Block ramps in curved rivers: morphology analysis and prototype data supported design criteria for mild bed slopes

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Abstract

Eco-friendly river restoration structures are a valid solution for river training projects. Among this structure typology, block ramps have been successfully tested to solve problems related to river sediment control, bed stabilization and energy dissipation. Despite the conspicuous literature dealing with block ramps design in straight rivers, there are no studies analysing the erosive process occurring in the stilling basin downstream of a block ramp in a curved river bend. Therefore, this paper represents the first systematic analysis of their behaviour and of the resulting downstream equilibrium morphology in such geometric configuration. A dedicated model was built to simulate a wide range of hydraulic conditions. Experimental data analysis allowed describing the erosion dynamics occurring in the stilling basin and, at the same time, to derive a useful design relationship by which it is possible to estimate the maximum scour depth. Furthermore, the model results were successfully validated by using field measurements collected in the Porębianka river (Poland). Both field data and laboratory experimental results allowed furnishing a comprehensive description of the scour phenomenon. The proposed relationship represents the first trustable and valid tool for hydraulic design of such structure typology in curved rivers.

Keywords: Block ramps, Curved rivers, Erosion, Model data validation, River Morphology.

1. INTRODUCTION

Rivers are complex dynamic systems which require a particular attention for a correct balance between anthropic use and natural evolution. In particular, it becomes fundamental to select appropriate river structures in order to preserve and positively affect the biological life of both macrobenthos and fish species.

In this perspective, the laboratory analysis can furnish precious insights on the physical phenomena occurring in the natural eco-systems and allow for a generalization of the results. Nevertheless, physical models are always affected by scale effects, therefore a field data validation is an optimal solution in order to generalize the proposed results (Bormann and Julien, 1991; Chinnarasri *et al.*, 2008; Pegram *et al.*, 2009; Heller, 2011). This paper focuses on the hydrodynamics and scour processes occurring in correspondence with selected mountain river restoration structures (i.e., block ramps), located in the Carpathian rivers, Poland.

The sediment bed load transport deeply affects river morphology and, at the same time, it can endanger river bank stability (Whitaker and Potts, 2007; Phillips, 2010). Lisle (1982) analysed natural gravel bed channels showing that the sediment transport contributes to modify pools and riffles morphologies. Therefore, in the last decades, grade control structures have been widely used to regulate the natural evolution of water bodies (Lenzi *et al.*, 2003; Marion *et al.*, 2004; Martín-Vide and Andreatta, 2006; Pagliara *et al*., 2016a). In particular, block ramps are low-head hydraulic structures whose main aim is to control sediment transport and to dissipate flow energy. They are made of stones which can eventually protrude the water surface (Bathurst *et al.*, 1987). In general, they are located on a mild slope bed (Oertel and Schlenkhoff, 2012; Pagliara and Palermo, 2013). Stones arrangement allows for fish and benthic macroinvertebrate (benthos) migration, resulting in a significant oxidation of water (Radecki-Pawlik *et al.*, 2013). Nevertheless, their hydraulic behaviour is quite complex and several issues requires particular attention during the design phase. Namely, the increase of energy dissipation occurring on the structure can reduce the energy of the exiting flow, but, very frequently, it is not enough to avoid downstream localized scour phenomena. Furthermore, in natural rivers, block ramps are sometime located in bends, therefore the scour phenomena become further complex, involving an asymmetry in the stilling basin equilibrium morphology.

Many studies have been conducted in the past dealing with localized erosive phenomena in correspondence with different hydraulic structures (e.g., Veronese, 1937; Hassan and Narayanan, 1985; Mason and Arumugam, 1985; Bormann and Julien, 1991; D'Agostino and Ferro, 2004; Dey and Raikar, 2005; Dey and Sarkar, 2006). Nevertheless, no studies were conducted on block ramps located in river bends. In addition, previous studies dealing with block ramps, conducted under both clear-water and live-bed conditions, focused on both hydraulic behaviour and scour related problems in straight channels, involving downstream tailwater and stilling basin geometry effects (Pagliara and Palermo, 2011). In particular, Pagliara and Palermo (2008a) analysed the main geometric parameters characterizing the equilibrium stilling basin morphology (i.e., maximum scour depth z_m, scour length and ridge height) in the presence of protection sills located in the stilling basin at different spatial positions (i.e., varying both the longitudinal distance (x_s) of the rock sill from the ramp toe and the vertical position of the upper rock sill edge (z_{op}) from the original bed level). Pagliara and Palermo (2008b) extended the findings of Pagliara and Palermo (2008a) including the effect of the channel bed material non-uniformity on the scour process in the presence of protection structures. Namely, they conducted preliminary reference tests (i.e., tests in the absence of any protection structure in the stilling basin), and derived an expression in order to predict the maximum non-dimensional scour depth $Z_m=z_m/h_1$, where h_1 is the water depth at the ramp toe. Their analysis focused on the scour process occurring in the presence of an F_{MB} jump type, i.e., when the hydraulic jump is entirely located in the stilling basin and it does not submerge the ramp. This last configuration is the same occurred in the analysed prototype during the modelled flood event. The basic equation derived for the reference tests (Pagliara and Palermo, 2008a) for uniform material ($\sigma \approx 1$) is:

$$Z_m = 0.58 \cdot i^{0.75} \cdot F_{d90}^{1.8} \qquad (1)$$

valid in the ranges: $0.0833 \leq i \leq 0.25$ and $1.0 \leq F_{d90} \leq 3.75$. i is the block ramp slope and $F_{d90}=V_1/(g'd_{90})^{0.5}$ is the densimetric Froude number, where $g'=g[(\rho_s-\rho)/\rho]$ is the reduced acceleration, V_1 is the average flow velocity at the ramp toe, ρ_s and ρ are the channel bed sediment density and water density, respectively. In the presence of a protection structure downstream of the ramp toe, Pagliara and Palermo (2008a-b) modified the previous Eq. (1) as follows:

