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Original Research

Performance of riffle structures on the stabilization of two successive knickpoints over a sandy bed

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A R T I C L E I N F O

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A B S T R A C T

Two successive knickpoints with a 10% slope were constructed 1 m apart on a sandy bed in a rectangular flume with a longitudinal slope of 0.003. Bed erosion and knickpoint migration were studied experimentally for different discharges. The performance of two grade-control structures—Newbury rock riffles (NRR) and cross-vane riffles (CVR)—were studied experimentally for the stabilization of each knickpoint. Both of the structures were successful in controlling the bed erosion; however, the NRR operated relatively better than the CVR for they could concentrate the flow at the middle part of the channel to produce more regular contours with less local erosion and bed settlement. The experiments demonstrated that the construction of a control structure was not only effective in the stabilization of a knickpoint but also retarded the migration of its neighboring counterpart.

1. Introduction

A knickpoint refers to a point with an abrupt change in the gradient of a channel (May, 1989). Reduction in the base bed level caused by tectonic reasons and riverbed erosion resulting from straightening of reaches or gravel mining are amongst the most important factors which cause knickpoints. When flow passes over a knickpoint, local scouring at the downstream toe creates a plunge pool and increases the height of banks until they eventually collapse, widening the river. The widening of the riverbed damages adjacent infrastructure, causing sedimentary materials to flow into the river (Papanicolaou et al., 2012). To achieve stability, the river system has to erode the bed at upstream and sediment must be deposited at downstream of knickpoints. This process implies the development and migration of the knickpoints. It causes damage to upstream structures and surrounding land. Moreover, sediment transport not only endangers aquatic life but also damages the river ecosystem. Experimental work simulating the headward migration of knickpoints over a non-cohesive sandy bed or a cohesive layered bed have been done by many researchers including Brush and Wolman (1960), Gardner (1983), Holland and Pickup (1976), Stein and LaTray (2002) amongst others.

The Sumbar River located on the border of Iran and Turkmenistan has migrated laterally from its conventional alignment since 1957 as a result of bank failure and meandering, resulting in the destruction of agricultural land. River realignment was on the agenda of the Iranian Committee of Trans-border Rivers in the mid-1990s and was implemented a few years later. However, the straightened river experienced an incised bed, many knickpoints emerged along the steep slope reaches caused by channel shortening. Richardson et al. (2001) reported the possibility of generation of successive knickpoints when a river reach is subject to bed degradation. The propagation of a series of knickpoints, observed in the form of multiple steps along with the longitudinal profile of the river, makes the riverbed unstable and susceptible to severe erosion. Begin et al. (1980, 1981) reported on the development of consecutive knickpoints produced by base-level lowering. Parker (1996) featured a train of upstream-migrating bed undulations bounded by hydraulic jumps as “cyclic steps”.

Cantelli and Muto (2014) described that under conditions of supercritical flow over an alluvial bed, an instantaneous drop in base level could lead to the formation of upstream-migrating knickpoints that did not dissipate. Grimaud et al. (2016) concluded that under a constant rate of base-level fall, knickpoints of similar shape were periodically generated. In both of these

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articles, multiple knickpoints were produced in a narrow flume with a width of only 2 cm to minimize planform complications such as bars.

Despite of so many previous studies on the retreat of a single knickpoint, research studies on the initiation, migration, and interaction of consecutive knickpoints, generated on steep slopes caused by the realignment of rivers, has yet to be explored. The current study attempts to determine in detail the behavior of two successive knickpoints in a sandy bed flume and examine their interactions at different discharges. Then, the performance of two in-stream, grade-control structures are compared for bed stabilization and arresting of the knickpoints under similar laboratory conditions.

2. Grade-control structures

Grade-control structures (GCS) are among the most popular structures for rehabilitation of small rivers. They reduce the river slope and flow velocity, and also stabilize the banks and bed. Field observations demonstrate that many of these structures cause river instability, contrary to their initial objectives, because of improper design and construction without the consideration of pattern, dimension, and profile of a stable stream, as well as the mechanism of sediment transport for the river considered (Rosgen, 1996).

In recent years, the desire to construct grade control structures using natural boulders has been increased to maintain the original beauty of rivers. Simplicity in design and construction, low cost and environmental compatibility may be the most important reasons for the prevalence of riprap grade control structures (Nakato, 1998). At-grade sills and sloping sills, made from boulders and cobbles placed at the riverbed, provide a hard point to resist erosive forces. The headward migration of knickpoints is stopped when it collides with these rocky structures and the bed is stabilized (Derrick, 2012; McLaughlin Water Engineers, Ltd., 1986; Stufft, 1965; Whittaker & Jäggi, 1986).

