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Scour due to rock sills in straight and curved horizontal channels

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Abstract

Scour characteristics and morphologies downstream of rock sills due to channel curvature have been analyzed at the hydraulic laboratory of the University of Pisa. Two series of experiments have been conducted. The first series included tests on scour downstream of rock sills in straight channel. Three different channel bends with different lengths were studied in the second test series. All experiments have been carried out in clear water condition. The results showed that the tailwater depth plays an important role on scour characteristics. In addition, it was experimentally proven that the stream curvature affects the morphology and the maximum scour depth, i.e., an increase of the bend radius causes a decrease in the value of the maximum scour depth. Finally, three scour morphology types have been distinguished. Useful empirical relationships have been proposed in order to evaluate the main features of the scour geometry.

Keywords: Grade-control structures; Hydraulic structures; River restoration; Rock sill; Scour

1. Introduction

The variation of flow conditions due to river bends or meanders can lead to riverbanks and structures failure, such as bridges, river passing pipelines, diversion dams, water intakes, and invert siphons. In-stream grade-control structures are used to stabilize riverbed, riverbanks, and improving aquatic habitat. Rock sills are in-stream structures commonly adopted to control stilling basins erosion and to protect river crossing structures.

Local scour processes and mechanisms are fundamental topics for river engineers. Among others, Schoklitsch (1932), Veronese (1937), Hassan and Narayanan (1985), Farhoudi and Smith (1985), Mason and Arumugam (1985), Bormann and Julien (1991), Whittaker and Jaggi (1996), Robinson et al. (1998), Dey and Sarkar (2006a, 2006b, 2008) gave important contributions on jet scour prediction and analysis.

Nevertheless, few experimental contributions, focused on grade-control structures, can be found in the literature. Przedwojski (1995) studied local scour process in rivers with banks protected by groynes. He showed that the depth of local scour varies with the groyne location. The maximum depth of local scour occurs at the groyne located downstream of the bend apex and it is significantly greater than the case of groynes installed at the entrance and the exit of the outer bank. Pagliara and Palermo (2008) and Pagliara et al. (2009) studied scour morphology downstream of block ramps, including the effect of protection sills in the stilling basin for different bed materials. Roca et al. (2007, 2009) showed that a well-designed horizontal foundation of the outer river bend, called footing, could protect vertical outer banks against erosion and at the same time reduce the scour depth. Bhuiyan et al. (2007) studied the flow turbulence characteristics and the scour development downstream of W-weir at river bends in clear-water and live-bed conditions. Bhuiyan et al. (2010) carried out an experimental study on bank-attached vanes for bank erosion control and river meanders restoration. They showed that multiple vanes angled at 30° to the bank line effectively relocate the deeper channel away from the outer bank in a bend.

Scurlock et al. (2012a) carried out experiments on the vane-dike in channel bends and derived a series of equations to estimate maximum flow velocities. Scurlock et al. (2012b) conducted an experimental study on scour downstream of in-stream structures designed by Rosgen (2001), like Cross-Vane structures and W-weirs in straight channels to estimate the maximum scour depth. Pagliara and Kurdistani (2013) carried out an experimental study on scour downstream of Cross-Vane structures for different bed slopes in straight channel and

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proposed equations to estimate the main scour parameters. Pagliara et al. (2013) studied the scour phenomenon downstream of J-Hook vane in straight rivers distinguishing three types of scour. Pagliara et al. (2014) conducted a series of experiments on scour downstream of W-weirs. They found that the tailwater depth plays an important role to predict the scour parameters. They carried out some tests with open W-weir and showed that the maximum scour depth decreases and its location shifts downstream respect to the case of classical W-weir.

Jamieson et al. (2013a) studied the effects of stream barbs (spur dikes or submerged groynes) to redirect the high velocity core from the outer bank and prevent erosion of the flood plain at the bend exit. They demonstrated that the outer bank between barbs may still be at risk of erosion or even increase erosion as their size and layout generates excessive secondary velocities that are opposing the primary secondary flow naturally occurring in channel bends. Jamieson et al. (2013b) expanded their study on turbulence and vorticity in a channel bend at equilibrium clear-water scour in the presence and absence of stream barbs and they showed that local scour near the barbs was associated with increased z-vorticity. Recently Guan et al. (2014) conducted a series of experiments to investigate the flow patterns and turbulence in a scour hole downstream of a submerged weir. They showed that the turbulence structures ahead of the recirculation zone govern the dimensions of the scour hole.

The main objective of this contribution is to study the effect of the meander radius on the scour characteristics downstream of rock sills.