$$Z_{ms} = Z_m \cdot \left(a\lambda^2 + b\lambda + c\right) \cdot \left(dZ_{op}^2 + eZ_{op} + f\right) \qquad (2)$$

where $Z_{ms}=z_{ms}/h_1$ is the non-dimensional maximum scour depth in the presence of a protection structure in the stilling basin, $\lambda=x_s/l_0$ and $Z_{op}=z_{op}/z_m$ are the non-dimensional longitudinal and vertical position of the rock sill. Note that z_{ms} is the maximum scour depth in the presence of a protection structure in the stilling basin, l_0 is the scour hole length of the reference tests (test conducted in the same hydraulic and geometric configuration in the absence of any protection of the stilling basin) and z_m is the maximum scour hole depth in the reference test. a, b, c, d, e and f are coefficients depending on the ramp slope i and rock sill position. But, the scour dynamic process is also affected by the upstream river flow conditions and morphology. In other words, if the flow has enough energy to mobilize the river bed material and transport it downstream (live-bed conditions), both the scour phenomenon and the hydraulic behaviour can be significantly affected (Pagliara *et al.*, 2012).

This paper will focus on the effect of different discharges on the erosive processes in the presence of a block ramp succession located in different curved channels. The influence of channel curvature is analysed under clear-water conditions and a useful design relationship is proposed to estimate the maximum scour depth. The proposed relationship is validated by using field data in order to generalize and test its predicting capability.

2. FIELD STUDY AREA

The catchment of Porębianka river is characterized by flysch rocks. It is located in the Polish Carpathians, about 60 km south from Kraków (Hajdukiewicz *et al.*, 2015; Zawiejska *et al.*, 2015). Porębianka river is a right-bank tributary of the Mszanka River. It is 15.4 km long and it is characterized by frequent flood events, mostly occurring during summer. The bed material of the stream consists of sandstone and mudstone pebbles and cobbles with a subordinate proportion of sandy and silty particles. A succession of block ramps is present in the river to control sediment transport and stabilize the river bed (Fig. 1). Both the head and the toe of the block ramps are stabilized using two rows of steel piles topped by a reinforced concrete cap (sills in Fig. 2). Generally, the slope of the ramp bed built in the river is i=0.083. A protected stilling basin is located downstream of the ramp toe, as shown in Fig. 2.

The protected stilling basin is characterized by the following dimensions: 5 m long and 1.2 m thick (i.e., the rock diameter used to create the protective end sill). In addition, in the central part of the ramp there is a channel whose bed is 0.2 m lower that the average ramp bed level, in order to facilitate fish migration during the periods of low discharge. The distance between the block ramps varies from 60 m to 250 m and their length is 12 m. The average diameter D_{50} of the stones constituting the block ramp bed is ranging between 0.9 and 1.2 m. Whereas, the river bed material is characterized by an average diameter d_{50} ranging between 40 and 65 mm. The average river bed slope S is less than 0.01. Figure 2 illustrates a typical block ramp located in the river, in which both the sills and the downstream protected stilling basin are evident. Figure 3 reports two examples of block ramps under low discharge conditions. It is evident that, in this case, the flow is concentrated in the central part of the ramp in which a channel for fish migration is built.

The hydrological characteristics were determined by using data collected at a station located in the central part of the of Porębianka river. The highest mean monthly discharges occur in April, due to snow melt. Conversely, the lowest discharges occur in February and October. The amplitude of water level variation is about 150 cm. The high variability of water discharge reflects low retention potential of the flysch bedrock and partial deforestation of the catchment.

Measurements of hydraulic parameters and river morphology were taken after a flood occurred in May 2010, for which the estimated discharge was $Q \approx 60$ m^3/s. Note that a significant variation of river bed morphology was observed after the mentioned flood. Therefore, the measured river bed morphology is essentially due to this flood event. Finally, samples of collected sediment were analysed in order to determine the granulometric characteristics in the river branches between block ramps.

3. MATERIALS AND METHODS

Four block ramps were modelled and the river curvature was accurately reproduced. Namely, block ramps termed ramp 1 and 2 (Fig. 1) are located in a river bend whose curvature is approximately R=660 m. In addition, other two ramps termed ramp 3 and 4 are located in a river bend whose curvature is approximately R=360 m. In the prototype, the river bend between ramp 1 and 2 is followed by an almost straight branch, which precedes ramps 3. The distance between ramp 1 and 2 is $L_{12} \approx 100$ m, whereas the distance between ramp 3 and 4 (L_{34}) and between ramp 4 and the successive ramp (L_{45}) is $L_{34} \approx L_{45} \approx 140$ m. The straight river branch length between ramp 2 and 3 is $L_{23} \approx 200$ m. Note that in this last branch there is also another block ramp located between ramp 2 and 3. The selected model scale was 1/60, therefore the channel width is B=0.5

m and the channel curvatures were R=6 m, R=11 m and $R\approx\infty$ (for straight branch). A uniform sand (d_{50}=1.75 mm, geometric standard deviation $\sigma=(d_{84}/d_{16})^{0.5}$=1.2 and density ρ_s=2214 kg/m^3) was used to simulate the river bed, whereas block ramps were modelled using rounded gravels whose D_{50}=22.7 mm. Prototype discharges up to Q=170 m^3/s were simulated, therefore including $Q\approx$60 m^3/s, i.e., the flood condition after which the river bed morphology was measured.

