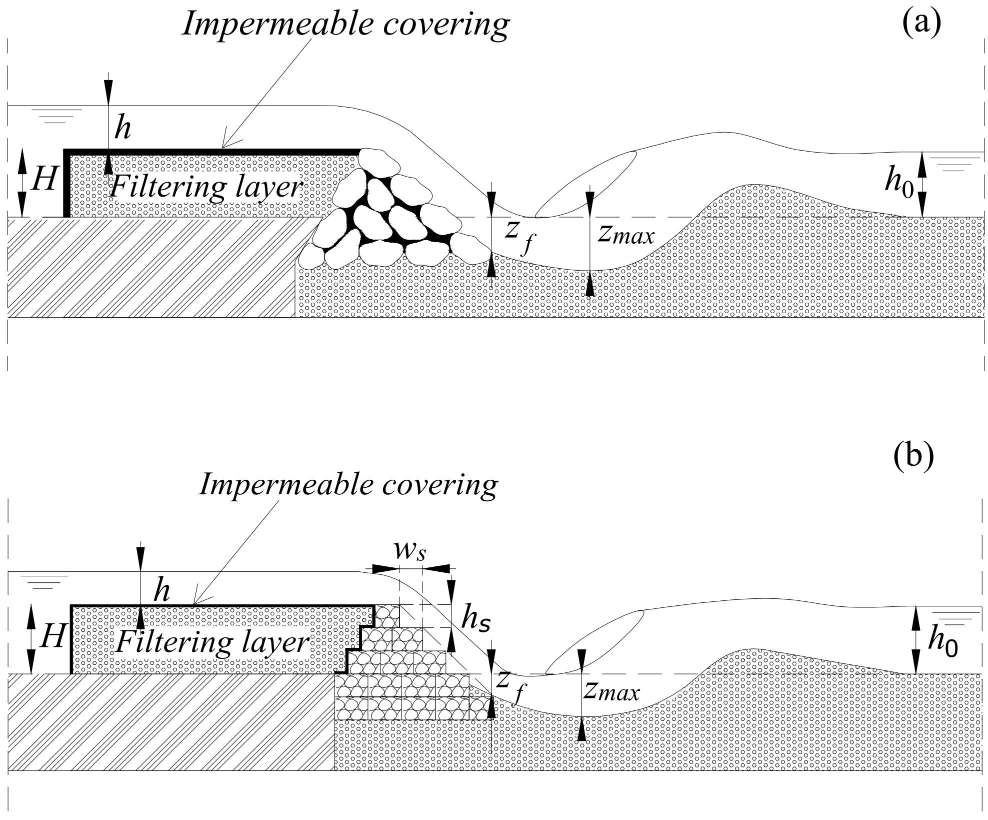

Figure 1. Diagram sketch of (a) rock grade control structures and (b) stepped gabion weirs including the main geometric and hydraulic parameters for various tested configurations

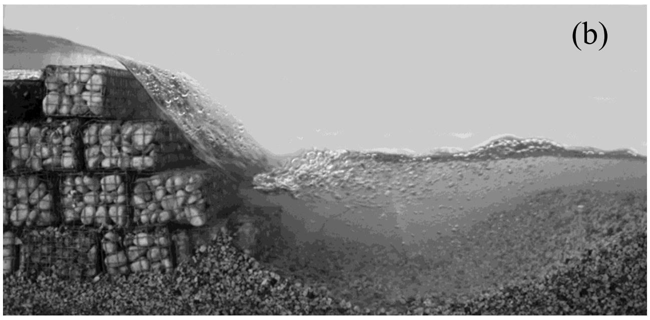

Figure 2. Picture of (a) rock grade control structure and (b) stepped gabion weir

3 RESULTS AND DISCUSSION

3.1 *Flow characteristics on the structures*

The close analysis of the flow structure on both stepped gabion weirs and rock grade control structures showed several similarities with stepped spillways, for which mainly three different flow regimes can be distinguished: *Nappe Flow*, *Transition Flow* and *Skimming Flow*. *Nappe flow* regime is characterized by a succession of plunging jets; whereas, in the case of *Skimming Flow*, the flow streams on a pseudo-bottom, below which vortex re-circulation takes place. The *Transition Flow* regime occurs when the water surface is quite undular and neither a direct jet impinging on the successive step nor a coherent flow stream on the structure occur. It means that for this last regime the flow structure shows intermediate characteristics between *Nappe* and *Skimming Flow* regimes. An example of *Skimming Flow* regime occurring on both a rock grade control structure and a stepped gabion weir is reported in Figure 2a-b, respectively.