Modern techniques for river restoration have increasingly focused on the re-establishment of the natural geomorphic processes, such as erosion and deposition to create aquatic habitats and floodplains (Beechie et al., 2010; Kondolf et al., 2006; Palmer et al., 2005). According to studies on high-gradient incised rivers, the stable profile of a riverbed may be formed in successive step-pool series, Fig. 1 (Chin et al., 2009; Lenzi, 2002).

The grade control structures designed and built, inspired by the stable step-pool morphology of rivers, are called Engineered Rock Riffles (ERRs). Many of studies have shown that, in addition to the stabilization of the bed and banks of a river, ERRs have a positive effect on the habitat of aquatic organisms and provide better conditions for reproduction, egg-laying, and feeding of the aquatic animals (Newbury & Gaboury, 1993). Field surveys, measurements, and sampling of rivers with and without step-pools showed that the interlocking of boulders, cobbles, and the accumulation of sands behind the steps stabilize this morphology and provide high biodiversity in the river ecosystem (Wang & Yu, 2007). Newbury Rock Riffles (NRR) have been devised to simulate this process and to repair and stabilize the erosive rivers and restore the aquatic animals and ecosystems (Newbury, 2008; Newbury et al., 1996). By evaluating the performance of various grade control structures on a wide range of incised rivers, Rosgen (2001) designed and proposed three types of vane rock riffles, termed as alphabet weirs. The specific design of these structures reduced shear stress and flow velocity near the banks while increasing them in the midstream, and, thus, an equilibrium state was established between sediment load and flow discharge.

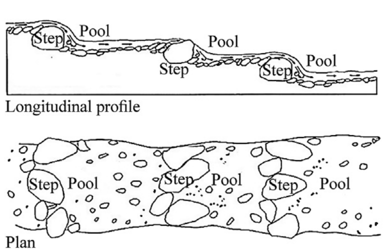

Fig. 1. Formation of step-pool morphology in riverbeds (Lenzi, 2002).

3. Effective dimensionless parameters

In general, the Froude number ($Fr = V/\sqrt{gh}$), Reynolds number ($Re = Vh/\nu$), and Shields number $\left(\tau^* = \frac{\tau_0}{(\gamma_S-\gamma)D} = \frac{hS_0}{(G_s-1)D}\right)$ are the most important dimensionless parameters affecting mobile bed models (Julien, 2002), where V is the flow velocity, h is the flow depth, g is the gravitational acceleration, ν is the kinematic viscosity, $\tau_0(=\gamma hS_0)$ is the bed shear stress, γ_S and γ are the specific weights of sediment and water, respectively, $G_s\,(=\gamma_S/\gamma)$ is the specific gravity of sediment particles, S_0 is the bed slope, and D is the particle diameter. If $Re < 500$ flow is laminar, if it is in the range of $500 < Re < 2{,}000$, the flow is transitional, and if $Re > 2{,}000$ it is turbulent (Chow, 1959). Where $Fr < 1$ the flow is subcritical, and where $Fr > 1$ it is supercritical. The critical value of the Shields number (τ_c^*) may be given by (Lamb et al., 2008):

$$\tau_c^* = 0.15 S_0^{0.25} \tag{1}$$

In a laboratory model with low flow velocity and depth, the effect of surface tension may be significant. This is shown in the form of the dimensionless Weber number ($We = \rho V^2 h/\sigma$) where ρ and σ are water density and surface tension, respectively. To discard the effect of surface tension, the Weber number may be in the range $10 < We < 100$ (Peakall & Warburton, 1996).

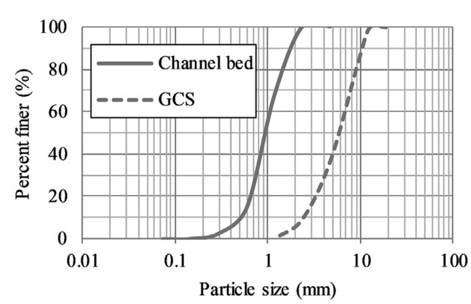

Fig. 2. The particle size distribution of bed materials and grade control structures (GCS).

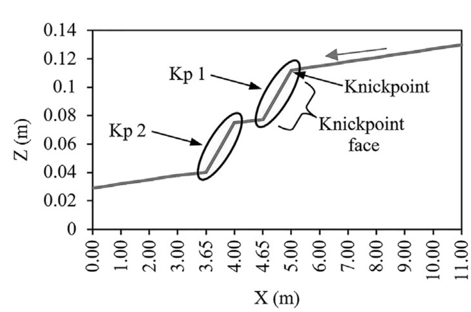

Fig. 3. Longitudinal profile of bed at the start of each test.

Table 1
Geometric and hydraulic conditions at the start of the tests.