Experiments were conducted reproducing ramps 1-2 and 3-4. The stilling basin between two consecutive ramps was horizontal and carefully levelled before starting the experimental test. Experimental test duration allowed to reach bed morphology equilibrium. During the tests, water levels were measured using a 0.1 mm precise point gauge. When the equilibrium scour condition was reached, the water flow was stopped and the bed morphology was carefully surveyed. For the tested discharges, clear-water conditions occurred. Note that after the flood occurred in May 2010, the analysis of the selected ramp surfaces revealed that a very small quantity of sediment was trapped between the stones, therefore it is reasonable to assume that clear-water conditions occurred also in prototype. Figure 4 shows a picture of the block ramp 4 simulation in the laboratory channel.

4. RESULTS AND DISCUSSION

4.1 Maximum scour depth

The prediction of the scour morphology occurring in the downstream stilling basin is fundamental in order to correctly design any hydraulic structures. Therefore, the stilling basin design appears particularly important in correspondence with this structure typology, also because of the dissipative processes that occur immediately downstream. As mentioned, the analysis of the scour process downstream of block ramps in the presence of protection sills located in the stilling basin at different spatial positions was conducted by Pagliara and Palermo (2008a-b) and Pagliara *et al.* (2016b). Note that in the prototype (Porębianka river), the stilling basin downstream of the block ramp is protected by rounded stones of the same dimensions of those constituting the ramp and they are located immediately downstream of the ramp toe. This configuration is quite close to that analysed by Pagliara and Palermo (2008a-b), in which the rock sill was located at the closest longitudinal distance from the ramp toe (λ=0.25 in Eq. 2). Furthermore, the protection stone layer adopted in the Porębianka river is located in such a way that the average level of the stone tops is almost the same of the ramp toe. It implies that this configuration is also very similar to that tested by Pagliara and Palermo (2008a-b), in which the rock sill upper edges were located at the same level of the original channel bed, i.e., Z_{op}=0 in Eq. (2). Based on these observations and assuming λ=0.25, Z_{op}=0, i≈0.0833 and the values of the coefficients *a*, *b*, *c*, *d*, *e* and *f* reported in Pagliara and Palermo (2008a), Eq. (2) can be re-written as follows:

$$Z_{ms} = Z_m \cdot (-0.8\lambda + 1.07) \cdot (-0.1Z_{op} + 1.05) = 0.912Z_m \tag{3}$$

From the previous equation, it is evident that the presence of a protection structures contributes to reduce the maximum scour depth. From Eq. (3), it can be easily interfered that the maximum scour depth occurring in the presence of a protection rock sill located immediately downstream of the ramp toe is 90% of the maximum scour depth occurring in the same hydraulic conditions and geometric configuration of the ramp when no protection structures are present in the downstream stilling basin. In conclusion, this equation can be considered valid for a protected straight river branch where a block ramp (whose slope is quite mild, i.e., i=0.0833) is located.

When a block ramp is inserted in a curved river, the equilibrium scour morphology occurring downstream of it is influenced by the curvature radius of the river bend. This occurrence is mostly due to the fact that, depending on the ramp position, both the flow pattern upstream and downstream of the ramp can be characterized by an asymmetric transversal velocity distribution. The asymmetry in flow velocity distribution generally results in a 3D equilibrium scour morphology. It can be easily observed from both experimental tests and prototype measurements that the three-dimensionality of the scour hole decreases with the curvature radius R and becomes more 2D in correspondence with straight river branch, i.e., when R≈∞. In addition, river bed width is also an important parameter affecting the scour morphology shape, because of the confining effect that river banks can have on the erosive process. Based on these observations and considering the functional relationships proposed by Pagliara and Palermo (2008a-b) for Z_{ms}, it can be easily observed that, in the case in which a block ramp is located in a river bend, the maximum non-dimensional scour depth $Z_{msc}=z_{msc}/h_1$ depends on the following variables, with z_{msc} maximum scour depth in a protected stilling basin located in a curved channel:

$$Z_{msc} = 0.912Z_m \cdot f\left(\frac{B}{R}\right) \tag{4}$$

Experimental tests allowed to derive the multiplicative function *f*(*B*/*R*). This function was derived in such a way that for straight channels ($R \approx \infty$), the final equation should be analytically identical to that proposed by Pagliara and Palermo (2008a-b). Therefore, the following general equation is proposed:

$$Z_{msc} = 0.912 Z_m \cdot \left(1 + \frac{B}{R}\right)^{2.82} \qquad (5)$$

Despite the complexity of the phenomenon, Eq. (5) reasonably well predicts experimental data (R^2=0.85), as shown in Fig. 5. Namely, Fig. 5a shows the comparison between measured Z_{msc} values with Eq. (5) for R=6 m, whereas Fig. 5b shows the comparison between measured and calculated (using Eq. 5) values of the variable Z_{msc} for all the experimental tests.

4.2 Validation of model results

The laboratory model simulated selected bends of the Porębianka river. Namely, the modelled bends are highlighted in the circles in Fig. 1. As specified above, after a flood event, whose peak discharge was $Q \approx 60$ m^3/s, the river morphology was carefully surveyed. In particular, downstream of each block ramp located in the river, the river bed morphology was measured in selected transversal cross-sections in order to estimate the maximum scour depth and identify the deposit and scoured areas. A river is a complex system, thus the understanding of its evolution results in a global analysis of all the variables influencing the equilibrium morphology. The presence of bars (deposit area) generally occurs close to the central part of the stilling basin, but their shape and extension is strongly influenced by the river curvature. The increase of river curvature causes a longitudinal extension of the sediment bars, resulting in sediment deposit areas mostly located in the inner part of the river branch. Nevertheless, the bar formation dynamics, such as the location of scoured areas mostly depend on the asymmetric transversal distribution of flow velocity. Namely, the transversal asymmetry in flow velocity distributions results in an asymmetry of the shear stresses distribution acting on the river bed sediment. In the outer part of a curved river bend, the shear stresses are more prominent; therefore, the sediment materials are transported downstream and shifted towards the inner part of the river bend. In addition, the presence of both sediment deposit areas, mostly located in the inner part, and the scoured regions, mostly located in the outer part of the river bend, results in a preferable path for water flow. In other words, a sort of channelization of the water flowing in the stilling basin takes place in its outer part, resulting in a prominent 3D river bed equilibrium morphology. Figure 6 illustrates two typical bar formation occurring in two different bends of the river. Namely, Fig. (6a) shows a bar formed quite far from the ramp toe in a significant curved river bend, whereas Fig. (6b) shows a longitudinal extended bar formed immediately downstream of the ramp toe.