Pagliara and Palermo (2012) analyzed the onset conditions characterizing the various regimes. In particular they specialized the analysis of Ohtsu et al. (2001) for the tested structure typologies. Namely, Ohtsu et al (2001) proposed a classification of the various flow regimes valid for stepped chutes based on two non-dimensional parameters: h_s/k_c and $\tan\alpha$, where h_s is the step height, k_c the critical flow depth and $\tan\alpha$ is the slope of the chute. They concluded that for $\tan\alpha=1$ (i.e. the case in which $\alpha=45°$, the same structure surface slope tested in the present study), the transition between *Nappe* and *Skimming Flow* occurs for $1<h_s/k_c<1.6$. But, it has to be noted that the conclusion of Ohtsu et al (2001) are valid just for the case in which the downstream water level does not submerge the structure. For the present tests, this condition is not preserved as several tailwaters were tested up to $h_0/H=0.82$.

Pagliara and Palermo (2012) specialized the analysis of Ohtsu et al (2001) for the tested structures including the effect of the previous parameter (h_0/H). They concluded that for rock grade control structures, assuming $h_s=D_{50}/2$ (as stones are partially protruding), the transition between *Nappe Flow* regime and *Skimming Flow* regime occurs for $0.9<h_s/k_c<1.1$. Furthermore, they experimentally proved that the influence of both the parameter h_0/H and the structure boundary configuration are relatively negligible on the transition between the two regimes. This is mainly due to the fact that the tested rock-grade control structures are practically impermeable as stones are linked by using a silicon glue, thus no filtration process from upstream can occur in the body of the structure.

Nevertheless, the authors conducted the same analysis for stepped gabion weirs concluding that *Transition Flow* regime mainly occurs for $1.1<h_s/k_c<1.5$ for all the tested structure boundary conditions, even if certain differences between the structure configurations (due to the fact that for some tested configurations the structure is not impermeable) can be noted varying h_0/H values. In synthesis, it can be noted that the classification valid for the tested structures appears very similar to that proposed by Ohtsu et al (2001) in the case in which tanα=1.

3.2 *Hydraulic jump features*

Two hydraulic jump typologies can be distinguished downstream of these structure typologies in the tested range of parameters. Namely, based on the hydraulic jump analysis performed by Pagliara (2007), Pagliara and Palermo (2012) stated that the hydraulic jump in the stilling basin can be either F_{MB} or S_{MB}. F_{MB} type is characterized by a clock wise flow circulation in the stilling basin. Furthermore, the sediment transport in the scour hole is directed both downstream and upstream. This occurrence contributes to have less scour depth respect to the case in which an S_{MB} hydraulic jump takes place. In fact, this last jump is characterized by a counter clock wise flow circulation and at the same time the sediment transport is practically completely directed downstream.

The analysis performed by Pagliara and Palermo (2012) contributed to classify and distinguish these hydraulic jumps typologies in terms of two non-dimensional parameters: h_0/H and A_{50}. This last parameter is equal to $q/[H\cdot[g\cdot d_{50}\cdot(\Delta\rho/\rho)]^{0.5}]$ (D'Agostino and Ferro, 2004), in which q is the unit discharge, g is the acceleration due to gravity, $\Delta\rho=\rho_s-\rho$, where ρ_s is the sediment density and ρ the water density. The analysis of experimental data showed that the transition between F_{MB} and S_{MB} occurs for $h_0/H>0.5$. In fact, being constant all the other parameters, an increase of the tailwater level contributes to submerge the jump, thus an S_{MB} type takes place.

