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A Review on Hydraulic and Morphological Characteristics in River Channels Due to Spurs

M. Alauddin, M. M. Hossain, M. N. Uddin, M. E. Haque

***Abstract*—**An optimal design of a spur is the first requirement to make it sustainable and function properly. In view of that, a thorough understanding to the hydro- and morpho-dynamics due to spurs is essential. This paper presents a literature review on the effect of spurs to obtain the most recent design criteria. Perpendicular and upstream aligned impermeable spurs have large disturbances to flow and less stability because of strong vortices and associated scour. Downstream aligned spurs minimize scour holes, but there is a chance of strong return current which could be controlled allowing flow through them. A series arrangement of spurs is important to have the desired results with a special care for the first one. Several equations have been presented in the paper for predicting the scour depth. But, they have to be used carefully. Different flow environments developed by spurs are favorable for various aquatic species. However, it is important to maintain almost a stable flow condition providing stable spurs.

***Keywords*—**Bed topography, flow pattern, scour, spur.

I. Introduction

SPURS are the structures extended from the bank into the stream. These have been used extensively in all parts of the world as river training structures to enhance navigation, to protect erodible banks, and also, to control flood due to bank failure. Spurs are of various types. Based on permeability, they are impermeable and permeable, and also, combination of these two. Impermeable spurs are built of local soil, gravels, stones, rocks or gabions, reinforced concrete (recently in Bangladesh), while permeable ones usually consist of one or several rows of timber, bamboo, steel or reinforced concrete piles. According to submergence, spurs can be submerged or non-submerged. Usually impermeable spurs are designed to be non-submerged, since severe erosion can occur along the spur at downstream side due to overtopping water in submerged spurs. Permeable spurs, however, can be made submerged, since they do not interrupt the flow much as the solid spurs do. Also, based on appearance in plan, they can be straight, T-head, L-head, hockey shaped, inverted hockey shaped, straight with pier head, a combination of different angles to the flow.

Through laboratory experiments and numerical simulation as well, many researchers enriched the literatures concerning spurs for local scour and flow pattern [1]-[4]; river course and bank stabilization by spur like structures [5]-[7]; velocity distribution in spur fields [8]-[11]; exchange processes between river and its spur fields [12], [13], and so on.

M. Alauddin is with the Department of Civil Engineering, Dhaka University of engineering & Technology (DUET), Gazipur (corresponding author, phone: +88-02-49274034 (2041); e-mail: mauddin@ duet.ac.bd).

M.M. Hossain, M.N. Uddin, and M.E. Haque are also with the Department of Civil Engineering, DUET, Gazipur (e-mail: monowar84@duet.ac.bd, nazimduet@gmail.com, enamul091@yahoo.com).

Bank materials of major downstream rivers like Bangladesh consist of loose non-cohesive sediments such as sand, silt and small amount of clay, which is highly susceptible to erosion. People might take full use of rivers including aesthetic and ecological values, if spurs are properly designed and arranged effectively. To explore the optimal design of a spur to make them sustainable and functioned properly, the effect of spurs on the channels has drawn much attention of researchers to investigate. Therefore, detailed up-to-date information on the effect of spurs on the hydro- and morpho-dynamics of channels is explored and summarized in this paper.

II. Design Criteria of Spurs

Intrusion of spurs into a channel causes scour near the head, erosion in the main channel and deposition in the spur field (Fig. 1). Based on these parameters, performance of a spur can be evaluated. The minimum local scour indicates the structural stability; erosion in the main channel maintains navigation facility and deposition in the spur field provides safety to the channel bank from erosion.

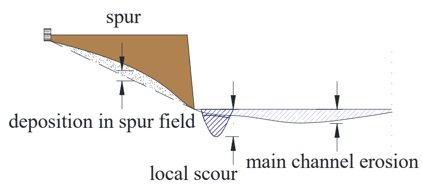

Fig. 1 Changes in channel bed due to spurs (Definition sketch)

Orientation of spurs affects the stream in a different way, and results in deflecting the flow away of different degree and hence, different amount of deposition of sediment in the spur field. A straight spur is usually installed from the bank with an angle and additional care is taken at the end to protect the spur head, especially when it is placed at 90^o or larger angle with the flow. The orientation of T-head spur is usually 90^o with the bank. In spurs combined with different angles, the first part (perpendicular to the flow) deflects the flow away from the bank and the rest part (60^o to the flow) concentrates the flow to favor erosion in main channel for navigation [14].