These two different bar formation mechanisms depend both on the river geometry and on the inflow conditions. Namely, in the first case (Fig. 6a), the river curvature is prominent both upstream and downstream of the block ramp. Therefore, the flow approaching the ramp entrance is already characterized by a significant transversal asymmetry in velocity distribution. This occurrence contributes to model the stilling basin equilibrium morphology, i.e., at the ramp toe, in the inner part, a relatively small bar formation can occur and a prominent and longitudinally extended bar forms farther downstream. In the outer part of the river body, a prominent and deep channelization takes place resulting in a flow distribution mostly concentrated in that section. This typical river configuration exists downstream of modeled ramp 4 (see Fig. 1 and 7). In fact, Ramp 4 is preceded and followed by a significantly curved river bends. Figure 7 shows both the modeled and surveyed stilling basin configuration downstream of Ramp 4, under the peak discharge $Q \approx 60$ m^3/s which was simulated in the laboratory model in order to analyse the equilibrium scour morphology. Namely, Fig. (7a) and (7c) show the 2D and 3D views, respectively, of the equilibrium morphologies downstream of the selected ramp, whereas Fig. (7b) and (7d) report the measured cross-sections and the sketch of the deposit areas in the prototype (Porębianka river). By comparing the model equilibrium morphology with field measurements, it is evident that they appear quite similar. In the outer part of the river branch, a prominent stilling basin channelization occurs, whereas the inner part is characterized by the presence of a deposited area. Furthermore, the qualitative analysis of Figure (7a) and (7d) shows a substantial similitude between model and prototype morphology. In particular, the maximum scour depth occurs in the outer part close to the ramp toe and two isolated deposit regions form in the central part of the stilling basin (bold lines in Figure 7d).

A similar resulting equilibrium morphology occurs in the stilling basin between Ramps 3 and 4. The most significant difference is in the approaching flow velocity distribution. Namely, the stilling basin downstream of Ramp 3 is located in a river bend whose curvature is practically the same as that characterizing the stilling basin between Ramp 3 and 4. Nevertheless, the river bend preceding Ramp 3 is almost straight. Therefore, the shear stresses distribution acting on the stilling basin material downstream of the Ramp 3 is more uniform and symmetric than in the previous case, resulting in much less prominent isolated deposit area formations located close to the ramp toe. In addition, the channelization of the stilling basin occurs closer to the center of the river bend and it is confined by a longitudinal bar. Even if the approaching flow conditions slightly modify the resulting equilibrium morphology, it was experimentally shown that its effect on the maximum scour depth is practically negligible. This evidence is further confirmed by field measurements. In fact, a similar value of the maximum scour depth z_{mcs} occurs between Ramp 3 and 4 and downstream of Ramp 4. Therefore, it can be concluded that, in terms of practical applications, the maximum scour depth mostly depends on the curvature of the river bend and the effect of the inflow conditions can be considered negligible. Fig. (8a) and (8c) show the 2D and 3D views, respectively, of the equilibrium morphology downstream of the selected Ramp 3, whereas Fig. (8b) and (8d) represent the results of the field investigation, i.e., cross-sections and the sketch of the deposit area in the prototype (Porębianka river).

Also in this case, a substantial qualitative similitude between modeled and prototype river branch can be pointed out, i.e., the maximum scour depth occurs closer to the center of the stilling basin and a longitudinal extended sediment deposit formation takes place.

A substantially different behavior can be detected if the river curvature increases. This is the case occurring between Ramp 1 and 2, which are located in a relatively mild curved river branch (R≈660 m). The asymmetry in the flow velocity distribution both upstream and downstream of Ramp 1 is much less prominent than in the previous illustrated cases. Therefore, a more uniform distribution of the shear stresses acting on the stilling basin material occurs. The resulting equilibrium morphology appears much more 2D and it is quite similar to that occurring in a straight channel. Namely, the increase of the curvature radius results in a scour hole morphology characterized by a limited channelization of the stilling basin. In addition, also sediment deposit areas occur downstream of the scour hole, thus forming a sort of ridge confining the scoured region. Figure 9 synthetizes the qualitative morphologic behavior of the stilling basin. Namely, Fig. (9a) and (9c) show the 2D and 3D views, respectively, of the equilibrium morphology downstream of the selected Ramp 1, whereas Fig. (9b) and (9d) report the results of the field measurements conducted in the prototype.

