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Stefano Pagliara
University of Pisa

Artur Radecki-Pawlik
Cracow University of Technology, Poland, rmradeck@cyf-kr.edu.pl

Michele Palermo
University of Pisa, michele.palermo@ing.unipi.it

Karol Plesiński
Agricultural University of Cracow, kplesinski@ar.krakow.pl

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A Preliminary Study of Field Scour Morphology Downstream of Block Ramps Located at River Bends

S. Pagliara[1], A. Radecki-Pawlik[2], M. Palermo[1] & K. Plesiński[3]
[1]*DESTEC-Department of Energy, Systems, Territory and Construction Engineering, Pisa, Italy*
[2]*Institute of Structural Mechanics, Faculty of Civil Engineering, Cracow University of Technology, Krakow, Poland*
[3]*Department of Hydraulic Engineering and Geotechnics, University of Agriculture in Krakow, Krakow, Poland*
E-mail: michele.palermo@ing.unipi.it

Abstract: *Block ramps are usually located in natural rivers. In particular, the location of the structure in river bends contributes to deeply modifying both the upstream inflow conditions and the downstream erosive process. The scour mechanism is affected by the kinematic field asymmetry, resulting in a significant three-dimensionality of the scour features. Therefore, it appears fundamental to deepen the erosive process occurring in correspondence with such structures in order to provide insights on the physics of the phenomenon and improve existing design criteria. Based on both field measurements conducted in the Porębianka River and laboratory model results, this manuscript presents a preliminary analysis of the resulting equilibrium morphologies downstream of block ramps located in river bends by highlighting the effect of the main hydraulic and geometric parameters on the scour lengths as well as on sediment bar formation.*

Keywords: *Block ramps, field measurements, hydraulics, laboratory model, river curvature, scour morphology.*

1. Introduction

In modern river management, new eco-friendly solutions are needed. Among them, blocks have become very popular in the last decades. They are made of natural stones and are used to stabilize small creeks and streams, especially in mountain areas. Furthermore, they facilitate fish and invertebrate migration (Skalski et al., 2012), contributing to aerate water (Oertel, 2013; Oertel and Schlenkhoff, 2012; Pagliara and Palermo, 2013; Pagliara and Palermo, 2012; Pagliara et al., 2017; Radecki-Pawlik, 2013; Radecki-Pawlik et al., 2013). Block ramps present the additional advantage of being easily built. In particular, they can be built in succession, mimicking natural rapids in rivers. They are also known as rapid hydraulic structures (Radecki-Pawlik, 2013) and have been extensively investigated in recent years (Pagliara et al., 2017; Plesiński et al., 2015; Plesinski and Radecki-Pawlik, 2017). Many studies analyzed hydraulics of block ramps and downstream scour process in straight channels (among others, Oertel, 2013; Oertel and Bung, 2015; Oertel and Schlenkhoff, 2012; Pagliara and Palermo, 2013; Pagliara and Palermo, 2012; Radecki-Pawlik, 2013). Nevertheless, the location of the structure in river bends contributes to deeply modifying both the upstream inflow conditions and the downstream erosive mechanism (Bormann and Julien, 1991; Breusers and Raudkivi, 1991; D'Agostino and Ferro, 2004; Hoffmans and Verheij, 1997). Only recently, scour process downstream of block ramps have been analyzed in curved channels, and useful relationships were proposed to compute the maximum scour depth (Palermo and Pagliara, 2017). Therefore, there is still a lack of knowledge regarding the equilibrium morphology configuration and the effect of both hydraulic parameters and river curvature on the erosive process (Pagliara and Mahmoudi Kurdistani, 2014; Pagliara et al., 2015; Pagliara et al., 2016). Based on field measurements collected at the Porębianka River (Poland) after flood events, this paper aims to deepen the downstream scour hole characteristics and the erosive dynamics. In particular, both the effects of inflow conditions and river curvature are analysed in terms of resulting equilibrium morphology. The hydrodynamics of the scour process and the effects of the boundary conditions (geometric configuration of the river branches) on the resulting scour morphology are highlighted. Figure 1 reports examples of monitored block ramps in the Porębianka River.