3.3 *Scour depth analysis*

One of the most important parameter, in the case of movable stilling basin bed, is the maximum scour depth. A detailed analysis for the tested configurations was conducted by Pagliara and Palermo (2012). They selected several non-dimensional parameters on which the erosive phenomenon depends and, after having analyzed the experimental data, they concluded that, for each tested configuration of both rock grade control structures and stepped gabion weirs, the non dimensional maximum scour depth z_{max}/E_0, for practical purposes, can be expressed as only function of the non dimensional parameter A_{50}, i.e. the following functional relationship:

$$\frac{z_{\max}}{E_0} = f\left(A_{50}\right) \qquad (1)$$

Note that E_0 is the total energy head upstream of the structure. For each tested configuration, it was experimentally proved that the effect of the parameter h_0/H is negligible in terms of practical applications. But a clear difference in data trend was observed for the various flow regime. For example, the following Figure 3, valid for rock grade control structure $B_{f\text{-}imp}$, reports the experimental data clearly showing that passing from *Nappe* to *Skimming Flow* regime the scour depth increases faster. The transition between the two regimes generally occurs for $0.5<A_{50}<0.7$.

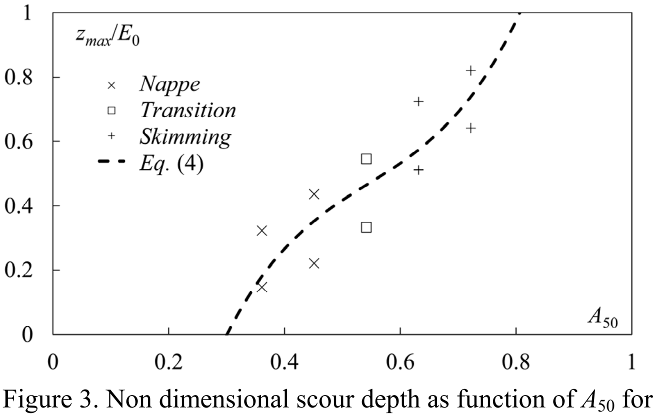

Figure 3. Non dimensional scour depth as function of A_{50} for different flow regimes and rock grade control structure $B_{f\text{-}imp}$

Pagliara and Palermo (2012) proved that, for rock grade control structures, the maximum non dimensional scour depth can be satisfactorily predicted by the following equations valid for grade control structure $B1$-$B2$ (Eq. 2), B_f (Eq. 3) and $B_{f\text{-}imp}$ (Eq. 4):

$$\frac{z_{max}}{E_0} = 3.28A_{50}^3 - 6.28A_{50}^2 + 4.74A_{50} - 0.95 \qquad (2)$$

$$\frac{z_{max}}{E_0} = 3.46A_{50}^3 - 6.96A_{50}^2 + 5.42A_{50} - 1.09 \qquad (3)$$

$$\frac{z_{max}}{E_0} = 13.46A_{50}^3 - 22.02A_{50}^2 + 13.12A_{50} - 2.32 \qquad (4)$$

For stepped gabion weirs, the analysis of experimental data showed that one unique equation is able to predict the totality of data, i.e. for practical purposes one single equation is able to catch the behavior of all the tested structures. Thus, Pagliara and Palermo (2012) proposed the following general equation valid for stepped gabion weirs GW_{imp}, GW_f, $GW_{f\text{-}imp}$:

$$\frac{z_{max}}{E_0} = 7.53A_{50}^3 - 11.53A_{50}^2 + 6.66A_{50} - 1.16 \qquad (5)$$

3.4 *Scour at the toe of the structures*

In terms of practical applications, the maximum scour depth at the toe of the structure is extremely important. In fact, the hydraulic functionality of the structure is assured if it remains stable. It implies that the foundation of the structure (i.e. a layer of stones (or more than one) in the case of rock grade control structures or layers of prismatic gabions for stepped gabions weirs) should not be affected by the erosive phenomenon occurring in the stilling basin. Namely, the scour depth at the toe of the structure has not to be so prominent to remove sediment at the base of the structure.

In this perspective it is clear that the knowledge of the maximum scour depth occurring at the toe of the structure is of fundamental importance for a correct design. The aim of this paper is to furnish quantitative criteria to estimate the maximum scour depth at the toe of the tested structure, based on the previous observations and deductions of Pagliara and Palermo (2012) which have been briefly synthetized in previous sections.

