Experimental Investigation of the Effects of Angle and Length of Bendway Weirs on Scouring and Sedimentation in a Meander River

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Abstract: Through conducting the experimental tests, this research aims at evaluating the maximum scour depth at the tip of bendway weirs and point-bar height at the inner bank side of the bend in a meander river. To achieve the purpose of this study, a meandering canal with movable bed (fed with a constant sediment discharge) were constructed. Different series of bendway weirs were constructed at the outer wall of the central bend at three inclination angles (60°, 75° and 90°), three lengths ratio (0.2, 0.3 and 0.4) and three discharges ratio (0.8, 1 and 1.2) while the height and distance between weirs were kept fixed. At the end of each test the maximum scour depth and point-bar height were measured using a laser distance meter. The results show that the changes of length ratio and inclination angle do not affect significantly the point-bar height, weirs construction reduced the point-bar height at high flow discharge ratio ($Q/Q_d \succ 1$); as point-bar generally reduced by 20% and 18% (for various angles and lengths ratio, respectively) after weirs construction. Also, $\alpha=60^o$ and $L_w/B=0.4$ have the maximum impact on the eroded surface of point-bar. Moreover length ratio of weirs equal to 0.3 and angle 75° has more effect on maximum scour depth than other parameters at the tip of weirs.

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1. Introduction

The general concepts concerning of bendway weirs were first introduced by Prokrefke (1977), who studied these structures in a physical movable-bed model reproducing a 20-mile long reach of the Mississippi river, as an attempt to improve navigation and address engineering and environmental concerns. Later on, bendway weirs have been tested in 11 physical models build up at the U.S. Army Corps of Engineers Waterways Experiment Station (WES) to improve both deep and shallow-draft navigation, align currents through Highway Bridge, divert sediment, and protect docking facilities. From 1989 to 1995, over 120 weirs have been built in 13 bends of the Mississippi River. Analysis of the five oldest weir installations show that from 1990 to 1995 dredging was reduced by 80%, saving 3million of U.S. $. In addition, towboat accidents were reduced, delay times at bends were reduced, sediment and ice management was improved, least tern nesting areas were undisturbed, aquatic habitat area was increased, and fish size and density in the weir fields increased significantly (Julien 2002). Event though bendway weirs and groins are similar in orientation with respect to the streambank, the design of the two structures is significantly different. Indeed, bendway weirs are designed to be, "…fully submerged during most or all flows…" (Fischenich and Allen, 2000), whereas groins "…project into the channel from the bank and extend above the high-flow, water-surface elevation..." (WDFW, 2002).

Some research has been done on hydraulics of bendway weirs at the Colorado University by Heintz (2002), Darrow (2004) and Kinzli and Thornton (2009). The model used in their study reproduces a reach of the Middle Rio Grande River at a Froude scale of 1:12. The model consisted of two bends separated by a significant transition. The model's section was trapezoidal with a side slope 1:3. The experiments of Kinzli and Thornton were carried out varying the flow discharge (8, 12, and 16 cfs), the weirs angles (90 and 60 degrees) and lengths (15%, 22% and 28% of the upstream channel width) and keeping fixed the width and height of weirs. Four equations were derived, from laboratory data to predict the velocity around the bendway weirs. Also, some velocity ratios were extracted by Darrow (2004) and Heintz (2002).

Jarrahzade and Shafai-Bejestan (2011) analyzed the maximum scour depth at the bank line and at the nose of submerged weirs built in a sharp bend. The analyses was carried out in a 90° bend of a flume with bend radius to flume width ratio, *R/B*, equal to 2. A series of weirs was installed at the outer bank of the bend with spaces "*S"* equal to 24, 32 and 40 cm (i.e., $3L_w$, $4L_w$ and $5L_w$). Three flow discharges, Q=14, 18, 22 l/s, were considered keeping fixed the flow depth, D=15 cm. The experimental results showed that the scour depth at the weir nose is deeper than the scour depth at the bank. In addition, it resulted that closer spacing of weirs is needed as the channel bend curvature increases.

