Ecological Engineering 83 (2015) 386–393

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Clear water scour at J-Hook Vanes in channel bends for stream restorations

Stefano Pagliara*, Sahameddin Mahmoudi Kurdistani

Department of Energy Engineering Systems, Land and Construction, University of Pisa, Via Gabba 22, Pisa 56122, Italy

ARTICLE INFO

Article history:
Received 10 March 2015
Received in revised form 15 June 2015
Accepted 4 July 2015
Available online 25 July 2015

Keywords:
Ecological engineering
Stream restoration
Eco-friendly instream-structures
Hydraulic structures
Grade-control structures
J-Hook Vane
Scour

ABSTRACT

J-Hook Vanes are in-stream river grade-control structures to reduce stress along the outside of the river bends and to promote scour in the pools and improving the aquatic habitat. The main purpose of this study is to investigate the effect of the channel curvature on the scour hole characteristics and morphologies downstream of J-Hook structures. The main scour geometry parameters have been analyzed at the hydraulic laboratory of the University of Pisa. Three different channel bends were studied. All experiments have been carried out in clear water conditions. Scour morphologies were surveyed using 3D laser technology. The results showed that an increase of the bend radius causes a decrease in the value of the maximum scour depth. The observations showed that the channel curvature is an important parameter to classify the scour morphology and directly affects the position of the maximum scour depth. Finally, different scour morphology types downstream of J-Hook Vanes are formed.

1. Introduction

River bends change the flow velocity direction towards the outer river bends, causing bank erosion and structures failure, such as bridges, river passing pipelines, diversion dams, water intakes, and invert siphons. J-Hook Vanes as In-stream grade control structures are used to stabilize riverbed, riverbanks, and improving aquatic habitat at the river bends.

During last decades, river engineers have done many contributions on local scour processes and mechanisms. Among others, (Schoklitsch, 1932; Veronese, 1937; Hassan and Narayanan, 1985; Farhoudi and Smith, 1985; Mason and Arumugam, 1985; Bormann and Julian, 1991; Whittaker and Jaggi, 1996; Robinson et al., 1998; Dey and Sarkar, 2006a,b, 2008) gave important contributions on local scour prediction and analysis.

Few experimental contributions, focused on grade-control structures, can be found in the literature. Przedwojski (1995) showed that the depth of local scour varies with the groyne location. The maximum depth of local scour occurs near the groyne downstream of the bend apex and it is significantly smaller 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 the effect of protection sills in the stilling basin for different bed materials on the scour morphology downstream of block ramps. 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 reducing the scour depth. Bhuiyan et al. (2007) studied the scour development downstream of W-weir at river bends in clear water and live-bed conditions. Bhuiyan et al. (2010) investigated on bank-attached vanes for bank erosion control. 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.

Zhou and Endreny (2011) studied stream wise and vertical velocity, vorticities and bed and bank friction coefficients using CFD model in base-flow and bank-full conditions. They showed that J-hook geometry and placement within natural meanders could be analyzed with CFD models to help restoration teams reach design goals and understand hydraulic impacts. Khosronejad et al. (2013) conducted an experimental and numerical study on local scour around three different rock grade-control structures including a rock weir, a cross vane, and a J-Hook vane in clear water condition. Khosronejad et al. (2014a) extended the coupled hydro-morphodynamics VLS3D model of Khosronejad et al. (2013) to simulate flow and sediment transport with arbitrarily complex rock structures in natural meandering streams under live-bed conditions. Khosronejad et al. (2014b) used VLS3D model with both URANS and LES approaches to simulate turbulent flow in different open channels, ranging from a stream to rivers, under

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* Corresponding author.
E-mail addresses: s.pagliara@ing.unipi.it (S. Pagliara), s.m.kurdistani@ing.unipi.it (S. Mahmoudi Kurdistani).

http://dx.doi.org/10.1016/j.ecoleng.2015.07.003

Notation

B	Channel width
d_{50}	Mean particle diameter
f	Functional symbol
F_d	Densimetric froude number $= Q'/\{l \times\ h_{\mathrm{st}}[g(G_s - 1)d_{50}]^{0.5}\}$
g	Gravitational acceleration
G_s	ρ_s/ρ
ζ_J	$= \left(\frac{h_{tw}}{h_{st}}\right)^{-0.5(\psi^{1.9})}$
h_{st}	Height of the structure (average height of the stones)
l_0	Length of the top part of the structure
l_1	Length of the structure arm
l	Length of the structure $= l_1 + (l_0 -\ \delta)$
l_m	Scour length downstream of the structure
l'_m	Ridge length
Q	Flow discharge
Q'	Effective flow discharge $= (b/B) \times Q$
y_0	Approach flow depth
$z_{1\mathrm{m}}$	Maximum scour depth downstream of the structure (internal scour hole)
$z_{2\mathrm{m}}$	Maximum scour depth (external scour hole)
z'_m	Maximum ridge height
Δy	Difference between water surface upstream and downstream of the structure
α	Structure arms angle with the tangent at the river bank
δ	Opening
η	$\mathrm{F}_d{}^2 \times \Delta y/h_{\mathrm{st}}$
ρ	Water density
ρ_s	Bed material density
σ	Particle uniformity factor $= (d_{84}/d_{16})^{0.5}$

live-bed conditions in the presence of different in-stream rock structures.