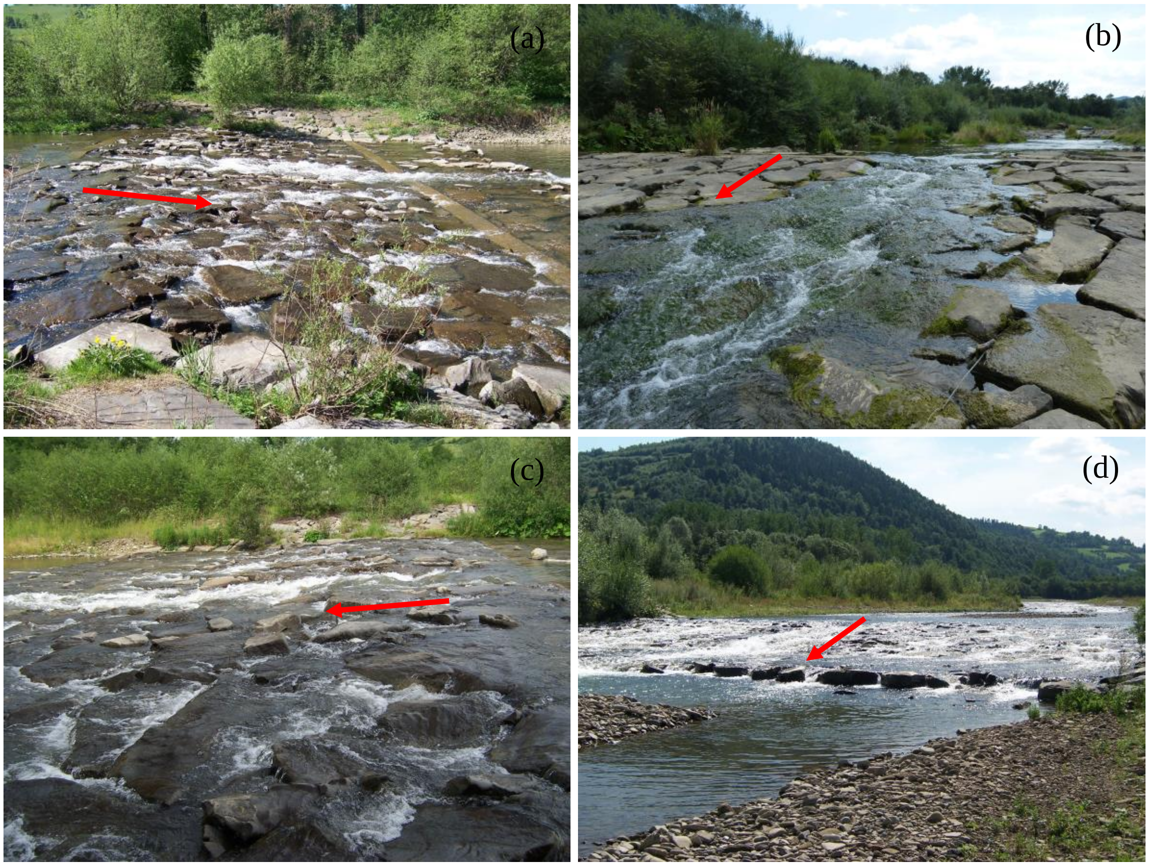

Figure 1. Example of samples of monitored block ramps (red arrows show flow direction)

