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RESEARCH PAPER

Control of River Bend Migration Using Permeable Rectangular Vane Made by Six-Pillar Concrete Elements

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Abstract

Controlling the bends migration in the large meandering rivers using common groins is too costly, time consuming and needs some types of river by passing. Developing deep scour around nose of groins can lead to failure of the structure. However, it is necessary to investigate the new measures and materials to have less scour and to easily be installed, respectively. The six-pillar concrete (SPC) element is one of the materials which have been used successfully in bridge scour control. By constructing rectangular vane with SPC elements (RV-SPC) can take advantage of both economy and scour mitigation. In the present experimental study, the application of new technique has been studied. Tests were carried out at 180° flume bend for high flow condition (Froude number = 0.263). Two series of tests were carried out: (1) the base line tests without installing RV-SPC and (2) with RV-SPC at various intervals (5*L*, 6*L*, 7*L*, 8*L*) with the effective length equal to 20% of flume width ($L = 12$ cm). By comparing the results of two series of tests, it was determined that by installing RV-SPC at interval of 6*L* from each other, the maximum scour depth around the structure is reduced up to 70.0%.

Keywords Bank erosion · Meandering rivers · Sediment management · 180° flume

1 Introduction

Meandering river migration is a natural process in which the form of a river and subsequent its floodplain is continually changed over time through the processes of erosion at the outer banks and deposition of point bars on the inner banks (Bierman and Montgomory 2014; Khorrami and Banihashemi 2019). River bend migration annually brings about damages to the urban, rural, agricultural and industrial lands and infrastructures (Keshavarzi et al. 2016). The rivers are dynamically stable; their cross-sectional fluctuations roughly move around an average position of the flow pattern and progress to the downstream (Garcia 2008; Karkheirana et al. 2019). The migration rate of course varies from river to river and bend to bend. The migration rate in some of the bends of the Karun River located in the south of Ahvaz has been measured to be in the order of 84 m from 2018 to 2019 (as shown in Fig. 1) which destroyed agriculture lands as well as a pumping station in addition large supply facilities for drinking water are at risk.

The main reasons for such migration are the particular conditions of the flow pattern which developed in bends (Odgaard and Kennedy 1982; Odgaard and Bergs 1988; Blanckaert 2010). The presence of centrifugal force causes the water surface elevation in outer (concave) bend to be larger than in inner bend which create a non-uniform transversal vertical pressure distribution within the cross section. This leads to the formation of a secondary flow. So that the top layers of the water surface move toward the outer bend and the lower layers to the inner bend. The interference of this current with the main stream leads to the formation of a helicoidally currents in the bend, resulting in formation of a scour hole in the bed of outer bank and accumulation of sediment near the inner (convex) bank which eventually

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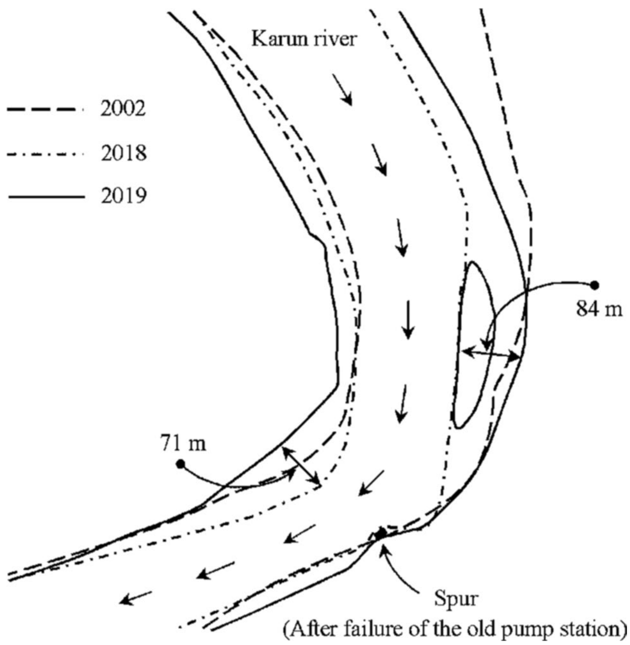

Fig. 1 Migration of Karun River bend south of Ahvaz (2018–2019)

causes lateral migration of the bend toward the outer bank (Shukry 1950; Dietrich et al. 1979; Jung and Yoon 1998; Brierley and Fryirs 2006; Hsieh and Yang 2003; Ghobadian and Mohammadi 2011; Vaghefi et al. 2016; Shan et al. 2017; Liu et al. 2018).

The point bars in the inner bank can effect significantly both flow and sediment patterns on bend and increase the rate of bend migration (Dietrich and Smith 1983). The migration rates of a river meander depend also on the river sediment transport capacity and the fact that the river is in degradation or aggradation. One of the methods used to control the displacement of river bends from the past decades is the use of groins (Biedenharn et al. 1997; Yan et al. 2012). Groins can be classified either as impermeable if the structure is made from rock, gravel, or earth, or permeable if it is made from wooden rods or piles (Przedwojski 1995). Groins are a massive structure that is usually constructed using gravel material, rocks or gabions with a length of 10–25% width of the river perpendicular to the outer bank of the river (Biedenharn et al. 1997). Groins are constructed consecutively at a certain along the entire length of the bend. Spacing of (1.5–2) L has been used to have deep channel for navigation, for bank protection space of 1*L* to 6*L* (USACE 1981; Copeland 1983) and 10*L* to 100*L* for banks where its toe is protected by riprap (Richardson et al. 1975). FHWA (1985) suggested spacing of 1*L* to 6*L* for bank protection considering the length, angle, transmissivity and curvature of the curved channel and Richardson and Simons (1974) suggested (1.5–2.0) L and (3–6) L along the condition of installation (for instance, 4*L* to 6*L* for a straight line or a curved groins with a large radius and 3*L* to 4*L* for a curved groins with a small radius).