In the tested cases, once the scour hole equilibrium was reached, the stilling basin morphology was carefully measured. In particular, for both the structural typologies the maximum scour depth at the structure toe z_f was analyzed. In the case of rock grade control structure, the foundation was made of stones layer having the same average diameter (i.e. the usual methodology to build this type of structure), which were located in such a way that the average downstream structure surface slope (45°) was preserved. Thus, the maximum scour depth at the toe z_f was assumed as the minimum distance of the scoured sediment surface covering the structure foundation from the original bed level (see Figure 1a). For stepped gabion weirs, the foundation was made of prismatic layers having the same characteristics specified in Experimental Set-up section. Thus, the plane passing through the steps edge, including those belonging to the foundation, had a slope equal to 45°. This occurrence led us to assume z_f as the distance from the original bed level of the interception of the virtual plane passing through the steps edges with the scoured surface (see Figure 2b). Note that the assumed z_f is also the minimum distance between the scoured sediment surface and the step surface of the eventual covered foundation layer. This choice implies coherent values of z_f for both tested structure typologies. Furthermore, for stepped gabion weirs it takes into account the most dangerous conditions in terms of stability, as it considers the minimum sediment covering of the prismatic foundation.

The analysis of experimental data were based on two observations: Breusers and Raudkivi (1991) proved that the scour hole geometry can be expressed by only function of its maximum scour depth and Pagliara and Palermo (2012) proved that there is a scour hole profile similitude for the tested configurations, i.e. the non dimensional profiles for each structure typology are essentially the same (same non dimensional scour hole profiles for all the tested configurations of rock grade control structures and same non-dimensional scour hole profiles for all the tested stepped gabion weirs). These two observations allow to asses that the non-dimensional scour depth at the toe of the structure can be expressed as function of the maximum non-dimensional scour depth in the scour hole. Data were analyzed for each structure configuration, considering also the non dimensional structure submergence and the flow regime occurring. Figure 4a-d illustrates the relationship between z_f/E_0 and z_{max}/E_0, for different h_0/H and flow regimes, for structure $B1$, $B2$, B_f and $B_{f\text{-}imp}$, respectively. It was experimentally proved that the for all the tested structures, the effect of flow regime and h_0/H on data trend is negligible, thus confirming the observations of Pagliara and Palermo (2012) and Breusers and Raudkivi (1991). In addition, there is no detectable difference between the various rock grade control structures in terms of the ratio z_f/z_{max}. In fact, one unique linear relationship can be used to interpolate the experimental data for all tested rock grade control structures (Figure 4a-d), whose expression is

$$\frac{z_f}{E_0} = 0.9\frac{z_{\max}}{E_0} \qquad (6)$$

This occurrence proves that the scour depth at the structure toe is almost 90% of the corresponding maximum scour hole depth. Thus, for practical applications, z_{max} can be considered as the main parameter to design structure foundations. The same analysis was conducted for stepped gabion weirs (see Figure 5a-c). Also in this case, a direct proportional relationship between z_f and z_{max} was found. Namely, the analysis was conducted for stepped gabion weirs GW_{imp}, GW_f and $GW_{f\text{-}imp}$ (Figure 5a, 5b and 5c, respectively) and it was found that the following expression can satisfactorily interpolate all experimental data.

$$\frac{z_f}{E_0} = 0.84\frac{z_{\max}}{E_0} \qquad (7)$$

Note that in this case the scour depth at the structure toe is almost 84% of the corresponding maximum scour hole depth, i.e. less than the previous case. This relatively slight difference between stepped gabion weirs and rock grade control structures in terms of z_f/z_{max} can be explained considering that the foundation of stepped gabion weirs is made of prismatic layers which furnish higher protection for the scour at the structure toe due to vortexes formations below the pseudo bottom. Furthermore, the structure itself is always permeable, whereas rock grade control structures are made gluing stones thus the internal structure permeability is practically negligible and less flow energy loses occur. Figure 5d illustrates the comparison between the measured and calculated values of the variable z_f/E_0 (using Eq. 6 for rock grade control structures and Eq. 7 for stepped gabion weirs). A good agreement was found between measured and calculated data. In synthesis, it can be concluded that for both the structure typologies the maximum scour depth can be assumed as reference parameter in order to correctly design the structure foundations, as it results to be very close to the scour depth at the toe of the structures.

