Conference Paper, Published Version

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Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/99907

Vorgeschlagene Zitierweise/Suggested citation:
Hossain, Makbul M.; Islam, Md. Rashedul; Saha, Suman; Ferdousi, Sara; Van Zwol, Boye; Zijlstra, Robert; Mosselman, Erik (2004): Laboratory Tests On Scour Around Bottom Vanes. In: Chiew, Yee-Meng; Lim, Siow-Yong; Cheng, Nian-Sheng (Hg.): Proceedings 2nd International Conference on Scour and Erosion (ICSE-2). November 14.–17., 2004, Singapore. Singapore: Nanyang Technological University.

LABORATORY TESTS ON SCOUR AROUND BOTTOM VANES[†]

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Bottom vanes can be used to create sufficient depth for navigation, to mitigate bank erosion or to change the division of sediment transports at bifurcations. Besides these intended effects, bottom vanes also produce local scour, which may interfere with the intended morphological correction and which is relevant for the structural stability of the vanes. We present the results from experiments on local scour around bottom vanes in a 45.6 m long and 2.45 m wide open-air flume at Bangladesh University of Engineering and Technology (BUET). The results lead to the formula $ds = 1.55\,(H_v\,L_v \sin\alpha\,/\,h)^{0.92}$, where ds denotes the maximum total depth at the scour hole, H_v is the vane height above the undisturbed bed level, L_v is the vane length, α is the vane angle with respect to the main flow direction and h is the flow depth. The coefficient of correlation is 0.82 based on 20 data points (4 vane heights × 5 vane angles). The results provide also simple formulae to compute volume and planar area of scour as a function of projected vane width.

1 Introduction

Vanes placed on an alluvial riverbed under an angle with the main flow generate a vortex that produces transverse transport of bed load and near-bed suspended load. This mechanism can be used to apply bottom vanes to correct the morphology of a river bed in a certain desired manner, for instance to create sufficient depth for navigation, to mitigate bank erosion or to change the division of sediment transports at bifurcations. Their efficiency has been studied by various researchers (Odgaard and Wang 1991, Odgaard and Spoljaric 1986, Jongeling and Flokstra 2001, Wang and Odgaard 1993). Besides this intended effect, bottom vanes also produce local scour. In the present study, scour around and downstream of a bottom vane has been studied experimentally to develop suitable formulae for predicting maximum scour depth, affected area and mean depth of erosion. These formulae serve the determination of a safe foundation depth for the bottom vanes.

[†] This work is supported by BUET-DUT Linkage Project, Phase-III.

2 Test Facility

A 45.6 m long and 2.45 m wide straight flume has been constructed at the open-air physical model facility of Bangladesh University of Engineering & Technology to conduct the test runs. The facility accommodates a re-circulating water supply system with storage pool, upstream reservoir, sediment trap and stilling basin. Two Rehbock weirs have been placed, one at the entrance of the flume and one at the re-circulation channel to measure the flow. At the downstream end of the flume, two tailgates can be exploited to adjust the water level in the flume. The model bed comprised sand of a median diameter (d_{50}) of 0.18 mm, which is representative for the majority of Bangladeshi rivers. The test flume is shown in Fig. 1.

Figure 1. Photograph showing model facility

The flume is equipped with point gauges at three locations along its length to measure water surface slope. For measurements of the bed topography, a self-devised instrument has been made out of an IPE100 beam, which spans the flume width and rests upon the flume sidewalls. Gauges are lowered manually through holes in the flanges of the beam until their sharpened tips hit the bed locally, after which the levels are read with respect to the beam level. Rubber cascades in between the flanges prevented the gauges from penetrating the bed. The vane in the experiments was a 0.40 m long and 4 mm thick sheet of durable perspex.

3 Test Runs

Mobile-bed tests were executed for a constant discharge of 200 l/s. The vanes were installed at four initial vane heights (0.06 m, 0.09 m, 0.12 m and 0.18 m) and five angles of attack (10°, 15°, 20°, 30° and 40°), leading to $4 \times 5 = 20$ test runs. For all experiments, the vane length L_v equalled 0.40 m. At the location of the vane, the water level was kept at 0.30 m above the initial bed level.

4 Methodology

Before each experiment, the vane was placed carefully at the desired location with proper vane height and angle of attack. Subsequently, the flume mobile bed was leveled at an elevation $Z = 21.8$ cm from an assumed reference. As soon as the preparation of the bed had been completed, the flume was filled with a thin layer of water by a back filling method to allow the bed to be set and to make a provision to minimize the bed level difference between the upstream and downstream ends. Each experiment began with the start of the pumps and then continued by gradually attaining the desired discharge that established a 30 cm flow depth. The experimental settings were verified periodically by measuring flow depth, discharge and water surface at 30-minute intervals. The scour depth was monitored at three locations on the pressure side of the vane with the help of a specially prepared depth profiler. Each experiment continued 30-40 running hours with the appropriate settings, depending on angle of attack and vane height. This duration corresponded to the time required to achieve equilibrium scour depth. After these running hours, the bed topography was measured with the help of the bed level measuring device on a grid with meshes of 10 cm × 5 cm (sometimes 2.5 cm × 10 cm depending on the bed topography) over an area of 3 m × 2.5 m spanning between 1 m upstream and 2 m downstream from the vane tip. The grid pattern was sufficiently dense to obtain a fairly accurate bed topography at the end of each experiment.