Figures (7)-(9) showed that laboratory model well represents the erosive process dynamics occurring in the prototype, therefore the general predicting equation (Eq. 5) derived from model data was validated by using field data. Namely, from a design point of view, it assumes a fundamental importance to provide a robust and trustable tool to predict the maximum scour depth in a wide range of hydraulic and geometric conditions. According to authors' knowledge, despite the conspicuous literature on block ramps, no studies report design formulas which have been validated using field data. Thus, due to the increasing interest of the scientific community on such structure typology, it is essential to test the predicting capability of Eq. (5). The proposed empirical equation will be validated by comparing the calculated values of the variable $z_{msc}=Z_{msc}\cdot h_1$ with those measured in the Porębianka river after a flood event in which the estimated peak discharge was $Q\approx 60$ m^3/s. During the flood event, there was not the possibility to measure neither the water depth on the structure nor that at the ramp toe (h_1). Therefore, in order to apply the proposed Eq. (5), it is necessary to give an estimation of the approaching flow depth h_1. According to Pagliara *et al.* (2009), block ramp is a short structure, thus uniform flow conditions can rarely occur. Nevertheless, the authors showed that for this structure typology (in particular for ramp slopes varying in the range 0.083-0.25) a reasonably good estimation of the variable h_1 can be given using Manning's equation (Eq. 6) and assuming the realistic hypothesis that B is the average width of the river bend (derived from transversal cross-sections measurements) and the hydraulic radius R_h is approximately equal to h, where h is the uniform flow depth. Note that Pagliara and Palermo (2010) showed that $h\approx h_1$ furnishing an empirical relationship to estimate the coefficient n valid for block ramp configurations and hydraulic conditions which include those characterizing the hydraulic structures located in the Porębianka river. Namely, they estimated the coefficient n by applying the following Eq. (7), in which D_{50} is the mean diameter of the stones constituting the block ramp.

$$Q=\frac{1}{n}h^{5/3}Bi^{0.5}\approx\frac{1}{n}h_1^{5/3}Bi^{0.5} \quad (6)$$

$$n=0.064\left(D_{50}i\right)^{0.5} \quad (7)$$

Therefore, by substituting Eq. (7) in Eq. (6), the estimated value of the parameter h_1 can be easily derived. Based on the previous observations, the calculated value of the maximum scour depth occurring in a protected stilling basin located in a curved/straight river branch can thus be derived by applying the following Eq. (8), in which Z_{msc} is calculated by using Eq. (5) and h_1 by using Eq. (6).

$$z_{msc} = Z_{msc} \cdot h_1 \quad (8)$$

Figure 10 shows the comparison between field measured and calculated values of the variable z_{msc}. It can be easily observed that, despite the complexity of the phenomenon, Eq. (8) furnishes a good tool to estimate the maximum scour depth occurring downstream of a block ramp, characterized by a relatively mild slope and located in a river bend whose non dimensional curvature B/R varies between 0 (straight geometry) and 0.08. It is worth noting that for practical applications a deviation of 30% between predicted and measured data is an appreciable result, considering that the proposed relationship is based on symplyfing assumptions and some field parameters cannot be measured during flood events (e.g., the water depth at the ramps toe).

5. CONCLUSIONS

This paper presents the results of an experimental investigation on scour processes occurring downstream of block ramps located in river bends. A dedicated model was built at the University of Pisa, Pisa (Italy). The laboratory model simulated selected structures located in the Porębianka river, Poland. Two different bends of the Porębianka river were simulated and for one of them a succession of block ramps were modelled in order to test the influence of the approaching flow conditions on the erosive processes. Both model and prototype data confirmed that the river curvature is the most important parameter affecting the maximum scour depth occurring downstream of the structure. In addition, it was experimentally shown that the decrease of the curvature radius causes a 3D equilibrium scour morphology, whereas it tends to be similar to that occurring in a straight channel when R increases. The effect of the inflow conditions on the scour process contribute to slightly modify the equilibrium morphology, resulting in a different distribution of the sediment deposit areas in the stilling basin but it can be considered negligible in terms of maximum scour depth. An empirical relationship to estimate the maximum scour depth in a wide range of hydraulic conditions was derived and validated by using field data collected in the Porębianka river after a selected flood event. It was experimentally proven that the proposed relationship well predicts field data and it can be considered a valid and trustable tool to design this structure typology. This is the first study present in literature dealing with scour process analysis occurring downstream of block ramps located in river bends.

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LIST OF FIGURES

Figure 10. Comparison between measured (in prototype) and calculated (using Eq. 8) values of the parameter z_{msc}.

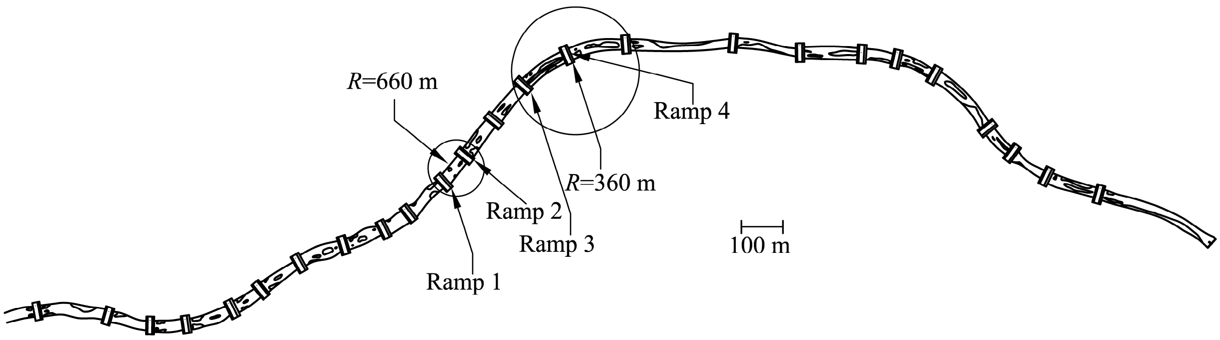


Figure 1. Scheme of the river and block ramps, with the indication of the modelled structures (in the circles).

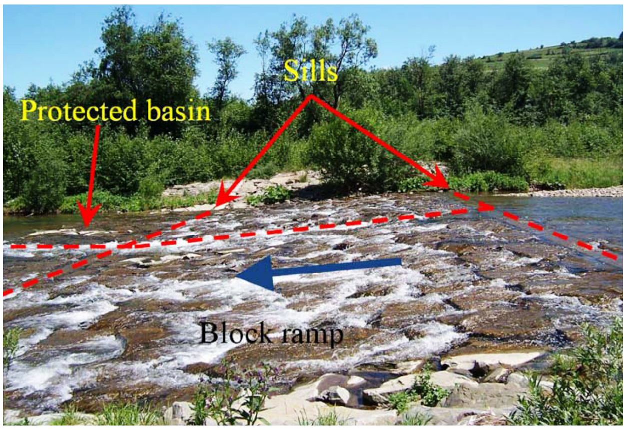


Figure 2. Picture illustrating a typical block ramp structure located in the Porębianka river.