A part of the total length of a spur is embedded in the bank which is called anchoring length, and the other part extended from the bank into the flow, called as working length. The area along the bank to be protected, the required depth for navigation purposes and the width of channel determine the length of spur. However, this length may vary based on the flow conditions: high flow or low flow. The anchoring length is usually maintained less than a quarter of the working length.

However, the working length is fixed adding the mean depth with the quarter of mean width of channel. This is also recommended to embed the root of the spur into the bank 4 to 10 meters [15].

The spacing between spurs is related to river width, spur length, velocity of flow, orientation of spurs to the flow, bank curvature, and purpose. It is often expressed as a multiple of the spur length. Richardson et al. [16] recommends a spacing of 1.5 to 6 times the upstream projected spur length into the flow. An aspect ratio (length of the spur field to the length of the spur) of 1.5 to 2.0 is recommended for obtaining a distinct channel for navigation purposes, and for bank protection purposes, the ratio of 2 to 6 is generally used. In a series, spacing of spurs should be fixed considering all related factors including both high flow and low flow conditions. If the water level changes, the working length of spur may vary, and hence the spur ratio can vary significantly. If the spacing between spurs is too long, a meander loop may form between spurs. However, if the spurs are spaced too close together, the system will not be cost effective.

The crest elevation of spurs depends on the purpose and possible problems due to overtopping of flow and ice. For bank protection, the crest level of spurs should be at least as high as the bank. The crest of spurs can be sloped downward towards the head or kept level. For sloping-crested spurs, the strong vortices and the return currents are partly counterbalanced, so that scour near spur head reduces, and sediment particles settle down in the spur field. Thus, these can be implemented for bank protection with a slope of 1:10 to 1:4 [17]. The spurs with sloped crest work best normal or angled upstream, whereas, level-crested spurs preferable for navigation purposes work best normal to the flow or angled downstream, as in [16].

III. Changes in Flow Pattern

The spur in a river bank confines a certain part of its cross section and affects appreciably the kinematic structure of the flow in its vicinity [18]. Mean velocity and specific discharge increase due to the constriction made by the spurs. An intense vortex action occurs at or near spurs. Intermittent vortices also occur on the upstream and downstream sides of spurs.

The flow field near spurs differs significantly in a single spur from that in the case of a series of spurs. The flow past a spur may be divided into four main zones [19]: main flow zone, return flow zone, shear layer, and reattachment zone (Fig. 2). From the tip of the spur to the opposite channel bank is called the main flow zone. The return flow zone is located at the downstream side of the spur, generally with two relatively large eddies. The center of the larger one is located at a distance of about six times the spur length. The other one is smaller, the center of which is about one time the spur length. A velocity difference exists between the main flow zone and the return flow zone, which leads to the formation of a shear layer between the two zones. The reattachment zone is usually defined by most of the researchers as a point at which the boundary streamline reattaches to the channel boundary. The reattachment point is located at a distance of about 14 times the length of the spur as in [19].

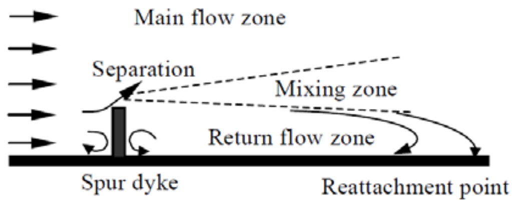

Fig. 2 Flow zones due to a spur [20]

From the laboratory experiments Molinas et al. [21] reported that the velocity at the spur head might be increased up to 1.5 times the approaching flow velocity, depending on the flow conditions and spur protrusion ratios. Similar results were also found by Ho et al. [22]. Also, from the field observations, it was found that the oblique flow reflected from the large sandbars in the Jamuna River attacked the Enayetpur spur in Bangladesh. The oblique flow approached towards the upstream side of the spur and then the concentrated flow with sufficient strength travelled in the upstream side causing huge scour. Also, huge circulation of flow was recognized at the spur-head [23].