Test no.	Location of measurement	S_0 (m/m)	Q (L/s)	V (m/s)	Normal depth, h_o (m)	Critical depth, h_c (m)	τ_o (N/m^2)	Reynolds no. *Re*	Froude no. *Fr*	Shields no. τ^*
1	Away from the knickpoint	0.003	0.44	0.167	0.009	0.006	0.236	1,343	0.577	0.017
	Knickpoint face	0.1		0.489	0.0030		2.854	1,426	1.43	0.199
2	Away from the knickpoint	0.003	0.56	0.183	0.010	0.007	0.272	1,700	0.588	0.019
	Knickpoint face	0.1		0.540	0.0035		2.307	1,823	1.44	0.231
3	Away from the knickpoint	0.003	0.68	0.198	0.011	0.008	0.305	2,053	0.597	0.021
	Knickpoint face	0.1		0.584	0.0039		3.722	2,220	1.45	0.260

4. Experimental setup

A laboratory flume with 12 m length, 30 cm width, and 40 cm height was used for experimental investigations. The walls and bottom of the flume were made of glass and stainless steel sheets, respectively. Water was pumped from the main reservoir with a discharge in the range of 0.4–0.7 Ls to a small header tank at the upstream end of the flume to promote quiescence. The flow rate was measured using a rotameter type flowmeter, with a capacity of 2–22 gpm for water at 60°F (15.6°C). The flow then spilled smoothly over a straight weir and moved over a sandy bed, placed in the flume. At the end of the flume, the water passed through a strainer to leave the sediment particles and return to the reservoir. The water temperature was in the range of 15–20°C all over the experiments.

The sandy bed of the flume had a coefficient of uniformity $C_u = D_{60}/D_{10} = 2.02$, median diameter $D_{50} = 0.95$ mm, and specific gravity $G_s = 2.54$ (note D_x is the diameter for which x percent of particles are finer). Fig. 2 shows a graph of the particle size distribution for the bed materials. Sand particles were stuck to the walls of the flume, to ensure a uniform roughness over the flume perimeter. The Manning roughness coefficient (n) was initially estimated to be about 0.013 from the empirical Strickler formula (Henderson, 1966) validated through measurements with a confidence of 95%.

Two consecutive knickpoints (Kp 1 and Kp 2) were constructed at an interval of 0.35 m with 3.5 cm height (10% slope) a few meters away from the end of the flume, Fig. 3. A series of experiments were done to investigate the performance of the knickpoints with the presence or absence of control structures. The channel slope was 0.003 up- and down-stream of the knickpoints and 0.1 at the knickpoint face. The bed material size, channel slope, discharges, and knickpoint face gradient were in a range similar to the tests of Brush and Wolman (1960). Local bed elevations were measured manually using a point gauge with an accuracy of 0.1 mm.

In Table 1 hydraulic characteristics and dimensionless parameters are listed for three different discharges at the knickpoint faces and away from them at the beginning of each experiment when the water spread over the width of the flume. Substituting for τ_c^* into the Shields number equation, the critical bed shear stresses may be determined as $(\tau_0)_c = 0.503$ N/m^2 away from the knickpoints and $(\tau_0)_c = 1.208$ N/m^2 at the knickpoint faces. The bed shear stresses in different experiments also are listed in Table 1. The bed and knickpoint slopes were set for the shear stress to be erosive only at the knickpoint face at the start of experiments without control structures. However, during the tests, the two knickpoints merged and developed a steep slope reach, in part of the flume, with a lateral bar due to erosion, incision, and deposition. The channel width reduced to 70% of the flume width, and the flow velocity accelerated. As a result, supercritical turbulent flow predominated, and surface tension effects diminished in that region. A similar situation was reported by Brush and Wolman (1960) and Cantelli and Muto (2014).

5. Test performance

A total of 9 experiments, with three different discharges according to Table 1, were done in two stages in the absence and presence of grade control structures. Typically, each experiment took about 5 h. In practice, reaching steady-state with no control structures was impossible, because the knickpoints were continuously migrating headward. In one case, the experiment lasted for about 24 h, so that the first knickpoint reached the upstream end of the flume and did not disappear. In experiments with a control structure, the majority of bed variations occurred in the very first hour and subsequent changes in later hours generally were slow. In cases where the control structure stabilized the knickpoint, no significant change in the bed was observed. After the completion of experiments, the changes in the bed level were compared with and without the control structures.

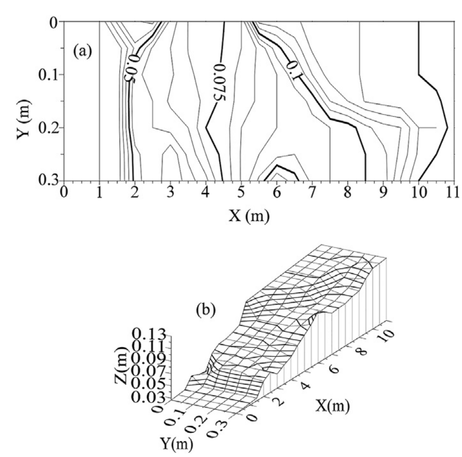

Fig. 4. (a) Contour lines, and (b) 3D shape of the bed features, ($Q_3 = 0.68$ L/s).