After constructing the groins, the maximum longitudinal flow velocity is transferred from the outer bank to the nose of the groins, and the location of the formation of scour hole, which was previously at the toe of the outer bank giving rise of bank failure, is shifted to the front of the groins' nose. Also, the vortex flow pattern is formed between the groins, which is gradually restored and stabilized the banks by depositing sediments in these areas. The high sedimentation rate, especially during the flood period between the groins, has led to the use of this measure for bank stabilizing and controlling the river bend migration as well as rectifying the navigable rivers (Copeland 1983; Carling et al. 2014; Shields et al. 2004).

The main problem of this structure is the development of scour hole around the nose of the structure, which leads to the destruction of the structure itself (Fazli et al. 2008; Zhang et al. 2012). Over the past decades, many studies have been conducted to predict the scour depth or to use different shapes or heights of groins to have less scour depth (Zhang et al. 2012; Ghodsian and Vaghefi 2009). In addition, the construction of this structure in deep rivers such as Karun in Ahvaz is very costly due to the need for drying around the banks or redirecting the river flow to build structures. So far, there has been extensive research on the use of groins such as King (2009), Ghodsian and Vaghefi (2009), Fazli et al. (2008), van den Heever (2013), Yan et al. (2012), Vaghefi et al. (2009), Pagliara and Mahmoudi-Kurdistani (2013) and Dehghani et al. (2013).

Submerged weir (or bendway) is a type of groins that is attached to the outer bank with an angle to the upstream and a gradient from the bank to its nose, is also very effective in reducing the depth of scouring around the nose (Derrick 1994; Davinroy et al. 1998; Abad et al. 2008; Jia et al. 2009; Jarrahzade and Shafai-Bejestan 2011; Cunningham and Lyn 2016). The use of triangular vanes (TV) attached to the bank is also another kind of groins that is studied first by Bhuiyan et al. (2010) in a sinus flume and then by Bahrami-Yarahmadi and Shafai-Bejestan (2016) in a 90° bend. Their results have shown that the use of TV reduces the scour depth of its nose up to 51% compared to the common type of groins. Constructing groins in bends of sand bed meandering rivers in plain areas requires transportation of huge massive gravel material from long distance which is costly. Therefore, engineers are interested in applying new materials that are both stable and economical, especially, once the proper sizes of rocks are not available near the construction site. Recently, the tetrahedron frames concrete elements have been studied by Wang et al. (2018) as an alternative for stabilizing the river bed.

In the present study, with the aim of using new materials called the six-pillars concrete (SPC) elements, efforts have been made to investigate the performance of a rectangular vane made of SPC. These elements can be used in areas where the supply of rock needed for construction of RV is not available. Each of these elements consists of two pieces of T-shaped concrete that are connected in the middle, thus having six-pillars (Fig. 2). The most important advantage of using SPC elements is that they can assure high stability by locking their legs together.

These elements are either tied together or uniformly aligned and locked from 6 directions with their side elements, thus acting seamlessly. The SPC elements weaken the main flow vortex which causing bed erosion and reduce the scour depth. These elements, while creating a cover on the bed, can provide conditions for vegetation to grow from their pores and contribute to the natural preservation of the river bank. In the case of the SPC, few studies have been carried out on structural and hydraulic considerations, which have generally been applied to the use of protection of bridge abutments (Thornton et al. 2001; Zolghadr et al. 2016). In the present study, the rectangular vane made of SPC elements would be permeable and the flow can passes the pores, as a result, the flow pattern of around it may be different compared to impermeable ones. Therefore, the purpose of this research is to investigate the applicability of RV-SPC in a 180° flume bend experimentally under supercritical flow conditions and to develop design criteria for using as a costly beneficial and environmentally friendly bend migration control structure.

2 Materials and Methods

2.1 Dimensional Analysis

In order to plan the experiments as well as analyze the results, this section extracts the non-dimensional parameters and presents a general relationship (Azamathulla et al. 2005). The important variables in scouring around permeable RV-SPC are geometric variables such as flume width (B), bend radius (R), flume slope (S_0), central angle of bend (δ). The geometric characteristics of the RV-SPC include the effective length of the vanes (L), its angle to the upstream direction (θ), the distance between each other (D) and its height (h). Hydraulic flow conditions include the approaching average flow velocity to the bend (U), flow depth (y) and acceleration of gravity (g), also, sediment properties such as median diameters (d_{50}), density of sediment particle size units (ρ_s), maximum scour depth around the nose (d_s), the fluid characteristics including density of the water (ρ) and dynamic viscosity (μ). Therefore, considering the main goal of the study to find the best layout of RV-SPC to have less scour depth at their nose, the following general relation can be written:

$$f\left(S_0, B, R, \delta, L, \theta, D, h, U, Y, g, d_{50}, \rho_s, d_s, \rho, \mu\right) = 0 \tag{1}$$

In the present study, some of the variables (S_0, B, R, δ, h, d_{50} and ρ_s) are kept constant (their effect will not be studied) and by selecting repeatable variables (U, Y and ρ) and applying the Buckingham's π theory the following general non-dimensional relation will be obtained:

$$\frac{d_s}{Y} = f\left(\frac{D}{L}, \frac{L}{Y}, Fr, Re\right) \tag{2}$$

where Fr is the Froude number and Re is the Reynolds number. The flow in all tests was fully turbulent ($Re = 78{,}000$), and the flow condition also was constant ($Fr = 0.261$ equal to Froude number of Karun river at flood with a two-year return period); thus, the effect of water viscosity is negligible and Re can be dropped, by dividing D/Y and L/Y new dimensionless parameter is obtained thus the final general dimensionless expression are:

$$\frac{d_s}{Y} = f\left(\frac{D}{L}, Fr\right) \tag{3}$$

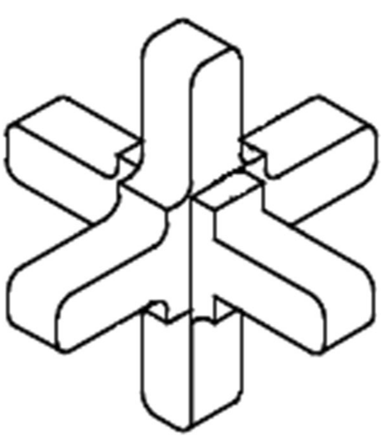

Fig. 2 Sketch of a single SPC

2.2 Experimental Apparatus

Laboratory facilities used in this research include a 180° flume bend with a valve for controlling the flow discharge, a ultrasonic flow discharge measuring device (with accuracy of ± 0.1 l/s), the entrance basin, 4 m straight path upstream of bend, the bend, 3 m straight path downstream of bend, the tailgate for water surface control within the flume and a V-notch weir at the downstream end (Fig. 3). As shown in the figure, the flume depth and width are equal to 60 cm and the ratio of bend radius to the width is equal to 3 which can be categorized as mild bend (Esfahani and Keshavarzi 2013). The RV-SPC elements were made by six-pillar element with