Past and present projects incorporating bendway weirs for outer bank protection have relied mostly on experience and engineering judgment. Therefore the development of optimum design criteria of the use of weirs is vital to improve and preserve bank stabilization in river bendways, especially in a meander river. The purpose of this study is to evaluate the maximum scour depth ratio at the tip of weirs and to compare the maximum point-bar height at the inner bank side with and without weirs in various angles and lengths ratio.

2. Material and Methods

2.1. *Characteristic of the Model*

The experiments have been carried out taking advantage of an existing model at the Institute of Water Researches of Tehran, Iran (Figure 1). The bend geometry has been chosen with reference to the actual morphology of the Karoon River, downstream of the Ahvaz city, Iran. The geometrical reduction scale was 1:80. Sediments and flow discharge were chosen so that the sediments were transported as a bedload at all the investigated flow discharges. The channel section is trapezoidal, with lower and upper width equal to 1.45 and 2.9 m, respectively, and, hence, a bank slope 1:1.5. The planform configuration is characterized by 3 consecutive bends, with central angles of 137.21°, 94.5° and 137.21°, respectively (see Figure 2). The channel flow is provided by a head tank (Figure 1, section A), and is measured through a 2 m wide rectangular weir (Figure 1, section B). The beginning of the first bend is located in section D. A straight reach FG, 4.89 m long, connect the first to the second bend. Similarly, the straight reach IJ, 4.89 m long, connects the second to the third bend. After the end of the third bend (Figure 1, section L) the flume joins through a smooth curve to a staring reach at the end of which is located a tail gate controlling the flow depth (Figure 1, section N). The water flowing over the gate is then collected on a storing tank from which the water is eventually pumped to the head tank. The length of the second bend, measured along the outer and inner banks, is 11 and 5.5 m, respectively. Sediments were fed in the system manually (Figure 1, section D*) and possibly collected at the end of section J.

2.2. *Relevant Parameters*

The ranges of variables are shown in table 1.

Table 1. Range of variables used in this study

Parameters	Range of variables
Angle (α)	60°, 75°, 90°
Length Ratio (L_w/B)	0.2, 0.3, 0.4
Discharge Ratio (Q/Q_d)	0.8, 1, 1.2

Weir spacing 'S' was kept fixed in all tests, and set equal to three times the weir length ($3L_w$). The height of weirs in all tests did not change and was equal to 33% of average flow depth, *D*. The bed sediment adopted in the test consisted of a uniform sand with mean grain size d_{s50}=1.6 mm and density 2400 kg/m^3.

2.3. *Experimental Procedure*

Two series of tests were performed without and with weirs. In the first series, a 35 cm thick layer of sand was initially placed in the flume and scraped. Then, water was slowly added to the model from both the downstream and upstream sections. After the water level was raised, upstream water discharge was carefully regulated. Firstly, a discharge ratio Q/Q_d=0.8 was set and then sediment were fed into the channel until nearly equilibrium conditions were attained (i.e., the mean water surface slope did not change any more and the bedforms stabilized). At the end of each test, the water flow was stopped and after slowly draining the channel, the bed topography was sampled with a laser meter. For each run, but the firs, the initial bed configuration was that obtained at the end of the previous test. In this case the movable channel bed attained an equilibrium condition quite rapidly.

In the second series of tests 3, 4 and 5 concrete weirs were built in the correspondence of the outer bank of the middle bend (i.e., between sections G and I of Figure 1) at the lengths of 0.4*B*, 0.3*B* and 0.2*B*, respectively. After weirs were arranged within the channel, sediments were accurately leveled and tests performed by considering the same flow discharge of the first series of tests. Also in this second series of runs sand was continuously fed in the channel. The time needed for reaching equilibrium conditions ranged between 6 and 18 hours, depending on flow discharge. At the end of each run the flow discharge was slowly decreased and the bed was drained completely. The channel bed was then surveyed using a laser meter with accuracy of 0.1 mm, with particular attention to the scour region occurring at the tip of weirs.