2. Experimental facilities

All the experiments were conducted in two channel setups made at the Hydraulic Laboratory of the University of Pisa. Channel setup I was used to study the scour parameters downstream of rock sills in straight channels and channel setup II was used to study the scour phenomena downstream of rock sills in curved channels. The experimental channel setup I included a horizontal rectangular channel 0.80 m wide, 20 m long and 0.75 m high. A tank supplied the approaching stable inflow. A standard weir measured the discharge with a precision of ±0.1 l/s. The water surface profiles and the morphology of the mobile bed have been surveyed using an ultrasonic distance measuring sensor with a precision of 0.001 m.

The experimental setup II consisted in a curved channel 0.5 m wide, 15 m long and 0.5 m high (see Fig. 1). Three bends with different radii (R = 1, 2 and 4 m) formed the channel. The curved parts of the model are separated by straight channels 2 m long in which grids are installed to straighten the approaching flow to the successive curve. Glass windows on the side walls enable to see the flow properties. An overhead tank supplied stable inflow. A magnetic current meter measured the discharge with precision of ±0.01 l/s. The water surface profiles were measured using a point gauge of reading accuracy of ±0.0001 m. At the end of each test, the bed morphology was surveyed using a Laser Scanner “HDS-4500 (Leica Geosystems)” with precision of ±0.001 m. Fig. 2a–c shows the plan view of the straight and curved channels along with a stream wise view of the channel, including the main hydraulic and geometric parameters for Setup II (Fig. 2a) and Setup I (Fig. 2b), where B is the channel width, y_0 is the approach flow depth, Δy is the difference between water surface upstream and downstream of the structure, z_m is the maximum depth of the scour hole, l_m is the length of the scour hole in the longitudinal section in which the maximum scour depth occurs, z'_m is the maximum height of the ridge, l'_m is the ridge length in the

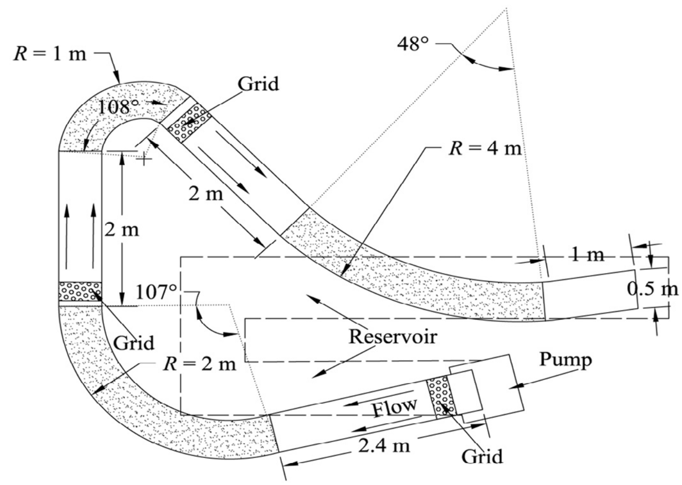

Fig. 1. Diagram sketch of the channel setup II.

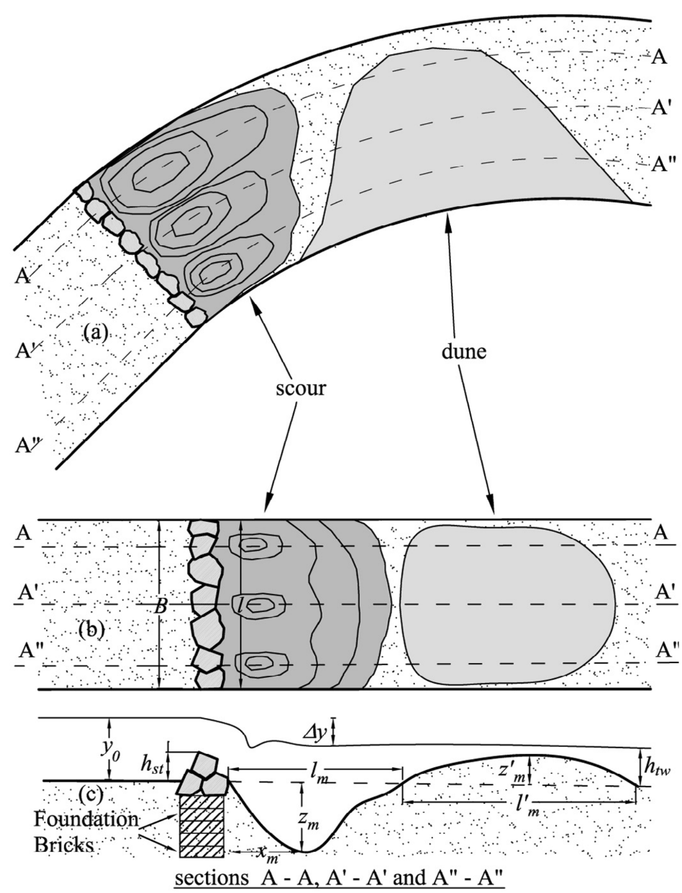

Fig. 2. Plan view of (a) channel setup II and (b) channel setup I; (c) stream wise view of the scour and dune morphology.