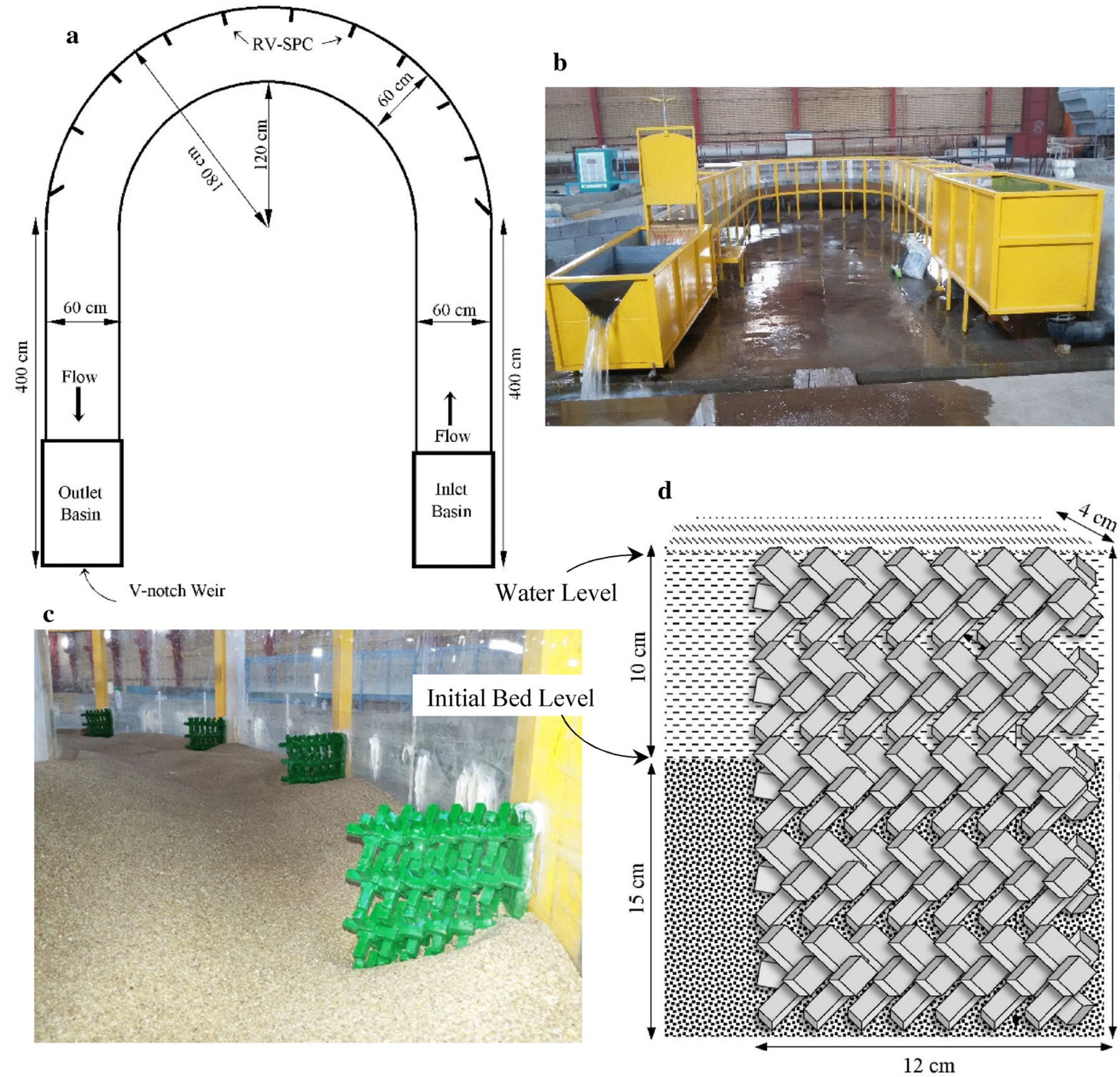

Fig. 3 **a** Plan view of the flume and the components of the experimental study; **b** view of the laboratory flume; **c** photograph of the installed RV-SPC in the bend and **d** cross-sectional schematic of the RV-SPC

4 cm in size (the actual size with scale of 12 is reduced). The elements are tight together to construct the RV. The permeability of the RV was 12%. The effective structures length (perpendicular to the flow direction) was equal to 12 cm which is 20% of the flume width. These RV-SPC are installed at 60° to the upstream flow direction from the outer bank. The height of the structures (above the flume bed) was 25 cm and from the sediment bed surface was equal to 10 cm equal to the flow depth.

