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Experimental study on bank erosion and protection using submerged vane placed at an optimum angle in a 180° laboratory channel bend

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ABSTRACT

Unsteadiness of the vertical velocity profile and secondary flow in open channel bends poses serious problems in hydraulic engineering design. Insertion of vertical submerged vanes in the channel bend at an optimum angle with the tangential component of flow can minimize the unsteadiness and generation of secondary flow resulting in the reduction of scour depth at the outer bank. A series of experiments were conducted in a 180° bend laboratory channel to study flow erosion and effective ness of the submerged vane in reducing scour depth. The average approach to flow velocity at 0.20 m flow depth above the lowest initial bed level was 25 cm/s. An Acoustic Doppler Velocimeter (ADV) was used to measure the three-dimensional time-averaged velocity components at different azimuthal sections on stabilized nonscoured beds without vane. Scour bed profile without vanes shows that bank erosion in a 180° parabolic-shaped bed channel occurs mostly at the zone from bend angles 120° to 140°. Vanes were installed at angles of 10°, 15°, 20°, 30°, and 40° to the tangential flow component maintaining a spacingof 75 cm distance from one vane to another. Experimental results show that a 15° vane angle produces best result in reducing outer bank scour in a parabolic-shaped channel. The data presented in this paper can also be used for validating three-dimensional turbulence models for simulating flows in a curved channel.

1. Introduction

Riverbed deformation, sandbar deposition, and river broadening accompanied with bank collapse in an alluvial river are triggered by the interaction of flow and riverbed or bank in the form of sediment transport (Zhang, 1989). Bank failures occurs throughout the entire fluvial process and would keep developing following specific rules according to corresponding river patterns (Nagata et al., 2000). To reduce erosional forces and stream power for a given discharge without a coarse-grained sediment supply for downstream aggradation, channel widening was the only mechanism for the silt bed streams to recover (Simon, 1994). Simon and Hupp (1992) observed that mean erosion rates are maximum on the outer banks of curved reaches, while along the inside banks of a curved channel and in straight reaches erosion rate is minimum. Secondary flow formation particularly at a bend is believed to be the main reason of erosion (Sin, 2010). Thomson (1876) first reported the existence of spiral flow pattern in channel bends. Mockmore (1944) conducted laboratory experiments to measure longitudinal velocity profiles in a 180° channel bend. He found that the flow from inner wall to outer wall is more than the flow from outer wall to inner wall. Yang (2005) studied the interaction of boundary shear stress, velocity distribution and secondary flows in open channels to justify the results using the governing equations of Reynolds stress distribution and boundary shear stress. Barbhuiya and Talukdar (2010) investigated three-dimensional turbulent flow fields and scour at a 90° horizontal forced bend. They found that maximum scour depth at the 90° horizontal bend occurs around the 30° azimuthal section and maximum flow velocity was observed near the concave bank. Roca et al. (2007) established that a properly installed wall footing minimises bend scour and protects the outer bank. They found that bend scour can be reduced by about 40% using wall footing. Scientific approaches for erosion control in the river emphasized the use of RCC kellyner jetties, submerged vanes, bank revetment or pitching, boulder spurs, and RCC porcupines. In this paper, river bank protection using submerged vane was experimented. Submerged vanes are a small hydraulic structure, flat vertical in nature, which is placed in an eroding bank at an angle $\boldsymbol{\alpha}$ with the main stream flow to divert the flow, resulting in deposition of sediments on the eroding bank. Erosion in the bend of a stream significantly undermines the outer bank by the approach current from the upstream of the river. Submerged vanes stabilize the deepening of the outer bank without affecting the sediment load and velocity at other parts of the stream. Odgaard and Kenndy (1983) worked with vanes to reduce near-bank velocity, to recover near bank depthsand to determine vane angle α at which scour holes will be minimum. They concluded, for $\boldsymbol{\alpha} \geq 20°$ flow separation occurred around submerged vane length and generated scour holes near the upstream end of each vane. Wang (1991) conducted laboratory experiments with submerged

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vanes installed in arrays with two or three vanes in each array for vane angle of 15° in a curved flume. They also conducted laboratory experiments with submerged vanes in arrays for $\boldsymbol{\alpha} = 20°$ in a straight channel. Odgaard and Wang (1993) observed that in order to modify the flow pattern and redistribute the sediment load, submerged vanes generated secondary flow, which reduced the total circulation. Further, two closely spaced vanes induced much more circulation than an isolated vane. The generation of circular motion was dependent on the spacing of submerged vanes. The greater the spacing, the smaller in reduction of circular motion and vice-versa. The efficiency of vanes in the presence of neighboring vanes and their mutual distances was experimented by Flokstra et al. (1998) and found that the efficiency is reduced by such neighboring conditions. Marlius and Sinhe (1998) conducted laboratory experiments to find the strength of secondary flow induced by submerged vanes and was found maximum at $\boldsymbol{\alpha} = 40°$. At larger vane angles, the flow resistance is increased and the vane is subjected to a relatively larger drag force. The main fact in the use of larger α has been the occurrence of unexpected local scour. Indication of scour reduction around a submerged vane has not yet been published, but many researchers (Gupta et al., 2010) recommended a collar as a scour retarder in case of bridge piers. Dey and Barbhuiya (2004) experiments on local scour at short abutments to study the effects of different parameters pertaining to scour at abutments. They observed that the scour depth at an abutment with an armor-layer in clear-water scour condition under limiting stability of the surface particles is always greater than that without armor-layer for the same bed sediments. Flow behavior in different channel bends has been studied earlier (Shukry, 1950; Odgaard and Spoljaric, 1989; Blanckaert and Graf, 2001), which provided only one- or two-dimensional mean velocity measurements. Recently, detailed three-dimensional velocity measurement methods, such as the acoustic doppler velocity profiler (ADVP) and the laser doppler anemometry (LDA) were introduced to identify flow characteristics — such as secondary flow in open-channel bends (Blanckaert and Graf, 2001). Albayrak and Lemmin (2011) conducted experiments to analyze dynamics of secondary current within the water column and at the free surface of an open channel flow over a rough movable bed using combined detailed ADVP, LSPIV, and hot-film measurements. They noticed undulations along the tangential direction and strong shear stresses at the bottom of the downwelling regions. Barbhuiya and Dey (2004) used ADV to measure a 3D turbulent flow field at a vertical semicircular cylinder, attached to the sidewall of a rectangular channel.