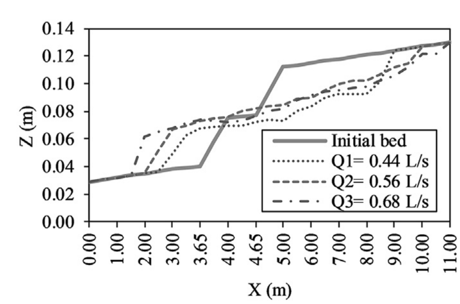

Fig. 5. Longitudinal profile of the bed for various discharges at the end of the three tests.

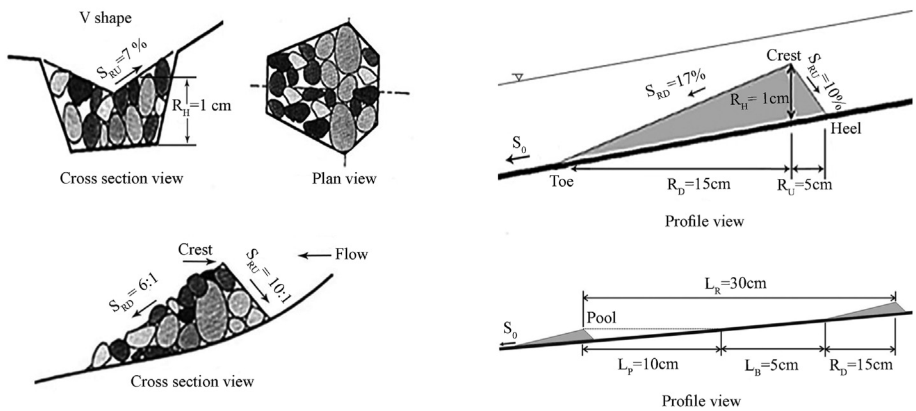

Fig. 6. Details of side and longitudinal views of the installed NRR.

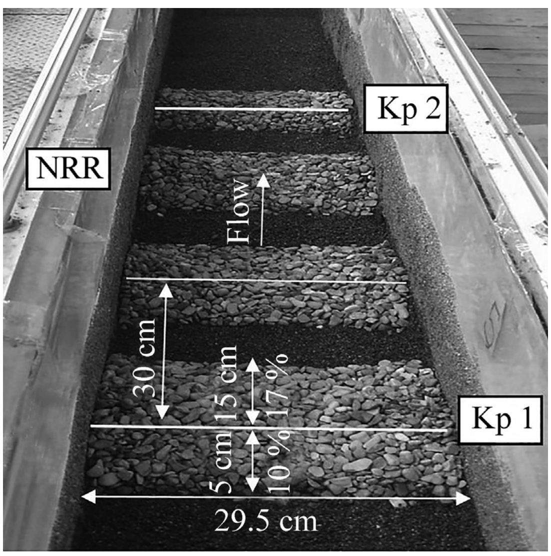

Fig. 7. Constructed NRR.

5.1. Experiments without the control structure

Bed erosion started as the water flow passed over the knickpoints. The first knickpoint retreated, steadily incising the upstream channel. The eroded particles deposited downstream of the knickpoints, extending a steep reach between them, gradually, with a slope sharper than the initial slope of the channel. Fig. 4 shows the contour lines and three dimensional (3D) shape of the incised bed at the end of the third experiment with the maximum discharge. Upstream bed incision due to knickpoint headward migration was asymmetric and generated a side bar in the downstream region; however, the walls of the flume confined the development of a meandering channel.

Fig. 5 shows the bed variation profiles along the thalweg for three different discharges at the end of each experiment. An increase in discharge resulted in further incision and knickpoints extension in the up- and down-stream directions. The bed level is lower in the first test ($Q_1 = 0.44$ L/s) due to less incision and sedimentation, and the slope of the upstream knickpoint is steeper, and that of the deposited material is milder in comparison with the other two tests.

5.2. Experiments with the control structure at the first knickpoint

There are several equations for determining the stable diameter of properly engineered riprap. For discharges less than 0.03 m^3/s and slopes up to 10%, Anderson et al. (1970) suggested

$$D_{50} = 0.01561\gamma R S_0 \quad (2)$$

where R is the hydraulic radius of the flow section ($R \simeq h$). Newbury and Gaboury (1993) gave a similar relation. For slopes between 2 to 20%, USACE (1994) gave:

$$D_{30} = \frac{1.95{S_0}^{0.555}(Cq)^{\frac{2}{3}}}{g^{\frac{1}{3}}} \quad (3)$$

where q is the design flood discharge per unit width and C = 1.25 is a flow concentration factor. With the maximum discharge, $D_{50} = 6.1$ mm and $D_{30} = 5.14$ mm are obtained from Eqs. (2) and (3) for the riprap particles. In the experiments of this study, an almost uniform grading size distribution was used for the construction of riprap structures, according to Fig. 2.