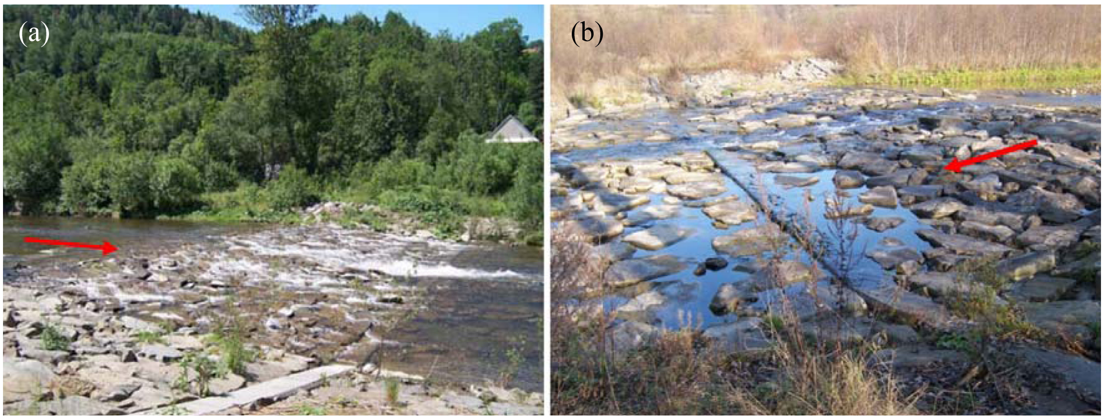


Figure 3. Block ramps under low water level conditions: **(a)** particular of the flow concentrated in the central part of the structure; **(b)** particular of the downstream protected stilling basin.

Figure 4. Picture of the experimental apparatus illustrating the modelled block ramp 4 (view from downstream).

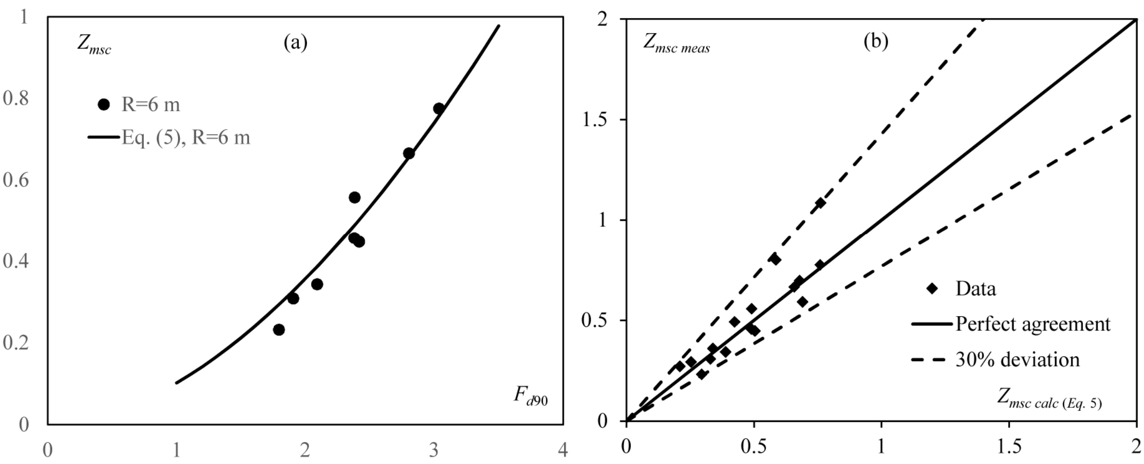


Figure 5. **(a)** Comparison of measured (in model) Z_{msc} values with Eq. (5) for R=6 m; **(b)** comparison between measured (in model) and calculated (using Eq.5) values of the parameter Z_{msc}.

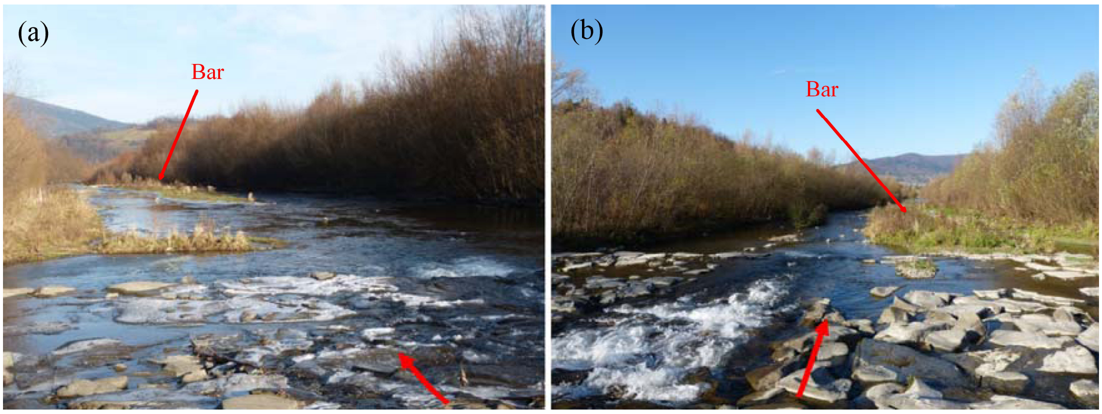


Figure 6. Bars formation downstream of two block ramps characterized by: **(a)** significant curvature both upstream and downstream of the structure and **(b)** mild curvature upstream and significant curvature downstream of the structure.