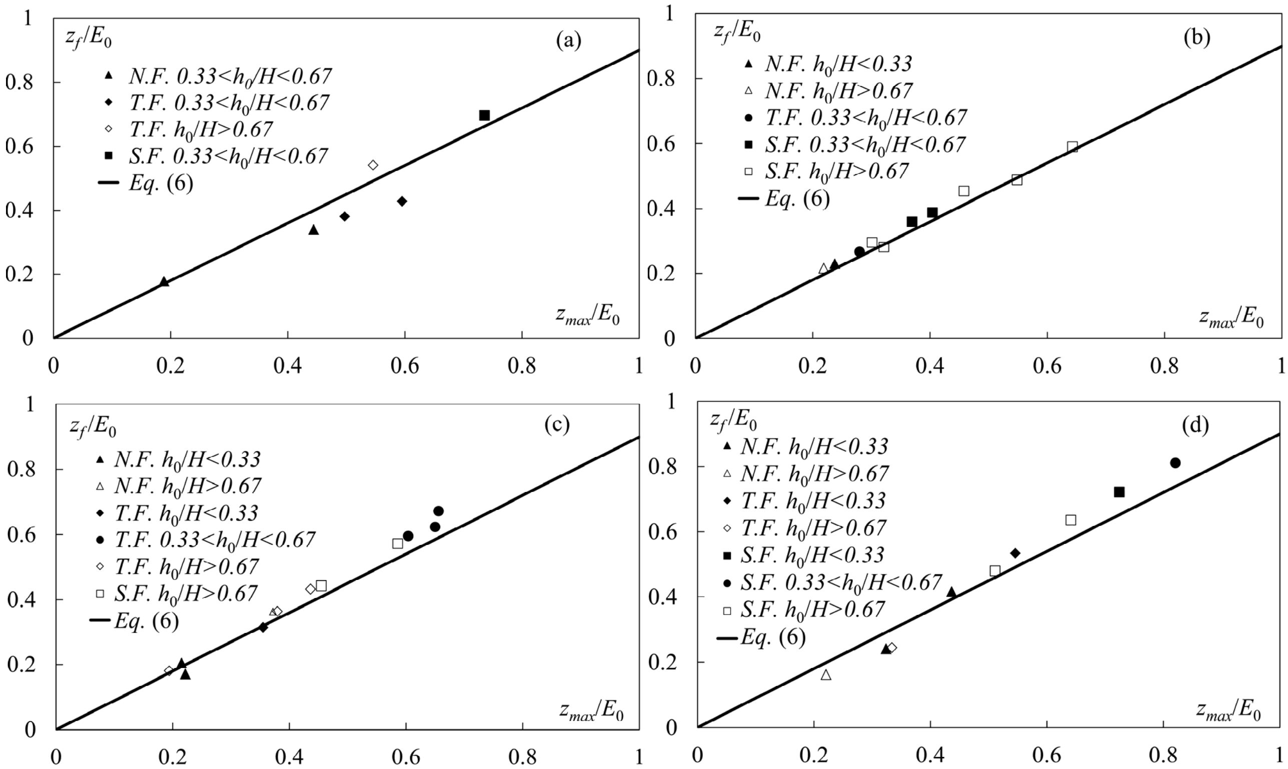

Figure 4. z_f/E_0 versus z_{max}/E_0 for different flow regimes (N.F.=Nappe Flow, T.F. Transition Flow, S.F.=Skimming Flow) and relative submergence and for rock grade control structure (a) $B1$, (b) $B2$, (c) B_f and (d) $B_{f\text{-}imp}$