Scurlock et al. (2012a) carried out experiments on the vane-dike in channel bends to study the 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 in a sloped straight channel and derived equations to estimate the main scour parameters. Pagliara et al. (2013a,b, 2014a, b, 2015) investigated the scour morphology in straight rivers downstream of J-Hook vane, W-weir, Log-Vane and Log-Deflector structures respectively. Pagliara and Kurdistani (2014) compared scour hole characteristics downstream of Cross-Vane and W-weirs, highlighting similitudes and differences in the respective ranges of application.

Jamieson et al. (2013a) studied the effects of stream barbs to redirect the high velocity core from the outer bank and prevent erosion of the flood plain at the bend exit. They showed that the outer bank may still be at risk of erosion or even increase erosion as barbs size and layout generates excessive secondary velocities that are opposing the primary secondary flow naturally occurring in channel bends. Jamieson et al. (2013b) continued 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.

Melville (1992) studied local scour at bridge abutments and derived simple equations to predict the maximum scour depth. Based on Melville's study, Kuhnle et al. (2002) conducted a series of experiments on local scour associated with angled non-submerged spur dikes. Melville (2014) classified his method for different types of structures and presented a new equation based on Shields critical velocity to predict scour downstream of submerged weirs. Guan et al. (2014a) carried out 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. Recently Guan et al. (2014b) studied live-bed scour at submerged weirs.

The main purpose of this study is to experimentally analyze the effect of the curvature radius on the scour characteristics downstream of J-Hook Vanes and compare with scour formation downstream of J-Hook Vanes in the straight channels.

2. Experimental facilities

All the experiments were carried out in a curved channel setup made at the Hydraulic Laboratory of the University of Pisa. A curved channel 0.5 m wide, 15 m long and 0.5 m high (see Fig. 1a) with three bends of different radius (R = 1, 2 and 4 m) formed the channel. Three straight parts of the channel separated the bends including grids to straighten the approaching flow to the successive curve. Glass windows on the sidewalls enable to see the flow properties. An overhead tank supplied stable inflow. A magnetic current meter measured the discharge with precision of ±0.1 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. 1b shows a 3D view of curved channel setup indicating main scour variables. Fig. 1(c–e) shows the plan and stream wise views of the curved channel, including the main hydraulic and geometric parameters, 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 tops from the original bed level), Δy is the difference between water surface upstream and downstream of the structure, $z_{1\mathrm{m}}$ is the maximum depth of the internal scour hole, $z_{2\mathrm{m}}$ is the maximum depth of the external scour hole. Because of occurring the secondary flow at the outer bend of the channel, practically two scour holes are unified and are not completely separated. Therefore, there are two points of scour depth ($z_{1\mathrm{m}}$,$z_{2\mathrm{m}}$) but there is just one scour length l_{m} corresponding to the unified scour hole, z'_m is the maximum height of the ridge, l'_m is the ridge length in the longitudinal section in which the maximum ridge height occurs, R is the curve radius, $l = l_1 + (l_0 -\ d)$ is the length of the structure where l_1 is the length of the arm of the J-Hook structure, l_0 is the length of the top part of the structure, α is the structure arms angle with the tangent at the riverbank. $\alpha = 20°$ has been selected to be comparable with the previous contribution (Pagliara et al., 2013a, b) in which J-Hook Vanes have been studied in straight channel with installation angle of $\alpha = 20°$ and δ is the width of opening. Experimental data are shown in Table 1.

According to Pagliara et al. (2013a,b), the densimetric particle Froude number is $F_d = Q'/\{1 \times h_{\mathrm{st}}[g(G_s - 1)d_{50}]^{0.5}\}$ where Q' is the effective 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. Uniform sand ($G_s = 2.60$, $d_{50} = 1.77$ mm with particle uniformity factor $\sigma = (d_{84}/d_{16})^{0.5} = 1.26$) was used as bed material, b is the total with of the channel occupied with J-Hook structure and B is the channel width. The effective flow discharge was calculate based on ratio b/B, so $Q' = (b/B) \times Q$ where Q is the total channel flow discharge. At the beginning of each experiment, the channel bed was carefully leveled. After each test the bed material was mixed in order to