2. Field Data Collection

The monitored field site is located in Polish Carpathians (Gorce Mountains), approximately 60 km south of Cracow. Figure 2 shows the catchment basin along with the Porębianka River and its tributaries. In particular, the monitored area is highlighted in a blue colour in Figure 2 and represents the end part of the Porębianka River. The monitored river branch is shown in Figure 3, along with the location of the 25 block ramps. It is characterized by flysch rocks. FlAsh floods generally occur during spring, when snow melts, and in July during summer rains. The Porębianka River is 15.4 km long and the average river bed slope is $S = 0.01$. The Porębianka River is a right bank tributary of the Mszanka River. The Mszanka is a tributary of the Raba and, finally, the Raba is a tributary of the Vistula (the main river in Poland). A succession of block ramps is present in the river to control sediment transport and stabilize river bed. Both the head and the toe of block ramps are stabilized using two rows of steel piles, topped by a reinforced concrete cap. Ramp bed slope is $i = 0.083$. The stilling basin is protected by using rocks. The protection layer is characterized by the following dimensions: 5 m long and 1.2 m thick. Block ramp beds are shaped in such a way that, in their central part, a sort of channel is built, whose average bed level is 0.2 m lower than that of the ramp. The ramp bed channelization allows for fish migration during the periods of low discharge, when the water levels are particularly low. Furthermore, monitored block ramps are characterized by uniform bed material, and their length is approximately 12 m. The average diameter of rocks constituting bed ramps ranges between 0.9 m and 1.2 m. In addition, block ramps are located in succession along the monitored river branch, and their longitudinal distance varies between from 60 to 250 m. Several flood events occurred in the Porębianka River. But, the most significant flood event occurred in May 2010. In correspondence with this event, the estimated discharge was $Q \approx 60\ \mathrm{m}^3/\mathrm{s}$, causing a relevant variation of the bed morphology. Therefore, it was reasonable to assume that bed morphology variations were essentially due to the event that occurred in May 2010. A systematic field measurement campaign was carried on. In particular, measurements of water velocities (taken up to 0.25 cm above the river bed) were carried out using a Valeport Model 801 Electromagnetic Open Channel Flow Meter. The flow sensor is designed for the portable measurement of very low flow velocities (from 0.001 m/s to 2.5 m/s). Samples of bottom substrate were collected for grain size analyses, revealing that the river bed material average diameter d_{50} ranges between 40 mm and 65 mm. The inflow conditions were measured by a hydrometric station (Niedzwiedz), located close to Sec. B in Figure 2.

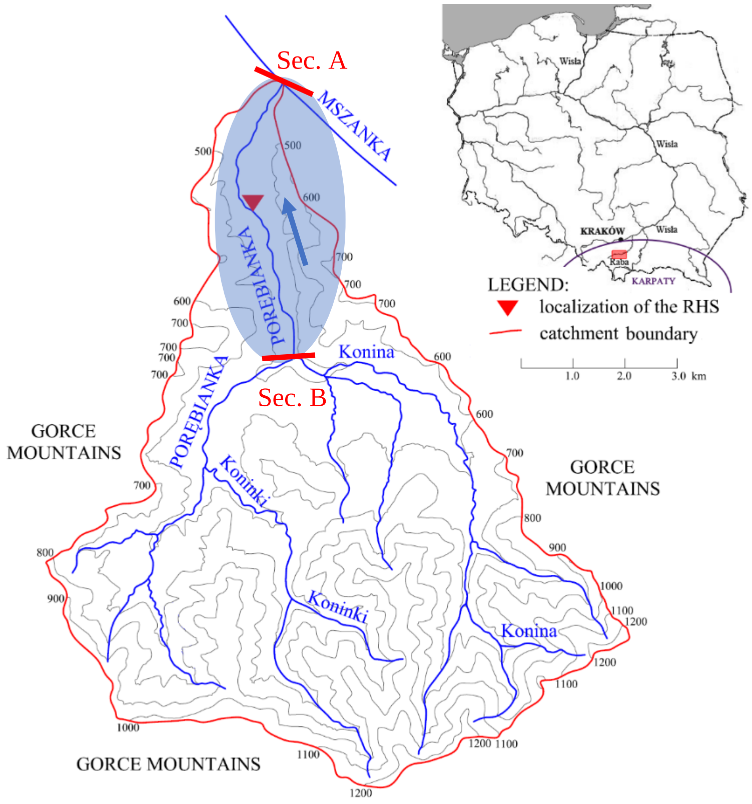

Figure 2. Location of the study area (from Sec. A to Sec. B)