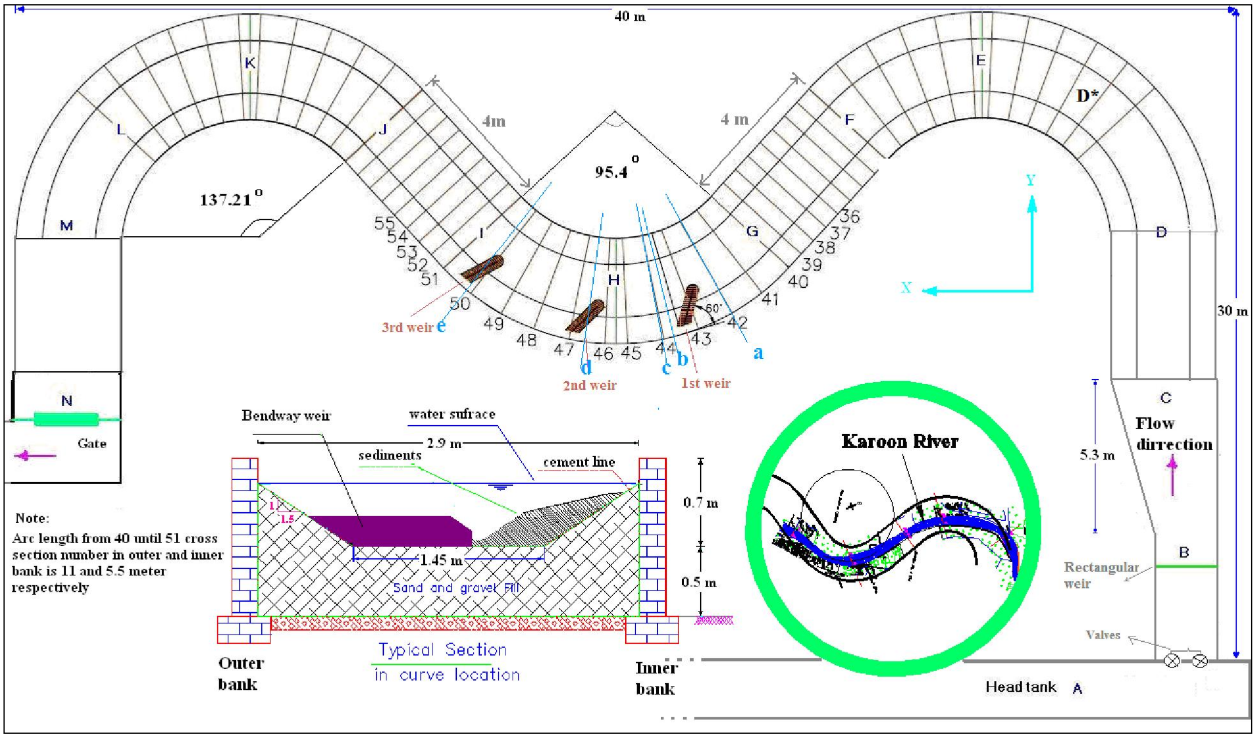

Figure 1. Plan view of the experimental setup.

3. Results and Discussion

3.1 Effect of the Length Ratio and Weirs Angle on Maximum Scour Depth Ratio at the Tip of Weirs

In order to evaluate the effects of weir inclination angle ‘α’ on scour depth, three angles of 60°, 75° and 90° were considered. Figures 2 and 3 show the ratio of maximum scour depth to weir height (H_s/H_w) as a function of α, for different discharge ratios. In all cases the maximum scour occurred at the tip of the downstream weir and was attained for α=75°, independently of the discharge ratio. The variations, however, are relatively limited. A much larger increment of the ratio H_s/H_w is attained by increasing the flow discharge, especially for α=75°. A much larger increase in H_s/H_w is observed for α=75° if the weir length is decreases from 0.4B to 0.3B.

Generally, it can be concluded that, for morphological configuration examined, the maximum scouring effects are observed for α=75° and by using four weirs (i.e., $L_w=0.3B$). This behavior clearly appears from figure 4, showing the plot of H_s/H_w as a function of L_w/B for the different discharge ratios and for α=60°. The scour depth increases with the discharge ratio and the maximum is attained for L_w/B=0.3, independently of Q/Q_d. Possibly this results is related to the fact that for L_w=0.3B the tip of the last weir was affected by the flow attack directly, and this could causes further erosion.