The flume bed was covered with uniform ($\sigma g = \sqrt{d_{84}/d_{16}} = 1.2$) sand size of o.73 mm. The size distribution is shown in Fig. 4. Trial tests were conducted to obtain the critical velocities (V_c) of the sand material which was found to be equal to 0.28 m/s. All subsequent experiments were conducted under clear water conditions ($V/V_c = 0.92$). To determine the equilibrium duration time

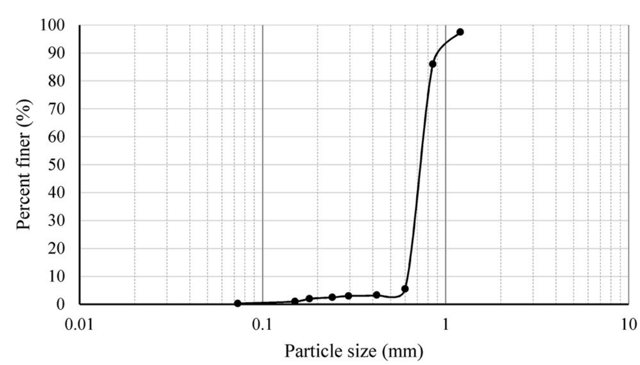

Fig. 4 Size distribution of the bed sediment size

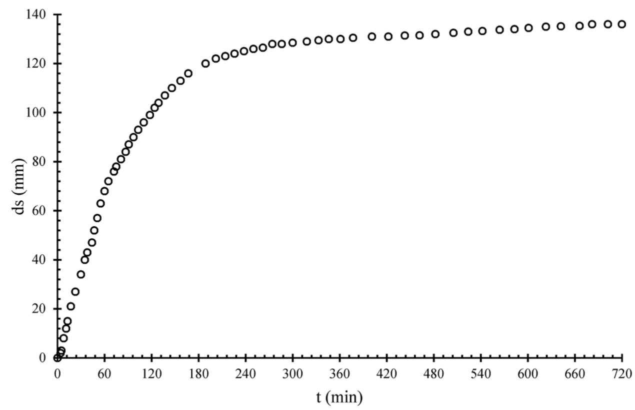

Fig. 5 Time development of scour depth

for maximum scour depth, the criterion of Ettema (1980) in which was defined as the time which in 3 h interval the change in scour depth is less than 1 µm was applied. For this reason, a long duration tests were conducted without installing RV-SPC structures at Froude number equal to 0.261 and the time development of scour was plotted which is shown in Fig. 5. It can be seen that the rate of scour depth decreased substantially after 3 h. Figure 5 presents record of scour depth variation with time to justify the use of 180 min for the experiments. As shown in the figure, the scour depth approaches some value asymptotically within 180 min. In addition, since the main purpose of this study is not to develop a scour depth predictor expression rather to compare scour depth among different alternatives; therefore, duration of 180 min was chosen to be satisfactory.

2.3 Test Procedure

For each experiment, the bed surface was completely flattened and controlled by laser distance meter. In the main experiments, the RV-SPC were placed at their respective intervals, and the level of the bed was then aligned. Then, the downstream gate is completely closed and the flow was allowed to enter the flume slowly to raise the water surface high enough to ensure that bed erosion does not occur before the test conditions are ready. Then, by simultaneously opening the valve and downstream gate the desired flow discharge and flow depths are achieved. It should be noted that during the test the flow depth was kept constant equal to 10 cm. At the end of test, the water level was lowered slowly by draining the water from the flume. At the end the topography of the bed was measured by the laser distance meter with a denser points around the RV-SPC. Table 1 shows the ranges of different variables in this study.

Table 1 Range of variables in this study

Flow discharge l/s	Flow depth (cm)	Reynolds number	Froude number	*L* (cm)	*D* (cm)
13.5–16.5	10	67,500–82,500	0.227–0.278	12	5*L*, 6*L*, 7*L* and 8*L*

L: Effective length of RV-SPC, D: Distance between elements

3 Results and Discussion

3.1 Bed Topography

Bed topography for the base line test and the main tests with different spaces between the structures is plotted using Tech plot software which are shown in Figs. 7a–e.

3.2 Baseline Test

Figure 6a shows bed topography for the base line test. The red color shows scour and blue color sedimentation. It is found that from the apex of the bend, scour occurs at the outer bank and the maximum scour hole occurs at 137.5° location which was measured to be 1.17y in which y is the flow depth. Such results also have been reported by other investigator in study of scour patterns in 180° river bends (Dey et al. 2017; Masjedi et al. 2011). The scour hole is attached to the outer wall of the flume. Sediments which eroded from the outer bank are transported further downstream toward the inner bank and deposited longitudinally along the flume close to the inner bank.

3.3 Main Tests

Bed topography for test with installed RV-SPC with 5*L* spacing is presented in Fig. 6b. Scour patterns have been shifted from the outer flume wall to the nose of the structures. In addition, erosion of the bed material at flume center occurred at almost beginning of the bend. This is mainly because of increase in bed shear stress due to narrowing of the flume width by installing the RV-SPC which increase the flow velocity greater than the threshold velocity and make it live bed condition exist throughout the flume. The scour hole is reached close to the outer wall of the flume from the fourth structure thereafter. The maximum scour depth occurred at the beginning of the second half of the bend at 119.46° location and at a distance of 1.25*L* (L = effective length of the structure). The largest scour hole with depth of 0.33Y occurs at 118.86° location. The eroded sediments are deposited in between most of the structures and between them and at inner bank, forming point bars. So that the maximum height of the point bar is 0.08y at the downstream of the seventh structure at a 105° location; the longitude length of the point

