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Research paper

Scour downstream of cross-vane structures

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Abstract

Cross-Vanes are hydraulic structures used to stabilize the riverbed and control the grade for river restoration. Scour downstream of Cross-Vane structures depends on the shape of the structure, the bed material and the river hydraulic conditions. This paper aims to predict the maximum scour depth and classify the scour morphology. Two series of experiments were carried out. In the first series, two types of structures, which are I-shape and U-shape structures have been studied in a horizontal channel. In the second series of experiments, riverbed slopes of 1%, 2.5% and 5% were tested. For each type of structure, three heights in different hydraulic conditions including densimetric Froude numbers and drop heights were tested. Results show, that the ratio between the length of the structure and the channel width is one of the most important non-dimensional parameter to classify the scour. New analytical functions have been derived from dimensional analysis to predict the maximum scour depth, the maximum length of the scour, location of the maximum scour depth and the maximum development of the scour width. All the experiments were conducted in clear water conditions. Based on dimensional analysis and using all collected data new equations have been obtained. Scour morphology downstream of Cross-Vane structure was classified in different scour patterns based on different flow hydraulic conditions, structures geometries and the ratio between the maximum length of the scour and the channel width.

Keywords: Cross-vane; Hydraulic structures; Grade-control structures; River restoration; Scour

1. Introduction

River restoration is an environmental and ecological aspect of river engineering that includes managing and restoring rivers to provide sustained hydro-environmental conditions for water resources. One of the most important topics in river restoration is the river grade control. Few experimental studies on grade-control structures are presented in literature. Bormann and Julien (1991) conducted a series of experiments including 231 scour depth measurements. They used steel plate for making the grade-control structure and downstream face of the structure was formed in different slopes, vertical, 1:1 (V:H) and 1:3 (V:H). They used the scour depth equation form proposed by Mason and Arumugan (1985) and showed that large-scale experiments extend the range of available local scour data including vertical jets, wall jets, free over-fall jets, submerged jets and flow over grade-control structures. Shields et al. (1995) arranged a field measurement study on 1 km long reach of Goodwin Creek stream in north-west Mississippi. They investigated the effects of stone grade-control structures that were constructed for fish migration. D'Agostino and Ferro (2004), based on dimensional analysis and experimental data found a unique parameter that can estimate approximately the maximum scour depth. This unique parameter was the ratio of the total head over the structure by the drop height. Ben Meftah and Mossa (2006) studied the effects of bed sills on scour geometry and found that the maximum scour depth and the length of the scour depend on the distance between sills. They presented two simplified formulas to estimate the maximum scour depth and the length of the scour hole. Pagliara (2007) carried out a series of tests on scour downstream of block ramps in clear water and free hydraulic jump in mobile bed

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condition. He found that both the scour depth and length are function of ramp slope, densimetric Froude number and sediment non-uniformity parameter and derived simple equations to predict the scour depth and length. Pagliara and Palermo (2008) used different types of sills to control the scour downstream of block ramps. Continuous sill, dentate sill and rock sill were types of protection which were studied. They developed equations to estimate the main geometrical parameters of the scour hole such as the scour depth, the scour length and the ridge height in the presence of a rock sill. Bhuiyan et al. (2007) studied the scour development downstream of W-weirs. Scurlock et al. (2011) developed one-dimensional model to predict Energy dissipation in U-Weir grade-control structures. Scurlock et al. (2012a,b) focused on maximum velocity effects from Vane-Dike installations in channel bends and found a series of equations which represent maximum changes in flow velocities at the outer-bank, inner-bank, and centerline locations within a channel bend from the installation of vane-dike fields. The last contribution on scour downstream grade-control structures was conducted by Scurlock et al. (2012a,b). They carried out a series of 27 experiments to evaluate the main scour geometry parameters downstream of three different types of grade-control structures A, U and W. They found three different equations to estimate the scour depth for each type of structures.

This study aims to experimentally analyze the scour formation downstream of two different types of Cross-Vane structures (Rosgen, 2001). I-shape and U-shape structures with different values of the ratio between the length of the structure (l) and the channel width (B) are analyzed. The scour holes were classified using the main scour geometry parameters.