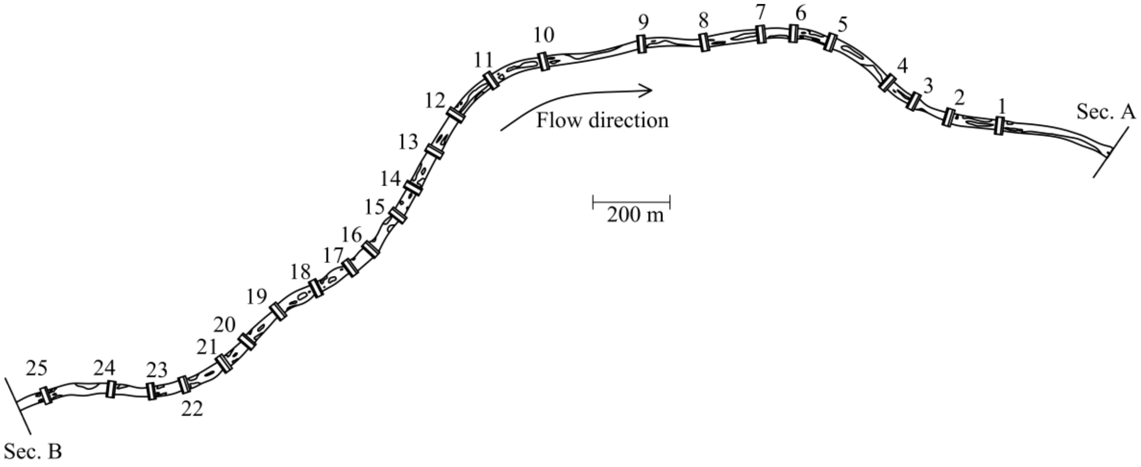

Figure 3. Monitored Porębianka river branch, along with the indication of block ramp locations

3. Results and Discussion

Scour morphologies have been carefully analyzed. Namely, the main aim of the paper is to understand the effects of a) upstream river configuration, b) downstream river configuration, and c) location of the block ramp on the equilibrium morphology in the downstream stilling basin. In this perspective, four examples of bed morphologies are discussed in the following. In particular, the analysis is conducted in details for the stilling basins downstream of block ramps 2, 6, 8, and 19. The choice of the mentioned block ramps essentially allows for the exploration of most of the possible inflow conditions, as well as the effects of river geometry on the downstream stilling basins. In fact, block ramp 2 is located within a river branch characterized by significant upstream and downstream curvatures. Conversely, block ramp 6 is located between a substantially straight upstream and significantly curved downstream river branches. The curvature of the downstream river bend is similar to that characterizing the stilling basin downstream of block ramp 2. Block ramp 8 is located between two bends characterized by very mild curvatures. Finally, block ramp 19 is preceded by a substantially straight and followed by a very mild curved river branch. Pagliara et al. (2017) conducted experimental tests in a laboratory channel, simulating a succession of a mild sloped block ramps located in different curved channel bends. Namely, they tested three different curvatures, i.e., R = 6 m, 11 m, and infinity (straight channel). They extended the empirical relationships proposed by Pagliara and Palermo (2008a) and Pagliara and Palermo (2008b), including the effect of the river curvature on a protected stilling basin. In other words, based on previous findings, Pagliara et al. (2017) showed that the non-dimensional scour depth downstream of block ramps in curved channels $Z_{msc} = z_{msc}/h_1$ can be estimated by the following equation:

$$Z_{msc} = Z_m \times (-0.8\lambda + 1.07) \times \left(-0.1Z_{op} + 1.05\right) \times (1 + B/R)^{2.82} \tag{1}$$

where

$$Z_m = 0.58 \times i^{0.75} \times {F_{d90}}^{1.8} \tag{2}$$

h_1 is the flow depth at the ramp toe, $Z_m = z_m/h_1$ is the non-dimensional scour depth in a straight channel and in the absence of any protection in the stilling basin, B is the channel width, R is the channel curvature, and λ and Z_{op} are the non-dimensional longitudinal and vertical positions of the stilling basin protection. Note that $F_{d90} = V_1/(g'd_{90})^{0.5}$ 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 particular, according to Pagliara and Palermo (2008a) and (2008b), Eq. (1) can be re-written as follows, for the stilling basin configuration characterizing the Porębianka river (i.e., presence of stilling basin protections (rocks) located downstream of the ramp at the same vertical level of the ramp toe):