Two series of tests with three different discharges were done with Newbury rock riffles and cross-vane riffles constructed near the first knickpoint as grade control structures. A detailed description of the design method and laboratory performance of the riffles on the knickpoints migration and bed stabilization is reported here.

5.2.1. Newbury rock riffles (NRR)

Design considerations: The particles were placed on the crest and downstream surface of the NRR in the form of a "V" to focus the flow towards the center of the stream away from the banks and reduce erosion. Following various studies on natural types of riffles in rivers, it is recommended that the downstream slope (S_{RD}) be between 20:1 and 5:1 and the transverse slope of the V-shape (S_{RV}) be between 4 and 8 percent (Newbury, 2008; Newbury et al., 1996). Other parameters including the effective height of the riffle crest (R_H), horizontal intervals between heel to crest (R_U) and crest to toe (R_D), the upstream slope of the riffle (S_{RU}), and the distance between two successive riffles $L_R = 30$ cm, were estimated based on the criteria given by Newbury (2008). The final design with the data for the maximum discharge is shown in Fig. 6.

In the current study, four riffles of this type were constructed from the beginning of the Kp 1 to the start of the Kp 2 as shown in Fig. 7.

Laboratory performance: The behavior of riffles was quite similar in all three experiments. At the beginning of the experiment, Kp 1

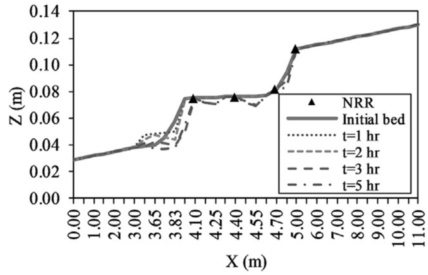

Fig. 8. Time variation of channel bed level in the third experiment ($Q_3 = 0.68$ L/s).

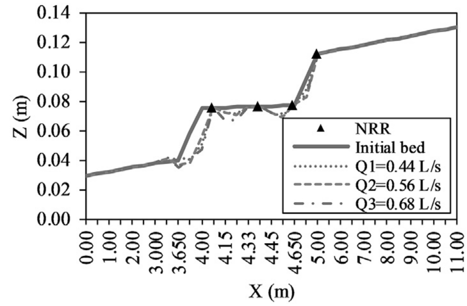

Fig. 10. Longitudinal profiles of the channel for different discharges at the end of each test.

remained fixed. Upstream of the first riffle the flow depth and bed roughness increased, and the Froude number decreased. A hydraulic jump was observed in the basin of each riffle, which dissipated the energy of the flow. The intensity of the jump decreased from the first to last riffle. Kp 2 retreated a short distance until it collided with the last riffle. Initially, scour undermined the structure and dislodged the riprap; however, later deposition fixed the bed level and completely stabilized Kp 2. The performance of the first three riffles was satisfactory, because no sediment deposition, sediment transport, or riprap movement occurred between them. By increasing the discharge, a shallow scour hole appeared between the riffles; however, it did not affect their performance. Fig. 8 shows the longitudinal profile of the channel bed along the thalweg at different times in the third experiment with the maximum discharge.

Fig. 9 shows the contour lines and 3D shape of the stabilized bed with Newbury riffles at the end of the third experiment with the maximum discharge. The bed irregularities, observed in the absence of control structures, disappeared because of the current concentration at the middle of the channel. Contour lines are uniform, and bed scour is relatively symmetric. The last riffle may be designed stronger and with a higher factor of safety to keep the rocks in place. For example, if scour is so severe that it could be destructive, preventive methods may be necessary such as sheet piling underneath the structure.

Fig. 10 shows the final profile of the bed along the thalweg for different discharges. The bed level upstream of KP 1 was fixed, the erosion and deposition between the riffles and downstream of Kp 2 were diminished, and the shape of both knickpoints was maintained. Scour holes were observed between the riffles; however, Kp 1 was stabilized in its own position, and Kp 2 was controlled after a