A similar scenario was observed for α=90°, as shown in figure 5. Nevertheless, comparing figures 6 and 7 it is clear that the difference in the amount of relative scour depth for the various length ratios is much larger when α=60°.

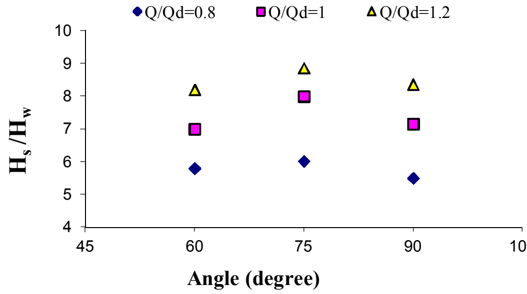

Figure 2. The maximum scour ratio H_s/H_w measured in the correspondence of the 3rd weir is plotted versus the inclination angle α for $L_w=0.4B$.

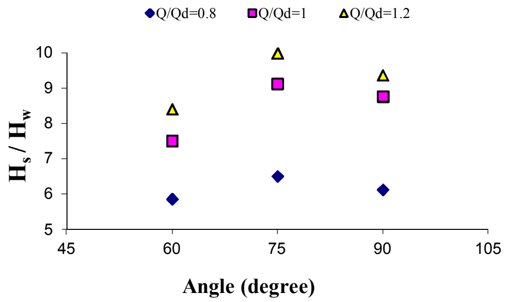

Figure 3. The maximum scour ratio Hs/Hw measured in the correspondence of the 4th weir is plotted versus the inclination angle α for $L_w=0.3B$.

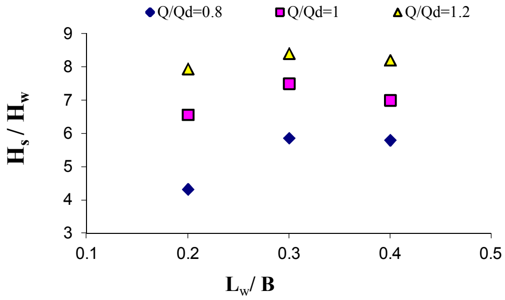

Figure 4. The maximum scour ratio H_s/H_w is plotted versus the dimensionless weir length L_w/B for different discharge ratios and $\alpha=60^o$.

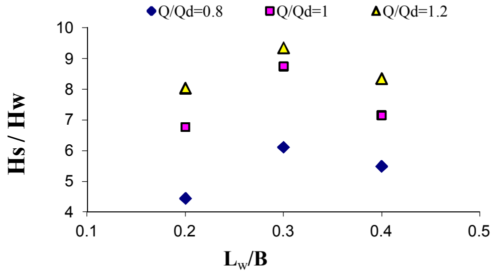

Figure 5. The maximum scour ratio H_s/H_w is plotted versus the dimensionless weir length L_w/B for different discharge ratios and $\alpha=90^o$.

3.2 Effect of the Length Ratio and Weirs Angle on Maximum Point-Bar Height Ratio at the Inner Bank Side

Another aim of bendway weirs is to control the point-bar at the inner bank side and, in particular, the maximum point-bar height. Figures 6 and 7 show the ratio of the maximum point-bar height in the presence of weirs, H_{b-w}, normalized with the maximum point-bar corresponding height, H_{b-n}, observed in the absence of weirs, as a function of α for different discharge ratios. For a given discharge ratio, H_{b-w}/H_{b-n} does not show any significant difference for the various inclination angles. However, increasing the discharge ratio the point-bar ratio tends to decrease. For example, for discharge ratios equal to 0.8 and 1.2, H_{b-w}/H_{b-n} attains the average values 1.25 and 0.81, respectively. Thus, for high flow discharge ratio ($Q/Q_d \succ 1$) the maximum height of point-bar decreases as a result of bendway weirs installation. The minimum point-bar ratio is 0.74 and was observed for α=75° and $Q/Q_d=1.2$.