5 Results and Discussion

5.1 Equilibrium Scour Depth

The maximum scour depths, ds, have been correlated with the flow depth, h, and the projected area of the vane, Ap ($Ap = H_v \cdot L_v \cdot \sin\alpha$, H_v denoting vane height above the undisturbed bed level, L_v denoting the vane length and α denoting the vane angle with respect to the main flow direction). Other parameters have not been considered because equilibrium live-bed scour does not vary with increasing velocity or grain size and depends only on flow depth for a given shape of obstruction (Vanoni 1977). The resulting formula reads

$$ds = 1.55\left(\frac{H_v L_v \sin\alpha}{h}\right)^{0.92} \tag{1}$$

The correlation coefficient is 0.82. Fig. 2 shows the regression curve.

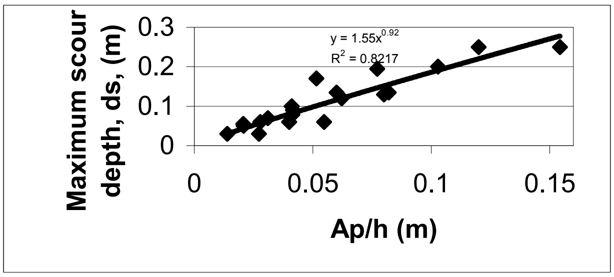

Figure 2. Regression equation for maximum scour depth prediction.

Equation (1) shows that the equilibrium scour depth *ds* is practically proportional to the projected area of the vane, *Ap*. This complies with scour formulae for rectangular bridge piers with oblique approach flows (Simons and Senturk 1992). In case of obstacles over the full flow depth, such as rectangular bridge piers, local scour usually increases with increasing flow depth (e.g. Chang 1992). However, the adopted scaling of vane heights with flow depth implies that the scour depth is roughly inversely proportional to flow depth (Fig. 3):

$$ds \propto H_v/h \qquad (2)$$

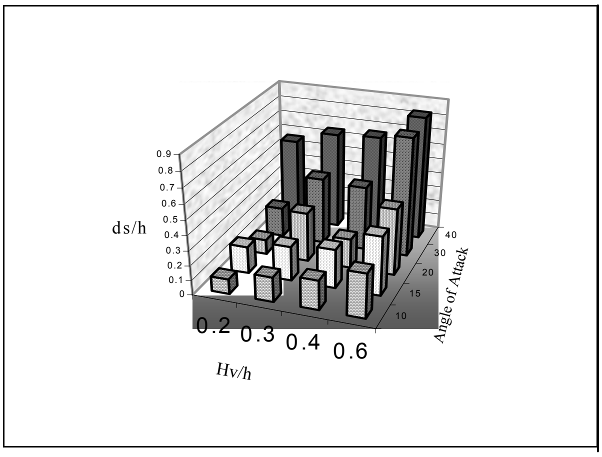

Figure 3. Relative equilibrium scour depth for different test runs.

In view of the resemblance between the shapes of the scour holes around bottom vanes and bridge piers, the use of scour relations for slender bridge piers to predict equilibrium scour depths at bottom vanes may seem appropriate, given the lack of information about scour at bottom vanes. However, the extreme values of the ratio of length to structural width for vanes do not relate to values for bridge piers. Secondly, unlike bottom vanes, a bridge pier causes a surface roller, which, compared to the horseshoe vortex at the base of the pier, has an opposite sense of direction. With decreasing flow depth, the surface roller becomes more dominant and weakens the downflow. Finally, scour relations for bridge piers do not account for submergence, whereas the results of the present experiments indicate that the scour hole dimensions also depend on the ratio of initial vane height to flow depth. If $h \leq H_v$, a vane would act as a rectangular bridge pier with extremely small structural width and the maximum scour depth should increase with increasing flow depth. Maximum scour depths predicted by Eq. (1) for $h = H_v$ can be compared with scour depths following from existing scour depth predictors for a rectangular bridge pier. Such expressions often use the projected width of the pier ($L_v\sin\alpha$). Table 1 provides such a comparison, where model parameters are modified by a scale factor of 60 ($h = H_v = 18.0$ m; Froude number $Fr = 0.15$).

Table 1. Comparison of scour predictors for rectangular bridge piers and Eq. (1).