The spur field is not really a part of the cross section of a river which can contribute to the flow. Accordingly, the flow pattern in spur field does not directly contribute to the discharge in the main channel. Reducing the stream velocity has little effect on the flow pattern; however, lowering the spur head affects the pattern as in [13]. The flow pattern inside a spur-field may change with the change in its geometry, location along the river (inner curve, outer curve, or straight part), and/or the orientation of spurs [24]. Also, there is an indirect effect of the discharge on the flow pattern in the spur-field. Because of the flow that is diverted from the main channel into the spur-fields, the water flows into the spur-field with low velocity through the downstream half of the interfacial section between the spur-field and the main channel. This water flows back to the main channel through a small width of that section, just downstream the upstream spur of the spur-field [25].

An important aspect of the flow field near a spur is the horizontal large eddies that shed from the tip of the spur. Through measuring the water level fluctuations along the centreline of the migrating vortices, it is found that there is a clear periodic water level fluctuation as in [19]. The water level increases in the upstream side of the spur and decreases in the downstream side, and continuously fluctuates as the horizontal eddies periodically shed from the tip of the spur.

Kurzke et al. [26] executed a laboratory test to calculate the exchange of water quantities between the main flow zone and the impermeable spur field. It was depicted through close observation that the flow pattern for emerged spurs was predominantly two-dimensional in the spur field. The small-scale three-dimensional turbulence plays a minor role in the mass and momentum exchange process between the spur-field and the main channel [27]. Further, he concluded his observation on the effect of geometry on the flow field that the spur-field length to width ratio determines the number and shape of eddies that emerge in the stagnant flow region. An aspect ratio close to unity gives rise to a single eddy. A larger aspect ratio gives room for two stationary eddies, a large one called primary eddy, in the downstream part of the spur-field, and a smaller secondary eddy, emerges near the upstream spur. In a long spur field with length to width ratio of around six, the flow penetrates into the spur field (Fig. 3). In order to provide safety to the channel bank from erosion by the return current, an aspect ratio less than three is recommended based on both numerical and experimental results [28].

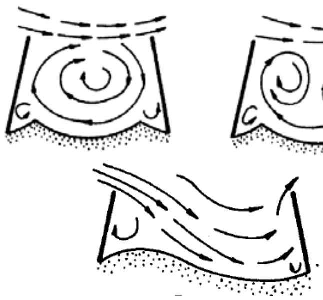

Fig. 3 Flow pattern in a spur-field as in [24]

The velocity pattern gets more complex when the spurs are submerged. In this case, the flow is accumulated from more than one direction. The flow over the crest first travels upward and then, a strong downward flow is introduced to the wake area behind the spur dyke as in [2]. Recirculation of flow is also present in this case. Thus, these affect highly the flow structures around the spurs [29], [30]. Furthermore, the over-topping ratio (water depth to spur height) has an important control on the flow pattern and hence, on the geometry of the resulting scour hole.

Complexity of the flow past a spur further increases with the development of scour hole. Three-dimensional (3D) flow characteristics are evident in the local scour, where several components of flow can be identified. A bow wave develops near the water surface in front of the non-submerged spurs and a downward component of flow can be marked because of still water made at upstream side. As a result of the flow separation, a horseshoe vortex develops in the lower part at upstream side of the spur as in [20] (Fig. 4).

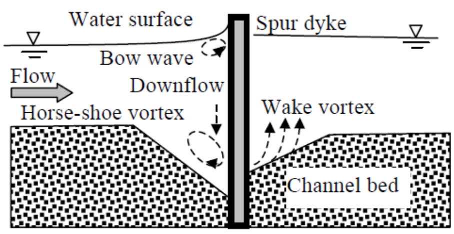

Fig. 4 Typical flow in a scour hole as in [20]

In submerged spurs, the complexity and three-dimensionality of the problem require advanced measurement techniques, and/or powerful three-dimensional computational abilities. There is a sharp decrease in the water level between the upstream and downstream sides of a spur [31]; this means that the water surface slope between two successive spurs is less than the slope in the main channel region. Three-dimensional numerical results were compared with experimental results and it was found that the flow pattern in the case of submerged spurs shows strong three-dimensional features behind them [32]. The recirculation size at the back of the spur is reduced gradually as the flow passes over the spur. Separation flow over the upstream spur may reattach the spur-field bed and the bed shear stress recovers its large value (that is usually reduced because of the spurs), if the spurs are spaced far apart. Too close spurs will prevent the flow reattachment to the bed maintaining the bed shear stress at low value, as in [32].