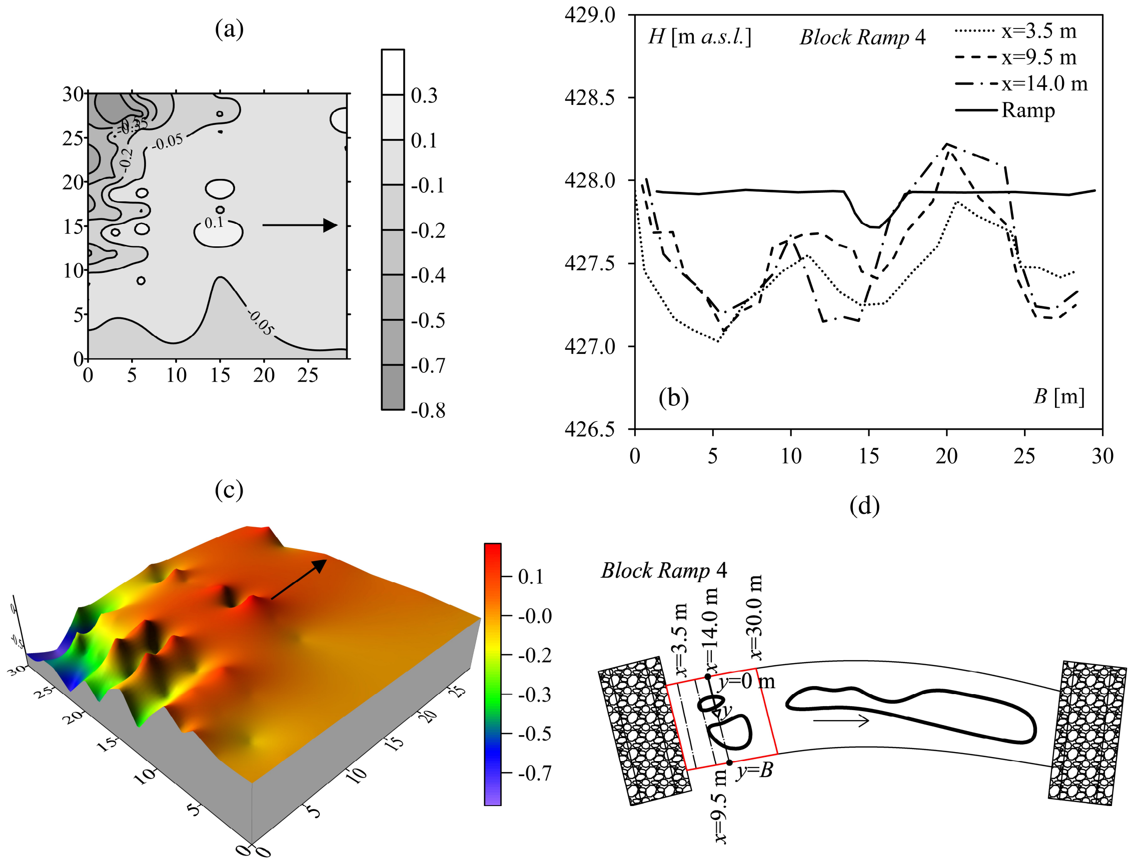


Figure 7. **(a)** Planar view and **(c)** 3D view of model equilibrium morphology (flow from left to right, see black arrow); **(b)** measured cross-sections at x=3.5, 9.5, 14 m from ramp toe; **(d)** planar view of sediment accumulations (bold lines) between the block ramps with the indication of the cross section locations (flow from left to right, see black arrow) along with the part of the stilling basin reported in **(a)** and **(c)**. All the dimensions are in m.