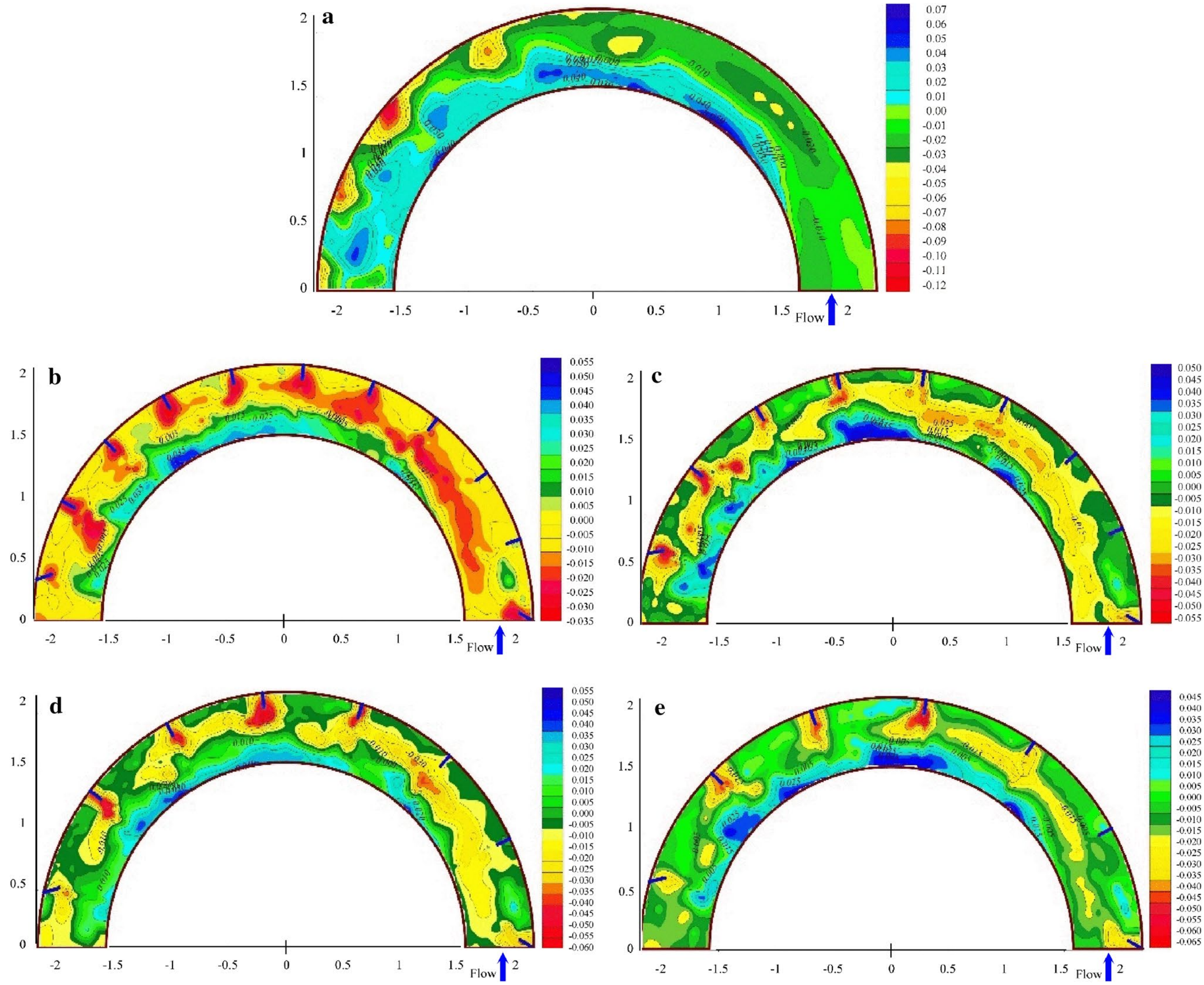

Fig. 6 Bed topography after each test: **a** Without RV-SPC elements; **b** $D=5L$; **c** $D=6L$; **d** $D=7L$; **e** $D=8L$

bar was observed between the 105° (downstream of the plate Seventh) up to 115° (upstream of the eight structure) with a length of 0.63*L*.

The results of bed topography after installing RV-SPC with 6*L* spacing are presented in Fig. 6c. Bed erosion on the middle of the channel has started from the beginning of the bend and continues to the end of bend. The maximum scour depth at middle of flume at distance of 1.67*L* (19.8 cm) from the outer bank at 94.7° location happened. The maximum scour hole at the nose of the eight structures located at 142.13° of the bend which was measured to be 0.35Y. The eroded sediments have been deposited in inner bend and attached to the outer bank in between the structures in the form of longitudinal point bars with maximum height of 0.013Y which was observed downstream of the sixth structure at 105° bend. The length of this point bar measured to be 0.57Y which cover the length between the sixth and seventh structure.

According to Fig. 6d with 7*L* spacing, bed erosion begins from the bend origin at the middle and lasted to the center and then started further downstream and after some discontinues start again. The maximum scour depth at the beginning of the second half of the arc at 94.7° bend occurs at distance of 1.65*L* from the outer bank. Generally, the maximum depth of scouring occurred in the central regions of the flume or at the nose of RV-SPC, which led to the forming the thalwege. The greatest scouring in the nose of the sixth structure located at an angle of 118.76° was calculated to be 0.4Y. In this test, longitudinal point bars also occur along inner bend and in between the structures with its maximum height of 0.24Y in between the fourth and fifth structure with length of 0.68*L*.