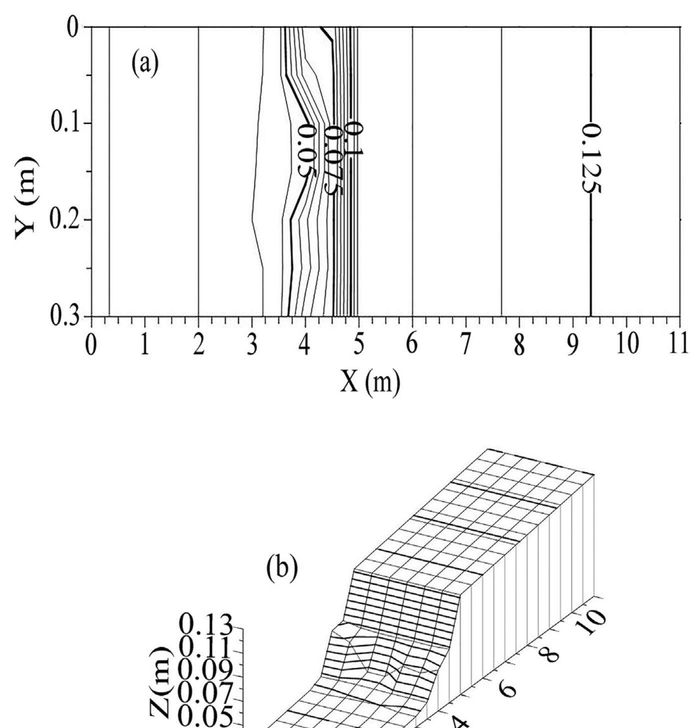

Fig. 9. (a) Contour lines, and (b) 3D shape of bed features in the presence of NRR. in the third experiment ($Q_3 = 0.68$ L/s).

collision with the nearest riffle. The riffles resisted against erosive forces even at high discharges.

5.2.2. Cross-vane riffles (CVR)

Design considerations: Alphabet rock weirs may be constructed in different types of A-, U-, or W-shape. In the current study, the U-shape known as a cross-vane riffle was used and designed based on the criteria suggested by Rosgen (2001). Each vane arm occupied about 1/3 of the flume width at a 30° angle to the stream axis. The vanes were built upstream with a reverse slope of 7 percent. Assuming an effective riffle height of $R_H = 1$ cm, the footer depth was about 6 times the effective height of the structure. However, it should not be greater than 0.9 times the length of the vanes (Fig. 11).

The distance, L_R, between the crests of cross-vane riffles is obtained from Rosgen (2001) as:

$$L_R = 0.082513 {S_0}^{-0.9799} W \quad (4)$$

where W is the channel width. For the current study at the kinck-point locations, $L_R \simeq 25$ cm. In a similar way to the NRR, four riffles of this type were constructed from the beginning of Kp 1 to slightly before the start of Kp 2, (Fig. 12).

Laboratory performance: The performance of these riffles was similar in all three experiments. In the beginning, the first two riffles significantly prevented Kp 1 from retreating. The eroded sediment deposited between the riffles and slightly reduced the bed slope. Kp 2 migrated upstream until the vane of the last riffle collided with it and collapsed. The bed incised, transversely, through the vane arm. This knickpoint was fixed when it interfaced with the sediment deposited between the last two riffles. The first three riffles remained almost intact until the end of the experiments. The upstream channel bed was stable, and the rock particles of the middle vanes did not collapse, though they did settle down somewhat.

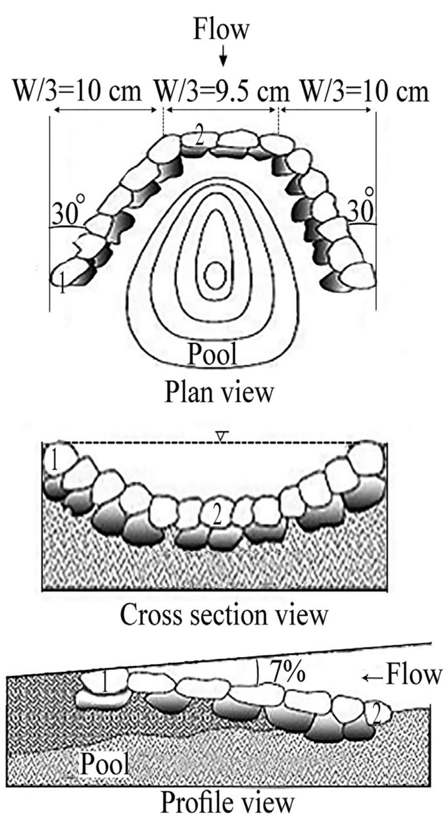

Fig. 11. Plan, cross section, and profile of a cross-vane riffle (Rosgen, 2001).

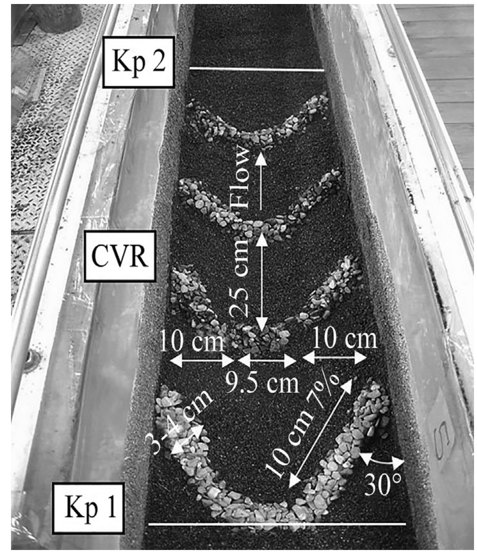

Fig. 12. Constructed CVR.