A similar scenario characterizes the effect of length ratios (L_w/B). For a given discharge ratio, there is no significant difference between the point-bar ratio as L_w/B is varied (0.2, 0.3 and 0.4). The point-bar height, however, decreased by 18% after weirs construction as the discharge increases (i.e., $Q/Qd \succ 1$), as shown in figures 8 and 9.

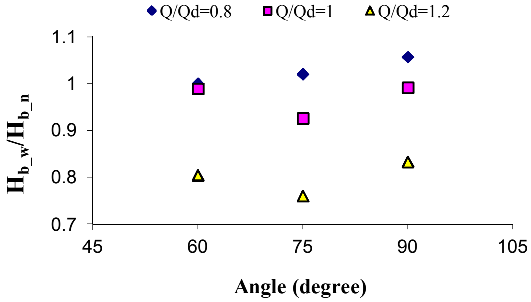

Figure 6. The maximum point-bar height ratio H_{b-w}/H_{b-n} is plotted versus the inclination angle α for $L_w=0.4B$.

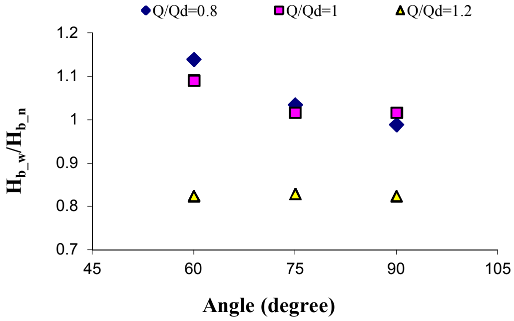

Figure 7. The maximum point-bar height ratio H_{b-w}/H_{b-n} is plotted versus the inclination angle α for $L_w=0.3B$.

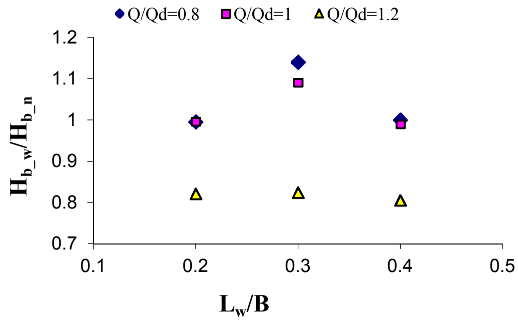

Figure 8. The maximum point-bar height ratio $H_{b\text{-}w}/H_{b\text{-}n}$ is plotted versus the dimensionless weir length L_w/B for different discharge ratios and $\alpha=60^o$.

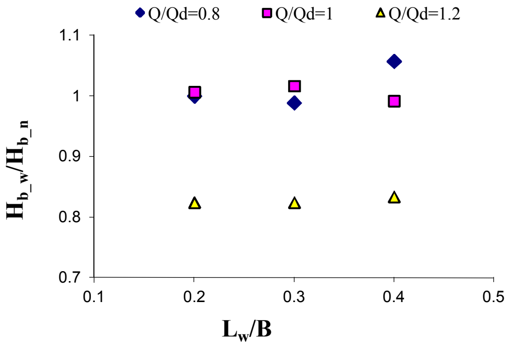

Figure 9. The maximum point-bar height ratio $H_{b\text{-}w}/H_{b\text{-}n}$ is plotted versus the dimensionless weir length L_w/B for different discharge ratios and $\alpha=90^o$.

3.3. Effect of Angle and Length Ratio on the Ratio of Cross-Section Area of Eroded Surface of Point-Bar (A/A_o)

As a result of weirs construction, the flow is directed away from the outer bank of the bend and towards the point-bar (Derrick, 1999); this enhancing erosion. The hachured area in figure 10 represent a typical example of the eroded surface of the point-bar at a given cross-section (48) for $\alpha=60^o$. Figures 11 and 12 report the ratio of cross-sectional eroded area to initial sediment area (i.e., the trapezoidal area of Figure 10) (A/A_o) as a function of the inclination angles and of the lengths ratio. The eroded surface ratio (A/A_o) decreased as the angle increased in most of the cross-sections (Figure 11); this means that $\alpha=60^o$ is more effective in capturing and redirecting the flow. Also, as the length ratio increases the eroded surface ratio increase. With increasing weirs length, greater flow volume can be captured and redirected towards the point-bar. Indeed the weir configuration with $\alpha=60^o$ and $L_w/B=0.4$ has the maximum impact on the eroded surface of the point-bar.