$$Z_{msc} = 0.912 \times Z_m \times (1 + B/R)^{2.82} \tag{3}$$

The analysis of the previous equation allows to establish that the maximum scour depth z_{msc} is deeply influenced by the river curvature, whereas it does not contain any variable accounting for both upstream and downstream flow conditions. In fact, experimental tests conducted by Pagliara et al. (2017) showed that the maximum scour depth decreases with R, whereas it is not significantly influenced by both inflow and outflow characteristics. In particular, the presence of an upstream river bend causes an asymmetric distribution of flow velocities upstream of the block ramps. Nevertheless, the mentioned asymmetry does not significantly affect the maximum scour depth if compared to the that occurring for straight upstream branch. In this paper, preliminary evidences shown by Pagliara et al. (2017) are analyzed by using field measurements. In particular, both the hydrodynamics of the scour process and the effect of river curvature are analyzed by considering four selected block ramps. Figure 4 reports the transversal cross sections measured after the flood event in downstream stilling basins. Namely, in Figure 4, x and y represent the longitudinal and vertical coordinates, respectively, i.e., x = 0 m at the ramp toe and y = 0 m at the hydraulic left bank of the cross-section. H is the bed morphology level above the see level (in meter). As shown in Figure 2, block ramp 2 is both preceded and followed by two significantly curved river bends. Therefore, the upstream kinematic field is characterized by a significant asymmetry, as well as the downstream one. The mentioned upstream asymmetry results in a significant three-dimensionality of the equilibrium scour morphology is shown in both Figure 4a and Figure 5a. In particular, the maximum scour depth is located close to the right bank (i.e., outer bank), where the flow acceleration is more prominent. In addition, the effect of the downstream curvature further contributes to reduce flow velocities in correspondence with the inner river bank in the stilling basin. This occurrence causes a sediment deposition in the stilling basin, mostly located at the left side of the river. A close observation of Figure 4a reveals that, for $x > 7$ m, the equilibrium bed morphology is characterized by H values bigger than those occurring at the ramp toe. In other words, if a ramp is both preceded and followed by river bends, the maximum scour depth occurs close to the outer river bank and bar formation takes place, resulting in a preferential flow path. Conversely, if a block ramp is preceded by a (quasi-) straight river branch but followed by a river bend (block ramp 6), the inflow kinematic field is characterized by a general symmetry. Nevertheless, the effect of the downstream curvature modifies the downstream flow conditions, resulting in an acceleration of the flow close to the outer river bend (hydraulic right bank for block ramp 6). The comparisons between Figures 4a and 4b, and Figures 5a and 5b, respectively, show that the effect of the downstream curvature is significant, resulting in a prominent equilibrium morphology asymmetry. Namely, the maximum scour depth downstream of the block ramp 6 also occurs in correspondence with the outer river bank. Nevertheless, bar formation occurs further downstream and is located closer to the center of the stilling basin. This main difference is due to the absence of inflow asymmetry, i.e., less reduction of the velocity field in correspondence with the inner river bank. But it is worth noting that the two configurations are similar in terms of maximum scour depth. It means that the maximum (local) scour depth is essentially influenced by the downstream configuration, and the effect of the inflow characteristics is negligible. This occurrence is reflected in Eq. (3) proposed by Pagliara et al. (2017). The same behavior can be detected during the scour evolution process, which essentially consists in a homothetic enlargement of both scour hole and ridge/bar shape. Finally, the scour process downstream of block ramps appears similar to that characterizing other low-head structures, which was extensively described and discussed by Palermo and Pagliara (2017).