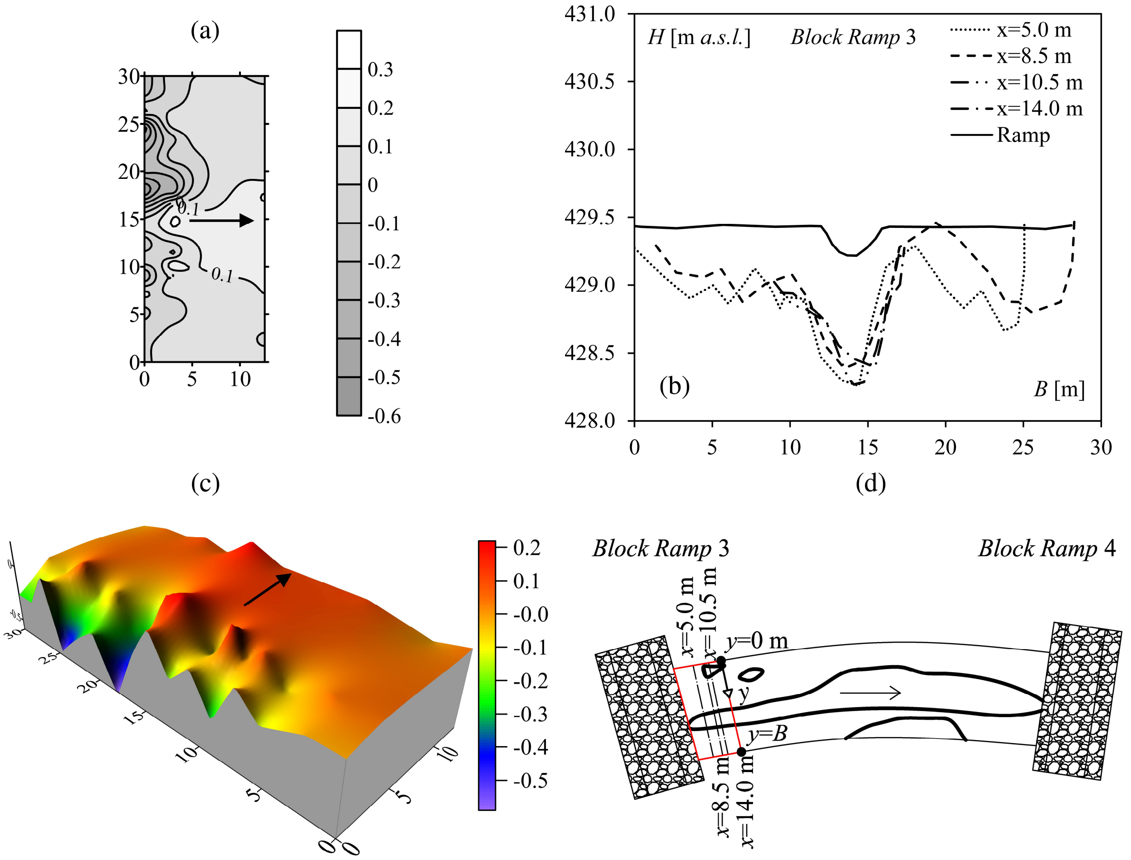


Figure 8. **(a)** Planar view and **(c)** 3D view of model equilibrium morphology (flow from left to right, see black arrow); **(b)** measured cross-sections at *x*=5, 8.5, 10.5, 14 m from ramp toe; **(d)** planar view of sediment accumulations (bold lines) between the block ramps with the indication of the cross section locations (flow from left to right, see black arrow) along with the part of the stilling basin reported in **(a)** and **(c)**. All the dimensions are in m.

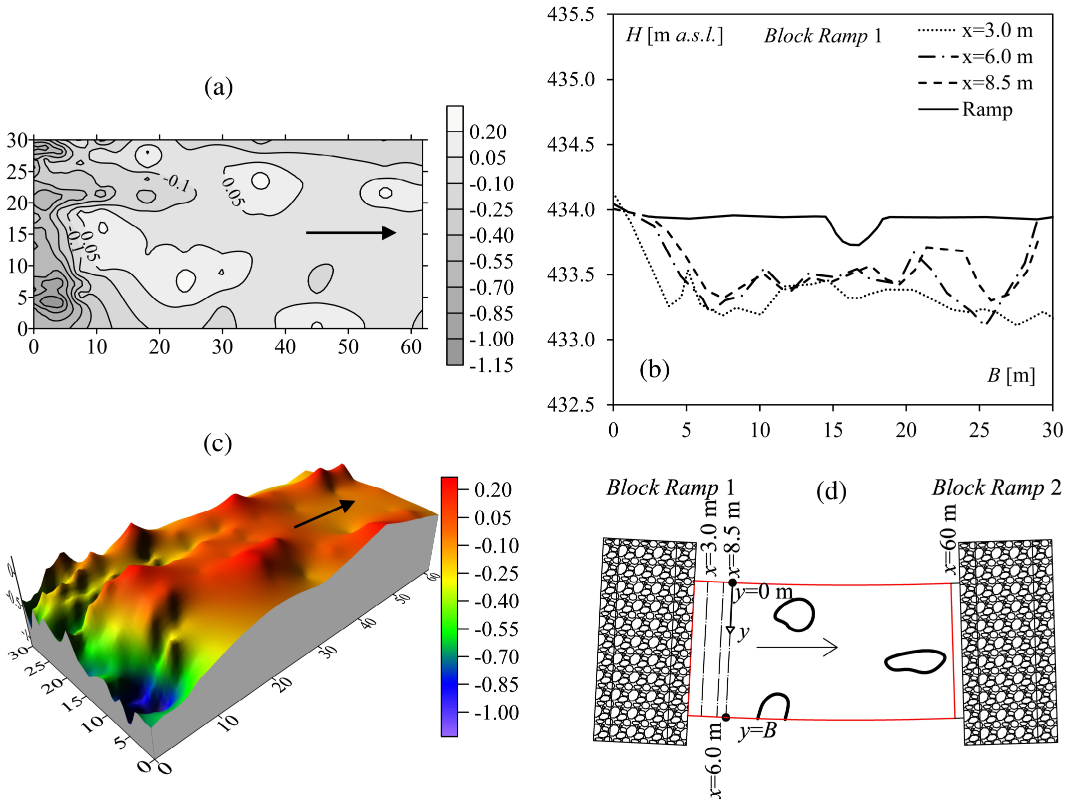
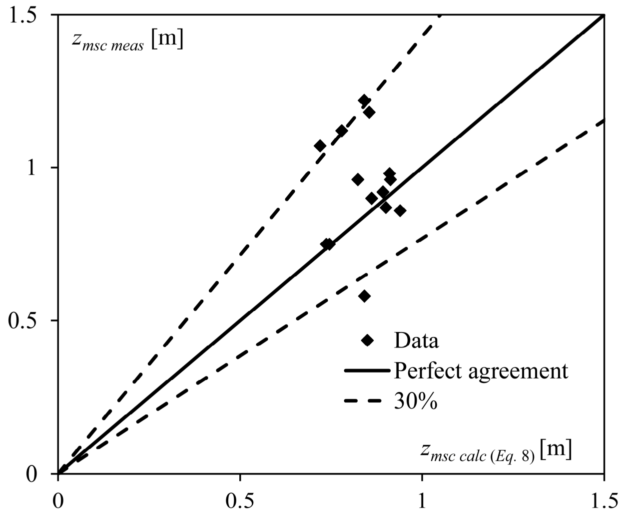


Figure 9. **(a)** Planar view and **(c)** 3D view of model equilibrium morphology (flow from left to right, see black arrow); **(b)** measured cross-sections at *x*=3, 6, 8.5 m from ramp toe; **(d)** planar view of sediment accumulations (bold lines) between the block ramps with the indication of the cross section locations (flow from left to right, see black arrow) along with the part of the stilling basin reported in **(a)** and **(c)**. All the dimensions are in m.



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