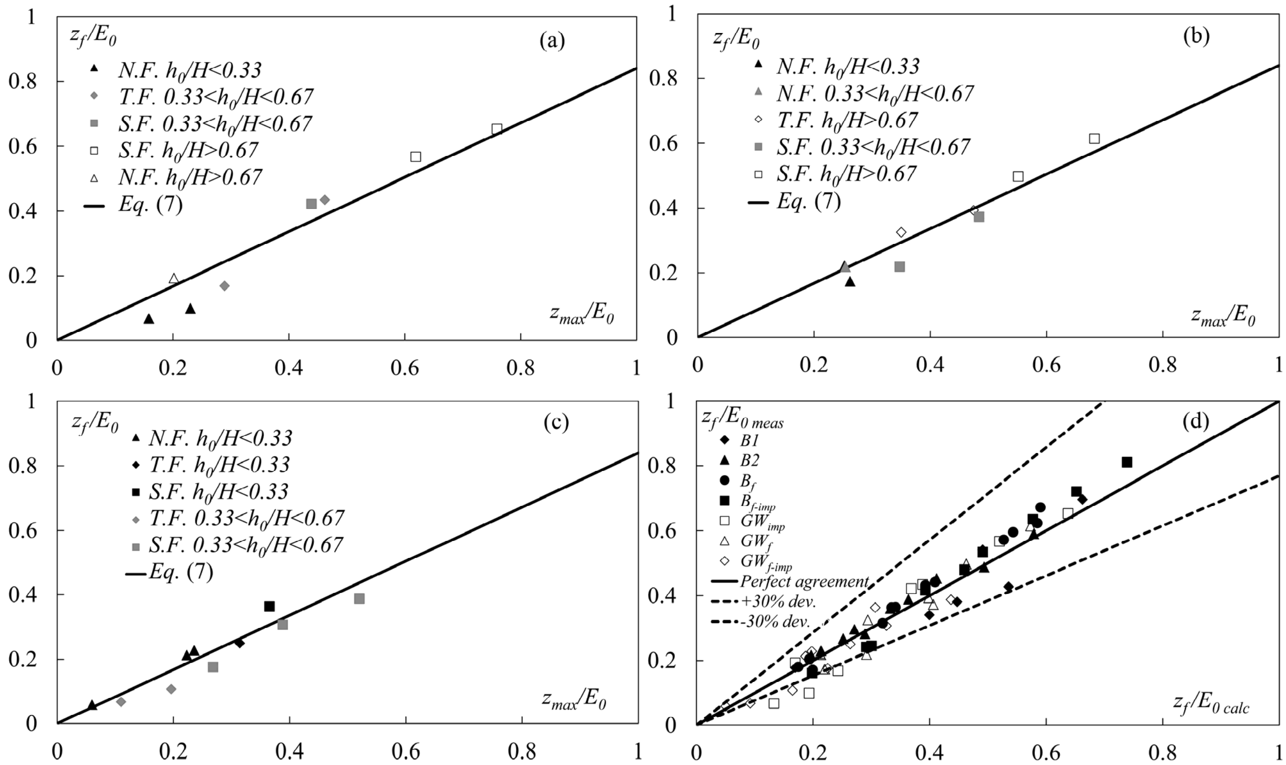

Figure 5. z_f/E_0 versus z_{max}/E_0 for different flow regimes (N.F.=Nappe Flow, T.F. Transition Flow, S.F.=Skimming Flow) and relative submergence and for stepped gabion weirs (a) GW_{imp}, (b) GW_f, (c) $GW_{f\text{-}imp}$. (d) Comparison between measured and calculated values of z_f/E_0 using Eq. (6) (rock grade control structures) and Eq. (7) (stepped gabion weirs)

4 CONCLUSIONS

An analysis of scour at foundations of low-head rock made structure was performed. Namely, the scour at the toe of rock grade control structures and stepped gabion weirs was analyzed in different hydraulic conditions and configurations. In particular different structure boundary configurations were tested for various submergence conditions. It was experimentally proved that the scour depth at the toe of the structure is almost 90% of the maximum scour hole depth occurring in the stilling basin in the case of rock grade control structures, whereas for stepped gabion weirs it is almost 84%. These occurrences allow to asses that for these structure typologies, the maximum depth in the scour hole can be considered as the reference parameter to correctly design the structure foundations in order to avoid structural risks and assure their stability. Furthermore, it was experimentally proved that this occurrence is not depending on both the submergence conditions and the flow regime occurring on the structure itself.

NOTATION

$A_{50} = q/[H\cdot[g\cdot d_{50}\cdot(\Delta\rho/\rho)]^{0.5}]$ non dimensional group.

D_{50}	average diameter of rock grade control structure material
d_{xx}	diameter of the channel bed and filtering layer material for which xx% of sediment is finer
d_{50}	diameter of the channel bed material and filtering layer for which 50% of sediment is finer
d_{90}	diameter of the channel bed material and filtering layer for which 90% of sediment is finer
E_0	total energy head upstream of the structure
f	function of
g	gravitational acceleration
h_0	tailwater level
h	water depth measured from the horizontal plane passing through the top structure
h_s	height of the steps
H	structure height
k_c	critical depth
Q	water discharge
q	unit discharge
w_s	length of the steps
z_{max}	maximum scour hole depth

$\Delta\rho = (\rho_s - \rho)$ reduced sediment density
ρ_s sediment density
ρ water density
$\sigma = (d_{84}/d_{16})^{0.5}$ sediment non uniformity parameter.

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