Fig. 13 shows the variations of the longitudinal profile of the thalweg at different times in the third experiment with maximum discharge. By increasing the amount of deposited material, reach slope between the two knickpoints became steep and the last two riffles were partially buried either because of sediment load or bed settlement.

Fig. 14 shows the contour lines and 3D shape of the stabilized bed in the presence of cross-vane riffles in the experiment with maximum discharge. By concentrating the flow in the middle part of the channel, the contour lines are moderately regular, and the bed scour is fairly symmetric.

Fig. 15 shows the profile of the bed along the thalweg at the end of the tests for different discharges. The riffles were fairly successful in the stabilization of knickpoints and fixing of the upstream bed level. However, major changes occurred at the knickpoint faces and downstream region where the bed and riffles degraded in all of the tests. The bed incision and vane collapse for large discharges proved that these types of riffles should be designed conservatively. By increasing the discharge, the depth of the scour hole increased at the downstream region of each riffle. Later on, Rosgen (2006) amended the design criteria for this structure by adding another row of riprap in the pool zone.

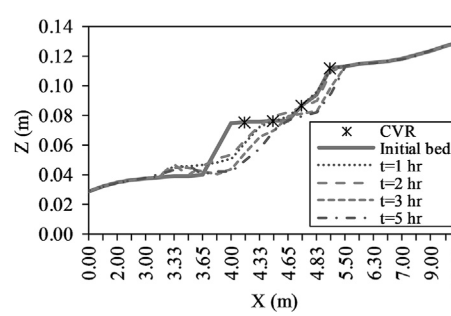

Fig. 13. Time variation of channel bed level in the third experiment ($Q_3 = 0.68$ L/s).

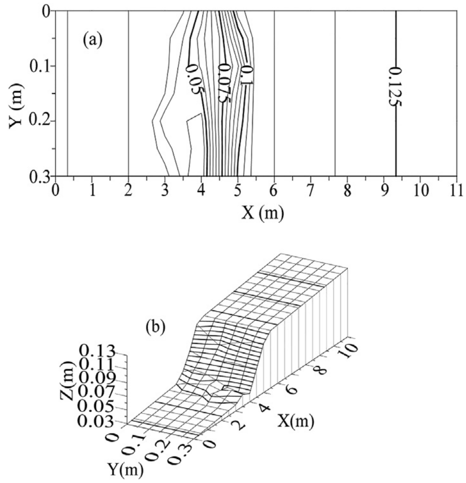

Fig. 14. (a) Contour lines, and (b) 3D shape of bed features in the presence of CVR ($Q_3 = 0.68$ L/s).

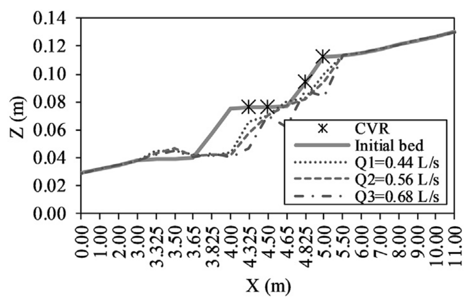

Fig. 15. Longitudinal profiles of the channel for different discharges at end of each test.

5.2.3. Comparison of riffle control structures

Fig. 16 shows the final bed profile along the thalweg at the end of the tests in the presence or absence of control structures for minimum and maximum discharges, respectively. Both of the control structures were relatively successful in bed stabilization and control of knickpoints. The control structures prevented upstream erosion and degradation and also downstream deposition in comparison with the case of no grade control structures. However, the NRR worked better than CVR, in concentrating the flow discharge in the middle part of the channel, having lower settlement and less local scour of the sandy bed between the successive riffles. These results may be attributed to the specific three dimensional shape of this riffle.

5.3. Experiment with the control structure at the second knickpoint (Kp 2)

In the next experiment, the Newbury rock riffles (NRR) of better performance were constructed with the same dimensions and intervals at Kp 2 to allow for incision and migration of Kp 1. The test was run for 5 h at the lowest discharge of 0.44 L/s. Fig. 17 shows the time variations of the bed profile along the thalweg. The depth of water upstream of the riffles increased, and the flow velocity and shear stress decreased. The bed was stable between the two knickpoints, and the retreat rate of Kp 1 decreased, however, the most upstream riffle was buried under the deposited sediment load from the bed incision and headward migration of KP 1 during the experiment.