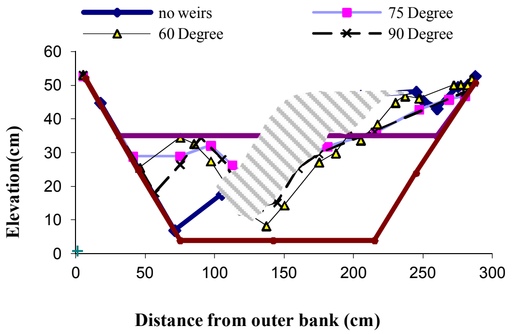

Figure 10. Schematic of cross-section area of eroded surface of point-bar, $L_w/B=0.4$, $Q/Q_d=1.2$.

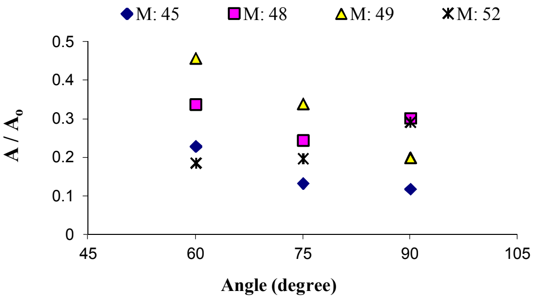

Figure 11. Eroded area of point-bar ratio (A/A_o) is plotted versus Inclination Angle α, for $L_w/B=0.4$ and $Q/Q_d=1.2$.

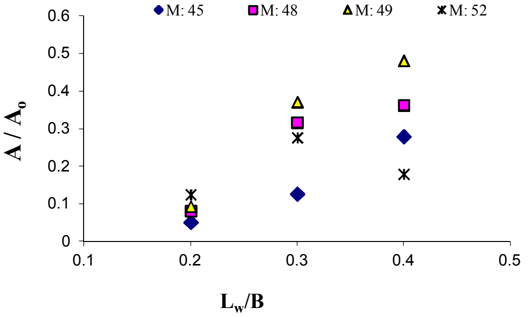

Figure 12. Eroded area of point-bar ratio (A/A_o) is plotted versus length ratio for $\alpha=60^o$ and $Q/Q_d=1.2$.

4. Conclusions and Recommendations

In this study experimental tests were conducted to investigate the effect of angle and length ratio of bendway weirs on maximum scour depth at the tip of weirs and on point-bar height at the inner bank side of the bend. The analysis of the experimental data has proven that the impacts of length ratio and angle were not significant on point-bar height, but weirs construction reduced the point-bar height at high flow discharge ($Q/Q_d \succ 1$). Generally point-bar reduced by 20% and 18% (for various angles and lengths ratio, respectively) after weirs construction. Also, choosing $\alpha=60^o$ and $L_w/B=0.4$ have the maximum impact on the eroded surface of the point-bar. Moreover length ratio 0.3 and inclination angle 75° provide the maximum scour depth at the tip of weirs.

Further investigations are however needed in the near future to address the effects associated with weir height, distance, permeability and crest slope on maximum scour as well as on sedimentation and erosion patterns.

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Notation

Variables

H_s = Maximum scour depth at the toe of weirs
H_w = Height of weir
$H_{b\text{-}w}$= point-bar height with weirs
$H_{b\text{-}n}$= point-bar height without weirs
α = Inclination angle of the weir
L_w = Project length of crest weir
B = Bankfull canal width at design flow
Q = Flow discharge
Q_d = Design flow discharge of bendway weirs
A= Cross-section area of eroded surface of point-bar
A_o= Initial area of sediment surface (i.e., the trapezoidal area)

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