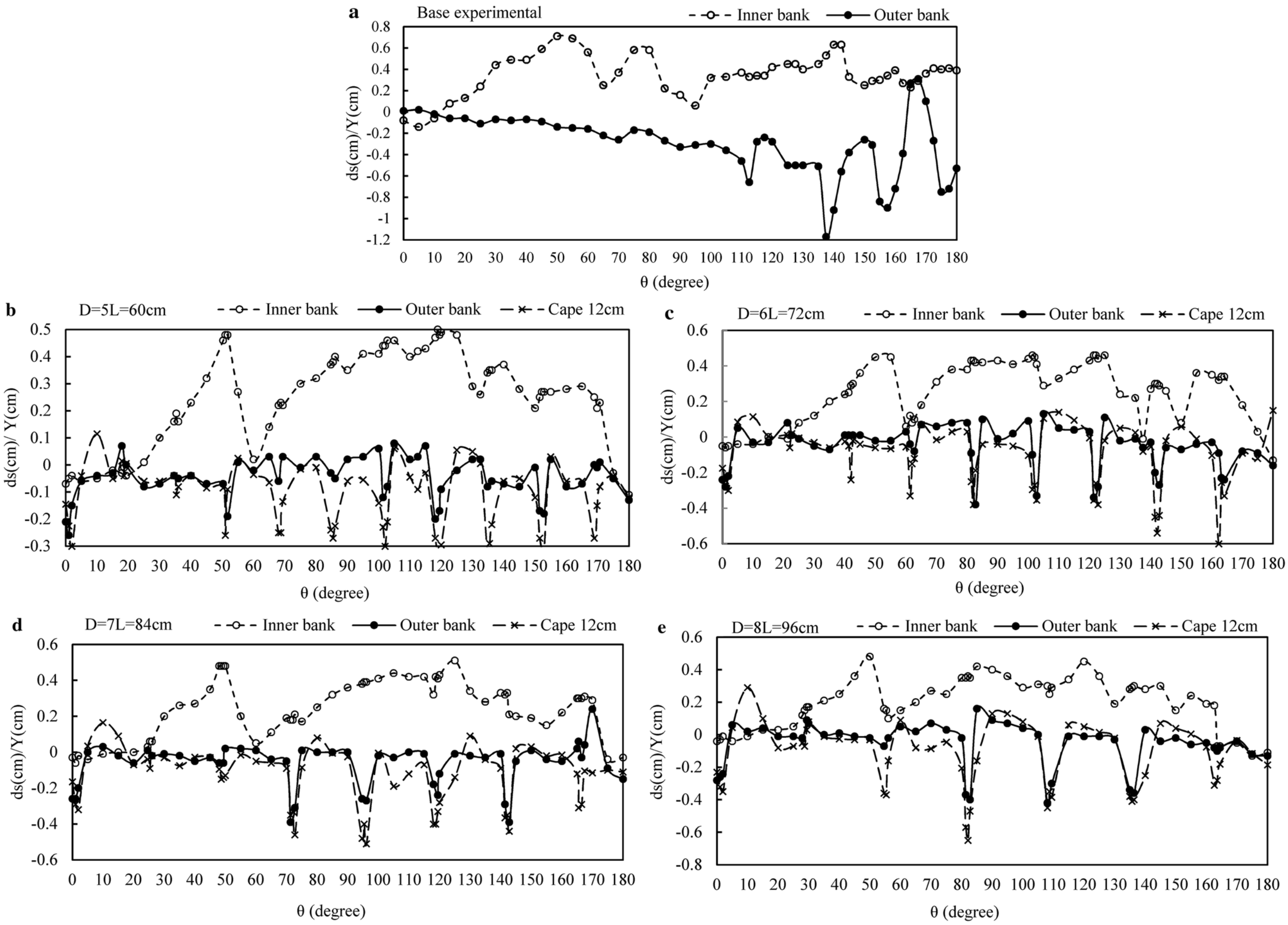

Fig. 7 Longitude scour and sedimentation profile in different tests: **a** Without RV-SPC elements; **b** $D=5L$; **c** $D=6L$; **d** $D=7L$ and **e** $D=8$L

The installing structures with space of $8L$ as it can be seen in Fig. 6e, river bed erosion at the start of the bend and start to be larger from the upstream of the first structure and continues up to third structure forming a low deep thalwege in the middle of the flume. The erosion patterns in the second half of the bend is different and mostly create a deep scour hole around the remaining structures. The scour hole reaches the outer bank at the third, fourth and fifth structure with its maximum which occur at the nose of the fourth structure. Deposition of the eroded sands has mostly observed in the central of the inner bank. Little deposition can be observed in between the structures. The highest depth of the point bars in between the fourth and fifth structure was obtained to be 0.16Y with length of $0.8L$.

3.4 Longitudinal Scour and Sedimentation

To see the longitude scour and sedimentation along the bend, Fig. 7a–e was plotted. Table 1 also shows the maximum scour at the outer bank for different tests. This figure shows the dimensionless scour at outer bank, at the nose of the structure and sedimentation at various bend locations. Results of the base line test are shown in Fig. 7a, and the scour around the outer bank has started from the beginning of the bend and reaches at deepest at 137.5°. Sedimentation also happened at the inner bank along the bend. For the case which RV-SPC are installed at $5L$ interval, the erosion at outer bank is very small compared to the base line test; however, erosion has also happened at the nose of all structure. In fact by installing the structures, the channel thalwege has shifted from the outer bank to the middle of the flume at the nose of the structures in shallower. The same phenomenon can be observed when the RV-SPC are installed at $6L$, $7L$ and $8L$ as shown in Fig. 7c–e, respectively. As the space between the structures increased the scour depth in both outer bank and at the nose of structure increased too. However, the magnitude of increased different from test to test. Table 1 presents the dimensionless scour depth both at the outer bank and at the nose of the structures. The main cause of the outer bank failure (which is the main cause of bend migration) is the occurrence of scour. Therefore, for control of bend migration the bank

Table 2 Dimensionless maximum scour depth (ds/Y) along bend

	Base line	$S=5L$	$S=6L$	$S=7L$	$S=8L$
Outer bank	1.17	0.26	0.38	0.40	0.42
Nose of the structure		0.37	0.60	0.52	0.68

scour depth should be minimized. Table 2 shows that this can be achieved when the RV-SPC are installed at interval of 5L. The outer bank scour depth in other alternatives is the same ($ds/Y=0.4$). The scour around the structure can led the failure of the structure itself. Therefore, for achieving minimum scour depth it is found from Table 1 that the space between the structures should be taken equal to 5L. However, if the structure is installed deep enough to withstand or the channel bed around the nose are protected, then one can select the 6L as the space between the structures. For the case of 7L or 8L, the scour at the nose of structure is too deep (up to 70% of the flow depth) which is great enough to fail the structure. Thus, it is not recommended.

In Fig. 7, the sedimentation profile which occurred along the outer bank in between the structures also is shown which reveals that in all alternative sediments are deposited. Such deposition is due to developing a free horizontal vortex in between the structures. Bahrami-Yarahmadi and Shafai-Bejestan (2016) in the study of flow pattern along the triangular shape of groins found that once the flow attacks the structure, a return flow toward the upstream direction is formed which lasts up to 6.9L. The sediment which is transported from the nose of the upstream structure is trapped within the horizontal vortex and deposited in the form of longitudinal point bar. In those tests with larger scour dimensions, larger point bar also can be observed. For this reason, selecting the appropriate alternative based on the sedimentation volume or height of point bar may not be enough accurate. However, the location in which point bars are developed is an important issue. For the case of bend migration, growing point bars at the inner bank forced the outer bend to migrate in higher rate. By looking at Fig. 7, it is seen that for the alternatives of 5L, 7L and 8L the point bars at the inner bank are formed. For the alternative of 6L spacing, the point bar in the inner bank is low enough although the scour depth in this alternative is deeper than in 5L alternative.