In the present study a velocimeter (ADV) is used to measure the 3D velocity components at different vertical points of the channel sections. The effectiveness of vanes in controlling outer bank erosion was tested in the Hydraulics Engineering Laboratory of NIT, Silchar, India. The dimension of the experimental flume was 9.57 m upstream length, 3 m downstream length and a 7.85 m 180° curve length, 0.8 m deep and 0.8 m wide. The centerline radius of the curved path of the channel was 2.02 m. Tests were conducted with bed materials having nonuniformity coefficient of 2.285. At the inlet section, a vertical steel screen with approximate porosity of 0.7 covered the full cross section for damping the flow disturbances through which water entered into the flume. The schematic diagrams of the experimental setup, top view of the flume, and test sections are shown in Fig. 1. An adjustable tailgate was installed at the downstream end of the flume to control the flow depth. The choice of the flume and location of the test section were chosen in such a way that:

- The flow became fully developed before it reaches the test section.
- The width of the flume bend was wide enough to generate 3D flow.

For turbulent boundary layer thickness along smooth flat plates the equation to verify the conditions of fully developed turbulent flow is

$$\delta = 0.37\mathrm{L_d}(\mathrm{UL_d}/\nu)^{-0.2} \tag{1}$$

where δ = boundary layer thickness, and $\mathrm{L_d}$ = distance along the streamwise direction. The calculated boundary layer thickness was greater than the mean flow depth, which conveys that for the entire experiment the boundary layer stretched out across the unseparated flow depth. The water supply system was connected to the underground reservoir to supply water to the laboratory flume. At the downstream end, a sediment trap of 1.5 m length was constructed to collect the scoured sediments. The main parameter for the vane test to reduce near bank settlement was the mean flow depth. Depending on mean flow depth, other parameters such as vane height, length of submerged vane, vane-to-bank distance, and tangential spacing were considered. The experimental parameters were designed based on the design specifications given by Odgaard and Wang (1991a,b).

2. Laboratory model experiments

The channel bed was prepared by placing sand as bed material over the entire length of the channel. Wet sieve analysis of a 500-g soil sample gives the value of the median size of bed particles (d_{50}) and nonuniformity coefficient (σ_g) as 0.28 mm and 2.285 respectively. For all experiments, sediment size was kept the same. The material was placed covering the entire length of the flume. The sand was then leveled, maintaining a 25-cm uniform thickness; then a trapezoidal cross sectional channel was prepared. The side slope of the trapezoidal section was made in such a way that the slope angle becomes almost equal to the angle of repose of the bed sediments. Once the bed was prepared, water was allowed to flow very slowly so that the side slope and the bed attains a stable cross section. The bed was then stabilized and kept for 2 days to enable flow measurement without change of bed profile. Bed profiles were then measured at different azimuthal sections along the radial distance from the inner wall with the help of a point gauge. Water was again allowed to flow at a predetermined depth and velocity by controlling the upstream and downstream gates. Three-dimensional time-averaged velocity components u, v, and w were then obtained by using an acoustic doppler velocimeter (ADV). At each cross section, velocity measurements were taken at six lateral positions (5, 20, 35, 50, 65, and 75 cm from inner wall) and vertical positions in the order of 0.5, 1, 2, 3, 5, 8, 10, 15 cm etc. from the bed. The average approach velocity (U) calculated with the help of ADV was 25 cm/s. The bed was again prepared as described above, and scour experiments were conducted after measuring the initial bed profiles at different azimuthal sections. In order to avoid the undesirable scour, which otherwise would happen by the action of sheet flow with inadequate flow depth, the flume was first slowly filled with water at a low rate. After that, the discharge was increased slowly to attain the required predetermined depth and velocity of flow. To reach the dynamic equilibrium of scour depth, the pump was allowed to run for about 8 h. The pump was then stopped and water was allowed to drain out slowly, and the scoured profile (Fig. 5A) was measured at different azimuthal sections along the radial distance from the inner wall to the outer wall. Notably, the time to reach dynamic equilibrium was assessed in a trial experiment. The channel bed was prepared again and then submerged vanes were placed on the bed. This experiment was repeated by placing the vanes at 10°, 15°, 20°, 30°, and 40° with the tangential component of the flow. Fig. 5B represents the bed profile after erosion using 15° vane angle. The detailed calculation of the submerged vane parameters is given in Table 1.

3. ADV data processing and performance

Filtering of ADV data involves two processes. The first process includes filtering of individual time series to remove low quality measurements within the time series. The ADV signal correlation COR, SNR, and despiking of aliased points (Wahl, 2000; Sontek Inc., 2001; Goring and Nikora, 2002) are the main factors that help this process. The COR and SNR filtering entails removing measured points within a time series