Pier width $b = L_v\sin\alpha$ (m)	Maximum scour depth ds (m)			
	Eq. (1)	Coleman $ds = 1.49\, b\, Fr^{0.1}$	Laursen and Toch $ds = 1.49\, b\, (h/b)^{0.3}$	Breusers $ds = 1.4\, b$
7.0	9.3	7.1	13.9	9.8
10.0	12.9	10.2	17.9	14.0
14.0	17.6	14.3	22.6	19.6
20.0	24.4	20.4	29.1	28.0
26.0	31.1	26.5	34.9	36.4

Table 1 shows that the maximum scour depths calculated by Eq. (1) for $h = H_v$ are within the range of outputs of the scour predictors for bridge piers. If $h > H_v$, the maximum scour depth predicted by Eq. (1) would be reduced gradually.

5.2 Volume and Planar Area of Scour

The volumes and planar areas of scour have been calculated from bed topography contour maps of each experiment. Both erosion volume and planar area were found to vary more or less linearly with the projected width of the vane. Dividing the volume by the planar area yields the mean depth of the scoured area. A regression analysis results in the following relation for the prediction of mean scour depth, *dm*:

$$dm = 0.0768\, L_v \sin\alpha \tag{3}$$

The correlation coefficient is 0.89. The regression curve is shown in Fig. 4.

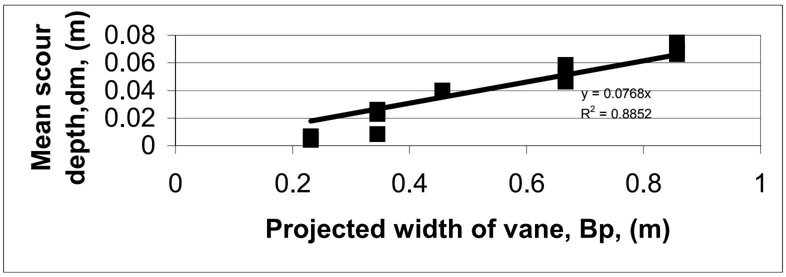

Figure 4. Variation of mean depth of scour with projected width of vane.

The following relation has been found for the scoured area, *As*, around and downstream of the vane:

$$As = 7.836\, L_v \sin\alpha \tag{4}$$

The correlation coefficient is 0.61. Fig.5 shows the regression curve.

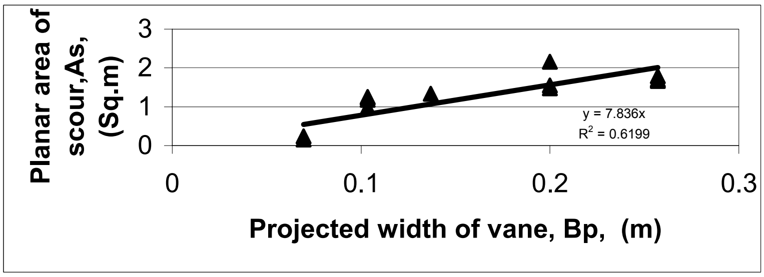

Figure 5. Variation of planar area of scoured region with projected width of vane.

Planar area and mean depth were found to correlate better with projected vane width than with projected vane area. They did not increase appreciably with increasing vane height.

5.3 Cross-Sectional Profiles

Cross-sectional profiles near the leading edge have been examined for all test runs. The scour depth at an angle of attack of 40 degrees has been found to be abruptly high for all vane heights (Fig. 6) and varies from 0.6 to 0.8 times the water depth. The maximum width of the scoured area is found to spread from y/h = -2 to +2 and appears to increase with increasing vane height and angle of attack. It is noteworthy to mention that, at the leading edge, the cross-sectional profiles of scour look semi-circular and symmetric with respect to the axis of the leading edge. The maximum scour is located near the leading edge. The scour depths at both pressure side and suction side seem nearly equal.

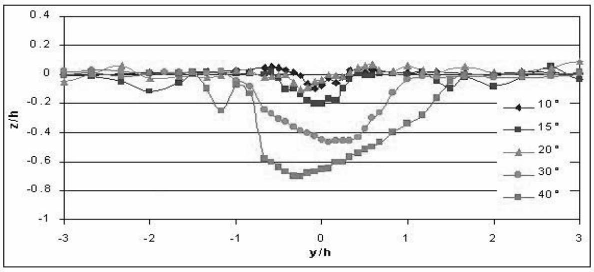

Figure 6. Bed profiles near leading edge of vane along transverse direction for $H_v = 9$ cm.

5.4 Bed Topography on Larger Scale

Bed topography contour maps reveal a longitudinal deposition berm and a parallel erosion gully after a streamwise distance of 3 m from the vane. At a distance of 6 to 7 m, only the deposition berm is present. Longitudinal profiles show that, in all cases, the mean bed level had been lowered in the vicinity of the vane, but had been raised slightly above the initial level after a streamwise distance of 3 to 6 m. The lowering of the mean bed level increased with increasing angle of attack.

6 Conclusions

The maximum scour occurs at the pressure side of the vane near the leading edge for the lower angles of attack, but shifts towards the trailing edge with increasing angle of attack. The maximum scour depth increases with increasing vane height and increasing angle of attack. Planar area of scour, volume of erosion and mean depth of erosion show linear variation with projected vane width. Suitable and simple formulae have been derived to assess the local scour at bottom vanes.

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