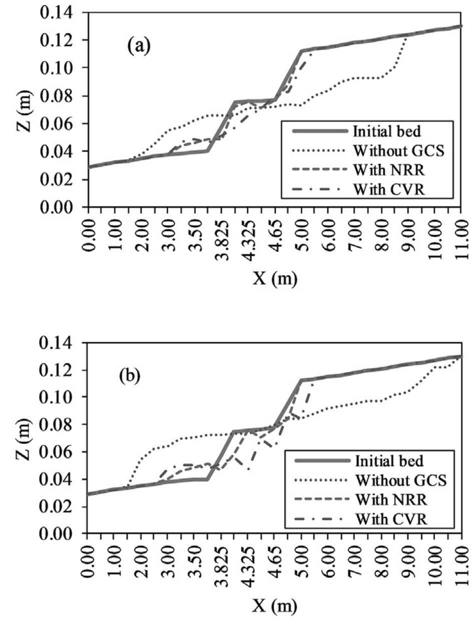

Fig. 16. Longitudinal profile of the channel with and without grade control structures (a) for minimum discharge ($Q_1 = 0.44$ L/s), and (b) for maximum discharge ($Q_3 = 0.68$ L/s).

Fig. 18 shows the performance of the riffles at Kp 1 or KP 2 on the bed erosion and knickpoint stabilization. In both cases, the Newbury riffles succeeded in arresting the knickpoint on which they were built, though the migration of the unprotected knickpoint was inevitable. The NRR also could considerably reduce the erosion rate.

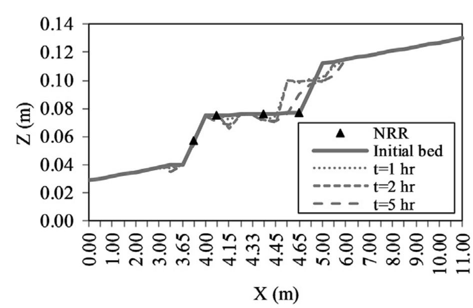

Fig. 17. Time variation of bed level along the thalweg ($Q_1 = 0.44$ L/s).

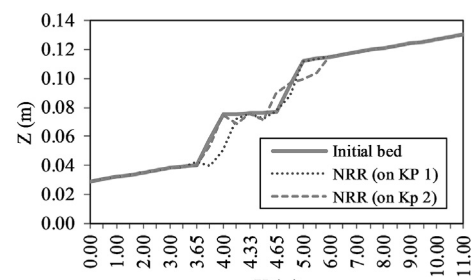

Fig. 18. Longitudinal thalweg profile of channel with NRR at two different locations ($Q_1 = 0.44$ L/s).

6. Conclusions

The migration of two successive knickpoints (KP 1 and KP 2) in a laboratory flume led to incision and degradation of the upstream bed and sediment deposition in the downstream channel. The performance of two different bed control structures: Newbury rock riffles (NRR) and cross-vane riffles (CVR) was studied experimentally in controlling the bed erosion and knickpoint stabilization. The construction of NRR and CVR at Kp 1 and between the two knickpoints prevented the incision of the upstream channel and stabilized both knickpoints for a range of erosive discharges. NRR operated better than the CVR in similar conditions, for they could develop more regular symmetric bed contours. Moreover, the channel bed eroded, and some parts of the side arms of the CVR were buried under the sediment load. The first knickpoint retreated at a lower rate when the NRR were constructed at KP 2. It may be concluded that the best place to construct all types of riffles to cease bed erosion and stabilize the incision is the most upstream of successive knickpoints.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Notation

C	Flow concentration factor (−)
C_u	Coefficient of uniformity (−)
CVR	Cross-vane riffle
D	Sediment particle diameter (m)
D_{50}	Sediment median diameter (m)
D_x	Sediment diameter for which x percent of the particles are finer (m)
Fr	Froude number (−)
g	Gravitational acceleration (m/s^2)
G_s	Specific gravity of particles (−)
GCS	Grade Control Structure
h	Flow depth (m)
h_c	Critical depth (m)
h_0	Normal depth (m)
Kp	Knickpoint
L_R	The distance between two successive riffles (m)
n	Manning's roughness coefficient (−)
NRR	Newbury Rock Riffle
Q	Flow discharge (m^3/s or L/s)
q	flow discharge per unit width (m^3/s.m or L/s.m)
R	Hydraulic radius (m)
R_D	Horizontal intervals between crest to toe (m)
Re	Reynolds number (−)
R_H	The effective height of the riffle crest (m)
R_U	Horizontal intervals between heel to crest of a riffle (m)
S_0	Bed slope (m/m)
S_{RD}	Downstream slope of a riffle (m/m)
S_{RU}	Upstream slope of a riffle (m/m)
S_{RV}	Transverse slope of a riffle (m/m)
V	Flow average velocity (m/s)
W	Channel width (m)
We	Weber number (−)
Z	Bed level (m)
γ	Specific weight of water (N/m^3)
γ_s	Specific weight of sediment particles (N/m^3)
ν	Kinematic viscosity (m^2/s)
ρ	Water density (kg/m^3)
σ	Surface tension (N/m)
τ_0	Bed shear stress (N/m^2)
$(\tau_0)_c$	Critical bed shear stress (N/m^2)
τ^*	Shields number (−)
τ^*_c	Critical Shields number (−)

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