Tests also were conducted for different flow conditions ($Fr=0.227$, 0.244, 0.261 and 0.278) to investigate the variation of scour depth which the results are presented in Fig. 8. In this figure, the dimensionless scour depth is plotted versus Froude number for different spaces between RV-SPC's structures. The scour depth shows almost the same trend as was discussed in detail for $Fr=0.261$. For $D=5L$, scour at the nose of structure for all Froude numbers is less and for $D=8L$ shows higher scour depth.

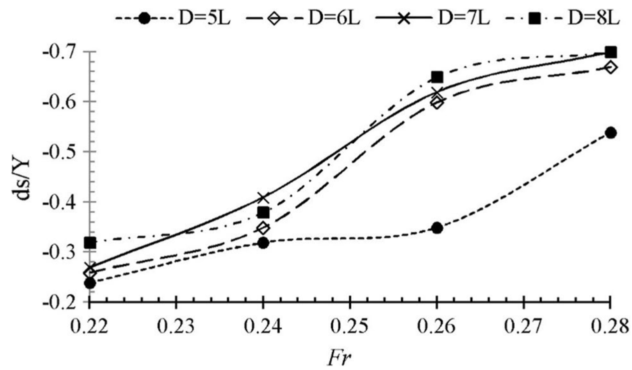

Fig. 8 Variation of dimensionless scour depth versus Froude number for different alternatives

Therefore, from the pint of aquatic habitats in which larger scour size can attract more fish for resting once they are migrating, alternative 6L is preferred over alternative 5L. Therefore, from the economy point view, safe design, better control of bend migration and aquatic habitats the RV-SPC structures should be installed at a distance of 6L from each other.

4 Conclusion

For the purpose of developing design criterion for new countermeasure against river bend migration, this experimental study was carried out. Series of rectangular permeable groins made by the six-pillar concrete elements are installed at different spacings to find out the best spacing for multi-application of the new measure. By comparing bed topography maps which was produced after each test, it was found the generally installing the new structures can significantly (up to 68%) reduce the scour depth at the outer bank. The thalwege of the channel is shifted from the outer bank to the middle of channel. The scour is developed around the nose of each structure, and the scour depth increases as the space between the structures increases as the space increase. It should be kept in mind, however, that since the scour is far from the outer bank, it will not be harm to the banks rather it may require to provide enough deep foundation for the structure nose or place riprap on bed around the nose of the structure. Finally, from the point view of economy, safe design, better control of bend migration and environmental better performance can be achieved when the RV-SPC structures are installed at interval of 6L each other. The application of the mathematical models to analyze the velocity, depth, and volume changes and investigating the permeability of the six-pillar elements can be considered in future studies.