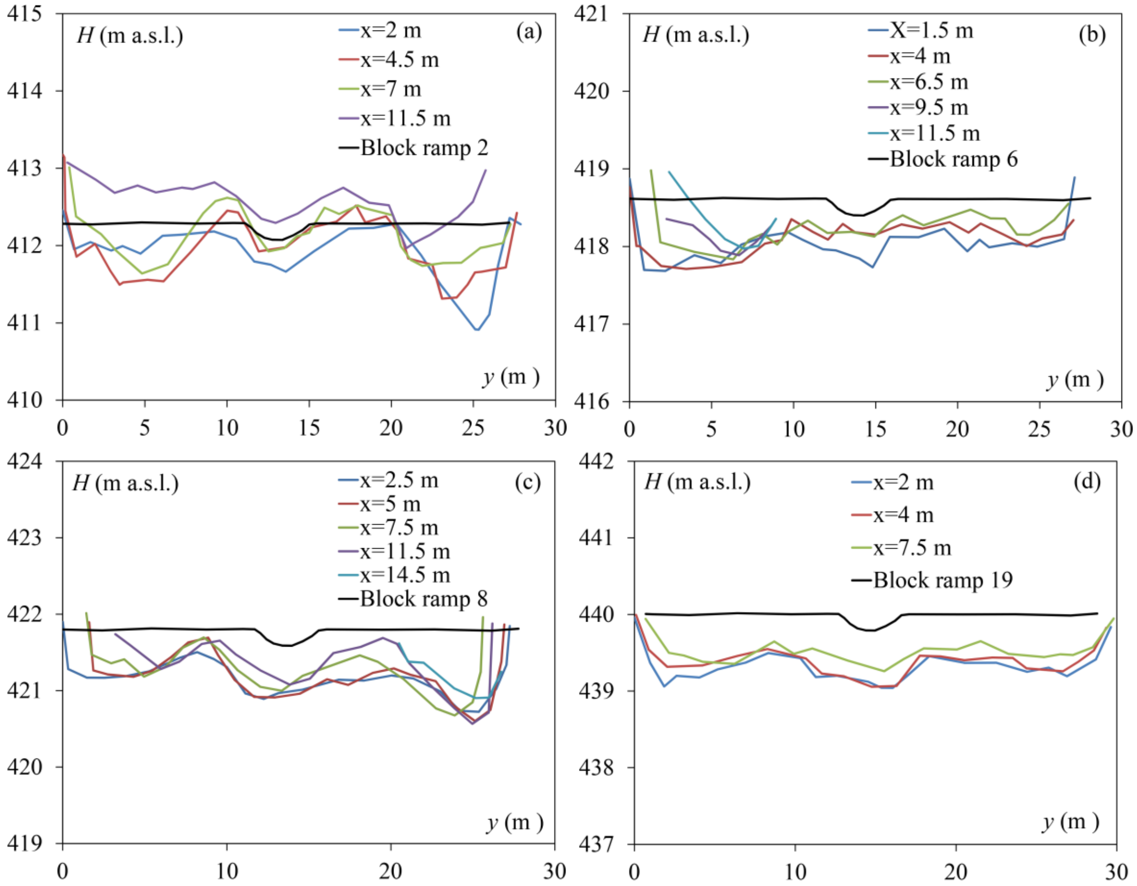

Figure 4. Equilibrium cross sections of block ramps (a) 2, (b) 6, (c) 8, and (d) 19