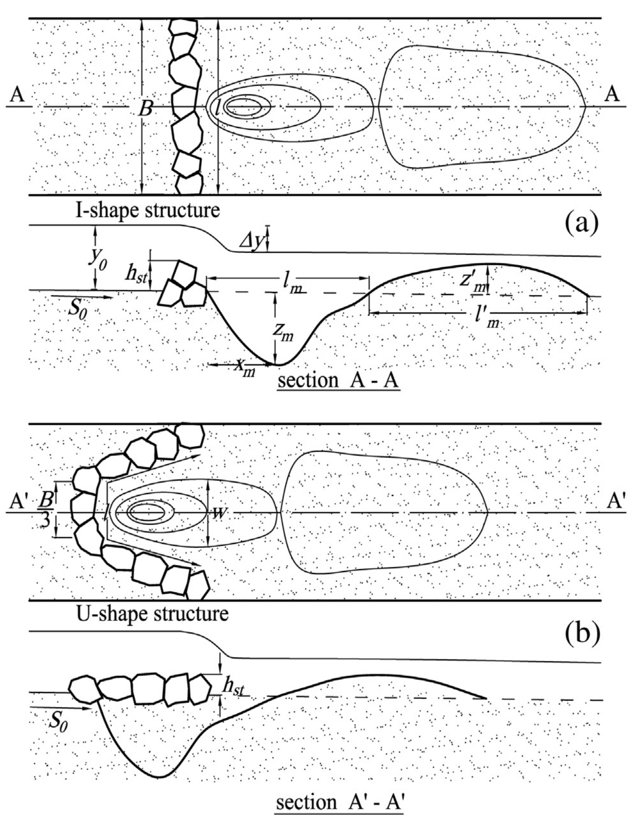

Fig. 1. Plan and stream wise view of the channel with the main parameters of flow and scour for (a) I-shape structure; (b) U-shape structure.

2. Experimental setup

The experimental setup included a horizontal rectangular channel 0.342 m wide, 7.00 m long and 0.63 m high. An overhead tank (1.00 m deep and of surface area 1.00 m × 1.00 m) supplied stable inflow. A magnetic current meter measured the discharge in precision of ±0.010 l/s. The water surface profiles were measured using a point gauge of reading accuracy of ±0.1 mm. Fig. 1 shows the plan and stream wise view of the channel with the main parameters of the flow and the scour for (a) I-shape structure; (b) U-shape structure, where B is the channel width, y_0 is the approach flow depth, h_{st} is the height of the structure (defined as the average height of the stones top), Δy is the difference between water surface upstream and downstream of the structure, z_m is the maximum depth of scour, l_m is the scour length, z'_m is the maximum height of the ridge, l'_m is the ridge length, l is the length of the structure, x_m is the location of the maximum scour, w is the maximum development of the scour hole width and S_0 is the channel bed slope. The test ranges are shown in Table 1. The densimetric particle Froude number is $F_d = Q/\{l \cdot h_{st}[g(G_s - 1)d_{50}]^{0.5}\}$ where Q is the flow discharge, $G_s = \rho_s/\rho$, in which ρ_s = bed material density and ρ = water density, d_{50} is the mean particle diameter and g = gravitational acceleration. One uniform plastic material was used for channel whose $G_s = 1.29$ and $d_{50} = 3.52$ mm which has practically the same non-dimensional Shields parameter of sand with $G_s = 2.44$ and $d_{50} = 1$ mm (Pagliara and Carnaciana, 2011). At the beginning of each experiment, the channel bed was carefully leveled. Two series of experiments were carried out. The first series included tests on I-Shape structure with $l/B = 1$ and U-Shape structure with $l/B = 1.7$ and 2.3 for different values of the structure height, discharge and Δy in horizontal channel bed. The second series of experiments included I-Shape structure with $l/B = 1$ in a channel with $S_0 = 5\%$ And U-Shape structure with $l/B = 2.3$ in a channel with $S_0 = 1$, 2.5 and 5%.

3. Results and discussion

The main parameters to determine the maximum scour depth are:

$$f(z_m, h_{st}, l, B, \Delta y, Q, \rho_s, \rho, g, d_{50}, S_0) = 0 \quad (1)$$

In which f = functional symbol.

Based on dimensional analysis and incomplete self-similarity (Barenblatt, 1987) Eq. (1) can be shown in a power-law expression as follow:

$$z_m/h_{st} = aS_0^b(l/B)^c \Phi(F_d, \Delta y/h_{st}) \quad (2)$$

Where a, b, c are constants to be experimentally obtained and Φ = functional symbol. The numerical form of Eq. (2) can