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References

Abad J, Rhoads BL, Guneralp I, Garcia MH (2008) Flow structure at different stages in a meander bend with bendway weirs. J Hyd Eng 134(8):1052–1063
Azamathulla HM, Deo MC, Deolalikar PB (2005) Neural networks for estimation of scour downstream of a ski-jump bucket. ASCE J Hyd Eng 131(10):898–908
Bahrami-Yarahmadi M, Shafai-Bejestan M (2016) Sediment management and flow patterns at river bend due to triangular vanes attached to the bank. J Hyd Res 10:64–75
Bhuiyan F, Hey RD, Wormleaton PR (2010) Bank-attached vanes for bank erosion control and restoration of river meanders. J Hyd Eng 136(9):583–596
Biedenharn DS, Elliott CM, Watson CC (1997) The WES stream investigation and streambank stabilization handbook. US Army Corps of Engineers, p 286
Bierman PR, Montgomory DR (2014) Key concept in geomorphology. Freeman Publishing, New York
Blanckaert K (2010) Topographic steering, flow recirculation, velocity redistribution, and bed topography in sharp meander bends. Water Resour Res 46:W09506. https://doi.org/10.1029/2009WR008303
Bozkus Z, Yildiz O (2004) Effects of inclination of bridge piers on scouring depth. J Hyd Eng 130(8):827–832
Brierley GJ, Fryirs KF (2006) Geomorphology and river management. Blackwell Publishing, London, p 398
Carling P, Jansen J, Meshkova L (2014) Multichannel rivers: their definition and classification. Earth Sur Pro Land 39:26–37
Copeland RR (1983) Bank protection techniques using spur dikes. Miscellaneous Paper HL-83-1, U.S. Army Waterways Experiment Station, Vicksburg
Cunningham R, Lyn D (2016) Laboratory study of bendway weirs as a bank erosion countermeasure. Journal of Hydraulic Engineering 142(6):04016004
Davinroy RD, Rapp RJ, Myhre RE (1998) Hydroacoustic study of fishes in bendway weir fields of the Middle Mississippi River. In: Proceeding of wetlands engineering and river restoration conference, ASCE Reston, VA, pp 890–895
Dehghani AA, Azamathulla HM, Hashemi-Najafi SA, Ayyoubzadeh SA (2013) Local scouring around L-head groynes. J Hyd 504:125–131
Derrick DL (1994) Design and development of bendway Weirs for the dogtooth bend reach, Mississippi river, Hydraulic Model Investigation. Technical Report HL-94-10, WES, Vicksburg, MS
Dey L, Barbhuiya AK, Biswas P (2017) Experimental study on bank erosion and protection using submerged vane placed at an optimum angle in a 180° laboratory channel bend. Geomorph 283:32–40
Dietrich WE, Smith JD (1983) Influence of the point bar on flow through curved channels. Water Resour Res 19(5):1173–1192
Dietrich WE, Smith JD, Dunne T (1979) Flow and sediment transport in a sand bedded meander. J Geol 873:305–315
Esfahani FS, Keshavarzi A (2013) Dynamic mechanism of turbulent flow in meandering channels: considerations for deflection angle. Sto Environ Res Risk Assess 27(5):1093–1114
Ettema R (1980) Scour at bridge piers. Rep No 216, University of Auckland, Auckland, New Zealand
Fazli M, Ghodsian M, Salehi SAA (2008) Scour and flow field around a spur dike in a 90° bend. Inter J Sed Res 23(1):56–68
FHWA (1985) Design of Spur-Type Streambank Stabilization Structures, US DOT, FHWA, Rep. No. FHWA/RD 84/101, McLean
Garcia MH (2008) Sedimentation engineering: processes, measurements, modeling, and practice ASCE publisher, p. 1132
Ghobadian R, Mohammadi K (2011) Simulation of subcritical flow pattern in 180 uniform and convergent open-channel bends using SSIIM 3-D model. J Water Sci Eng 4(3):270–283
Ghodsian M, Vaghefi M (2009) Experimental study on scour and flow field in a scour hole around a T-shaped spur dike in a 90 bend. Inter J Sed Res 24(2):145–158
Hsieh TY, Yang JC (2003) Investigation on the suitability of two-dimensional depth-averaged models for bend-flow simulation. J Hyd Eng 129(8):597–612
Jarrahzade F, Shafai-Bejestan M (2011) Experimental investigation of thalwege under effect of submerged weirs in a 90° sharp bend. W Manage Res 97:17–29
Jia Y, Scott S, Xu Y, Wang SSY (2009) Numerical study of flow affected by bendway weirs in Victoria bendway, the Mississippi River. J Hyd Eng 135(11):902–916
Jung JW, Yoon SE (1998) An experimental study on the characteristics of flow and bed topography with changing bed material in a curved channel. J KWRA 31(3):291–301
Karkheirana S, Kabiri-Samania A, Zekrib M, Azamathulla HM (2019) Scour at bridge piers in uniform and armored beds under steady and unsteady flow conditions using ANN-APSO and ANN-GA algorithms. ISH J Hyd Eng 11:1421
Keshavarzi A, Hamidifar H, Ball J (2016) Bed morphology in vegetated estuarine river 488 with mild-curved meander bend. Hydrol Sci J 61(11):2033–2049
Khorrami Z, Banihashemi MA (2019) Numerical simulation of sedimentation process in reservoirs and development of a non-coupled algorithm to improve long-term modeling. Int J Sedim Res. https://doi.org/10.1016/j.ijsrc.2018.10.003
King H (2009) The use of groins for riverbank erosion protection. In: Proceeding of river hydraulics, stormwater and flood management conference. University of Stellenbosch
Liu X, Zhou Q, Huang S, Guo Y, Liu C (2018) Estimation of flow direction in meandering compound channels. J Hyd 556:143–153
Masjedi A, Akbari I, Abyar H (2011) Evaluating scour at L-shape spur -dike in a 180° bend. W App Sci J 15(12):1740–1745
Odgaard AJ, Bergs MA (1988) Flow processes in a curved alluvial channel. Water Resour Manage 24(1):45–56
Odgaard AJ, Kennedy JF (1982) Analysis of Sacramento River bend flows, and development of a new method for bank protection (No. IIHR-241). Iowa Institution of Hydraulic Research, Iowa City
Pagliara S, Mahmoudi-Kurdistani S (2013) Scour downstream of cross-vane structures. J Hydroenviron Res 7(12):236–242
Przedwojski B (1995) Bed topography and local scour in rivers with banks protected by groynes. J Hyd Res 33(2):257–273
Richardson EV Simons, DB (1974) Spurs and guide banks, open file report. Colorado State University Engineering Research Center, Fort Collins, Colorado
Richardson EV, Stevens MA, Simons DB (1975) The design of spurs for river training. 16th IAHR Cong San Paolo Brazil B 47:382–388
Shan Y, Liu X, Yang K, Liu C (2017) Analytical model for stage-discharge estimation in meandering compound channels with submerged flexible vegetation. Adv Water Resour 108:170–183
Shields FD, Morin N, Cooper CM (2004) Large woody debris structures for sand-bed channels. J Hyd Eng 130(3):208–217
Shukry A (1950) Flow around bends in an open flume. Trans Am Soc Civil Eng 115:751–779
Thornton CI, Abt SR, Watson CC (2001) Field assessment of a-jacks installation, a case study of Brush Creek, Kansas city, Missouri Powell Creek, Waukegan, Illinois. In: Proceedings of the wetlands engineering and river restoration conference Reno, Nevada

USACE (1981) The streambank erosion control evaluation and demonstration Act pf 1974 Section 32, Public Low 93-251 U.S. Army Corps of Engineers (USACE), Final Report to Congress, Waterways Experiment Station, Vicksburg, Mississippi

Vaghefi M, Ghodsian M, Salehi-Neyshaboori SAA (2009) Experimental study on the effect of a T-shaped spur dike length on scour in a 90 channel bend. Arab J Sci Eng 34(2):337–348

Vaghefi M, Akbari M, Fiouz AR (2016) An experimental study of mean and turbulent flow in a 180° sharp open channel bend: secondary flow and bed shear stress. KSCE J Civil Eng 20(4):1582–1593

Van den Heever A (2013) An investigation of the use of groynes as a means of riverbank erosion protection. MSc Thesis Department of Civil Engineering Stellenbosch University

Wang JM, Yang XG, Zhou HW, Lin X, Jiang R, Lv EQ (2018) Bed Morphology around various solid and flexible grade control structures in an unstable gravel-bed river. Water 10:822–834

Yan L, Baomin W, Yong L (2012) Research on application of removable non-rescue sub-merger groins in lower yellow river training works. Proc Eng 28:781–785

Zhang H, Nakagawa H, Ogura M, Mizutani H (2012) Bed morphology and grain size characteristics around a spur dyke. Inter J Sed Res 27(2):141–157

Zolghadr M, Shafai-Bejestan M, Rezaiazadeh M (2016) Investigating the effect of six-legged element placement density on local scour at wing-wall bridge abutments. World Environmental and Water Resources Congress, ASCE, USA