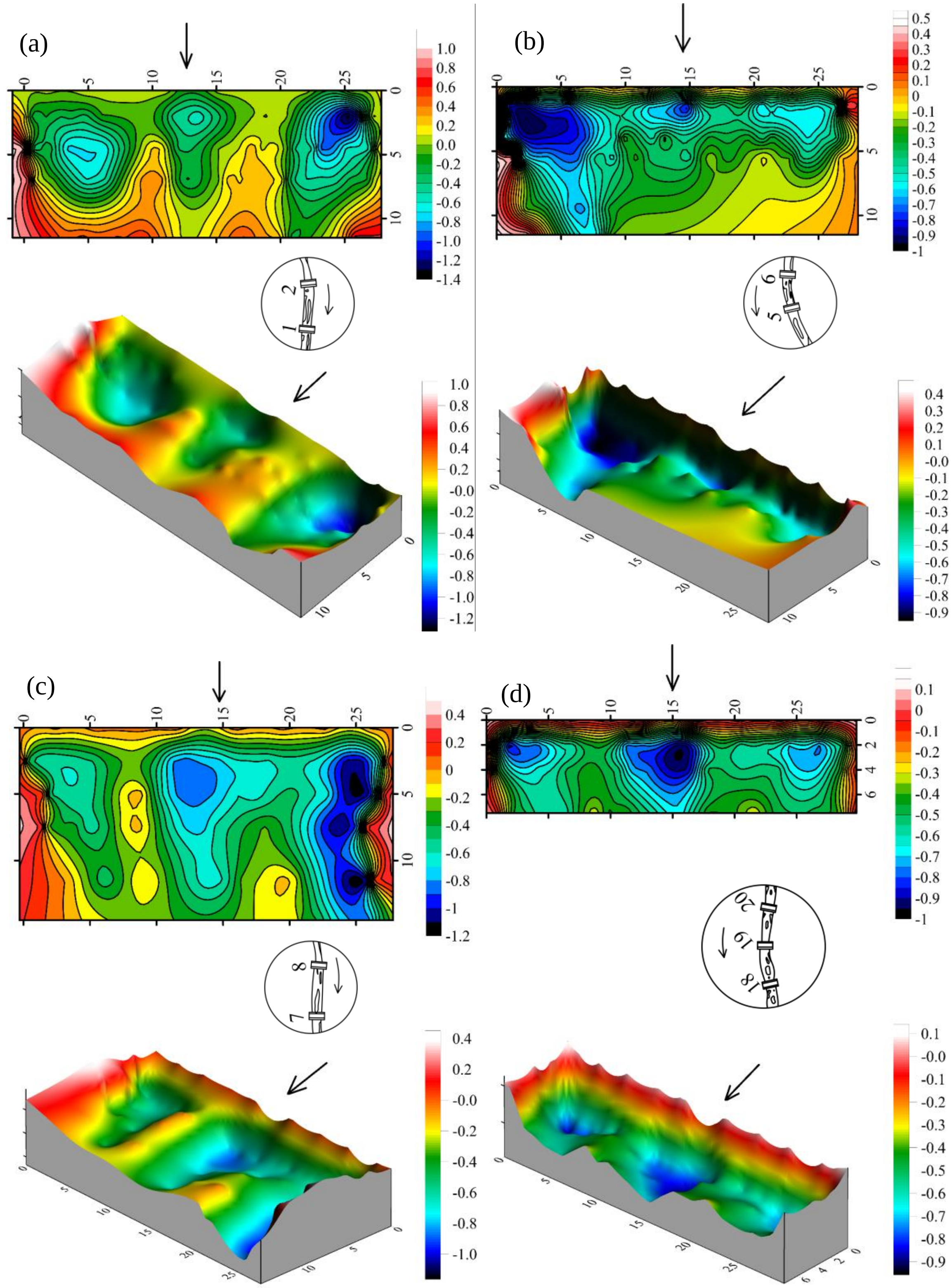

Figure 5. 2D and 3D equilibrium morphologies downstream of block ramps (a) 2, (b) 6, (c) 8, and (d) 19 (lengths in meter)

The analysis was extended to the stilling basin equilibrium morphology downstream of block ramps 8 and 19. In particular, block ramp 8 is preceded and followed by very mild curved river bends characterized by an opposite curvature. Therefore, it should be expected that the downstream curvature should have a more prominent effect than the upstream one on the resulting morphology. In fact, also in this case (see Figures 4c and 5c), the maximum scour depth occurs closer to the downstream outer river bend (hydraulic right bank). This is a further confirmation of the fact that upstream inflow conditions slightly influence the erosive dynamics. Finally, block ramp 19 is located in an almost straight river branch. This means that a substantial symmetry of the kinematic field should be expected both upstream and downstream of it. By observing Figures 4d and 5d, it is easy to note that the equilibrium scour morphology is essentially 2D. The maximum scour depth at the center of the stilling basin is essentially due to the presence of the central channel on the ramp. Based on previous observations, the role of the river curvature downstream of the stilling basin is evident. Namely, the three-dimensionality of the equilibrium morphology essentially depends on the downstream river curvature. Furthermore, upstream inflow characteristics do not significantly affect neither the maximum scour depth nor its location. But they influence bar formation, which can occur either close to the ramp toe or further downstream. Further experimental tests are going on to understand the effect of block ramp geometry and stilling basin protection location.

4. Conclusions

In the present manuscript, an analysis of equilibrium morphology downstream of block ramps was conducted in order to understand the effects of both river curvature and inflow characteristics on the scour process. Accurate field measurements were conducted in correspondence with 25 block ramps located in the Porębianka River (Poland). Field data were compared to experimental evidences obtained by the same authors in a laboratory flume. It was observed that:

1) the downstream equilibrium morphology does not depend on the upstream river curvature and inflow conditions;
2) the three-dimensionality of the scour is essentially due to the downstream river curvature, resulting in a more prominent asymmetry by reducing the curvature of the river bend;
3) the maximum scour depth and its location mainly depends on the downstream geometric configuration of the stilling basin, as well as on the downstream tailwater level, i.e., lower downstream water level results in a maximum scour depth located close to the ramp toe; and
4) the sediment deposition dynamics is influenced by the downstream curvature, which reduces flow velocities in correspondence with the inner river bank. Similarly, the downstream water level influences bar longitudinal extension, i.e., it decreases with tailwater.

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