IV. Changes in Bed Topography

A. General

Scour, a localized lowering of riverbed, is usually linked to structures. This can be subdivided into constriction scour and local scour. Constriction scour arises from the constriction of the waterway by the presence of the structure. It changes the cross section geometry in the area near the structure, and normally it does not extend to a longer distance. Local scour is resulted from the effect of the structure on the local flow pattern and the generation of macro-turbulent in its vicinity. It is always more pronounced than the constriction scour. The local scour may be – in most cases – superimposed on constriction scour. The term degradation, in contrast to scour, implies a lowering of the riverbed that extends over a long distance. Usually, channel bed degradation is accompanied by change in the river slope. Degradation may progress in the downstream direction, upstream direction, or in both directions. When a series of spurs are constructed, there are combined effects of bed degradation due to the long constriction and vortices at the end of each spur causing local scour. Thus, the bed forms near the spurs change, and the spurs function more better way than a solitary spur does. The following sections explain about bed level changes due to spurs.

B. Scour Due to Spurs

The scour depth is related to the Froude number, contraction ratio, sediment transport characteristics, main channel geometry and flow at the spur [15]. According to Garde et al. [33] grain size and velocity are the important parameters which are responsible for scouring near spur, and they commented that the maximum scour depth to be greatest for a spur which was placed perpendicular to the bankline and that was reduced for all other orientations upstream and downstream. Laboratory experiments were conducted for scour pattern around diverse cases of impermeable spur with changing geometry [34]. Scour depth was found higher with the high values of the blockage made by the spurs, Froude number, and the angle of inclination of spur with respect to the flow direction. The greatest width of scour hole was found corresponding to the 135 degree spur, but they provided improved aquatic habitats and minimized the possible erosion of the channel bank. The local scour around single straight impermeable submerged spur installed in a channel with different angles with respect to the flow direction was studied by Ezzeldin et al. [35]. The researchers showed that the main reason for the drift is vortex, which takes the form of a horseshoe around spur, but its impact disappears when it reaches Froude number that lessens the intensity of the flow around the spur. Hence, the vortex causing erosion becomes weaker and slower, and ability of flow to carry sediment decreases. The half horse-shoe vortex generally results in a local scour which has a conical shape with relatively mild slope in the downstream [36]. On the other hand, the horse-shoe vortices around the pile group, which are compressed, develop a valley-shaped scour. Alauddin [37] conducted extensive studies to comprehend the flow and morpho-dynamics against various orientations and configuration, non-submerged spurs in straight sand-bed channels. It was found from his study that the spurs with smaller angles to the flow altered the flow pattern in the main channel to cause deepening of the channel as required at low flow condition for navigation purposes, and reduce depth of scour near spur at high flow time to provide safety to the structure. These can be understood from Fig. 5. Strong vortices due to perpendicular spur (impermeable) caused huge local scour, whereas, it was reduced when its alignment was modified with downstream aligned part. However, in the case of downstream aligned impermeable parts, there is a tendency of strong return currents which can attack the same bank where the spurs are installed for protection. This tendency was minimized when the downstream aligned part is made permeable. The flow passes through the permeable part obstructed the flow to take turn towards the bank. Thus, analyzing the changes in flow pattern and bed level due to interactions with various impermeable and permeable spurs, this was argued that there might be a way to achieve a balance in the channel response when impermeable and permeable parts are suitably combined in a spur.

C. Scour Estimation

Due to intrusion of spurs, the turbulence associated with vortices causes bed materials to become suspended from the bed near the spur head resulting in scour holes. In designing spurs, the expected scour depth should be taken into consideration to determine the depth of base. Prediction of scour at spurs is usually based on prior experience with a particular river or by the use of physical model studies. However, equations can be used to predict scour because of limited resources. Several equations were derived from tests in laboratory flumes with limited verification by prototype testing. Prototype data are very difficult to obtain due to filling of the scour hole in the time of flood recession and there is inconvenience and dangerous working condition at high river stages.

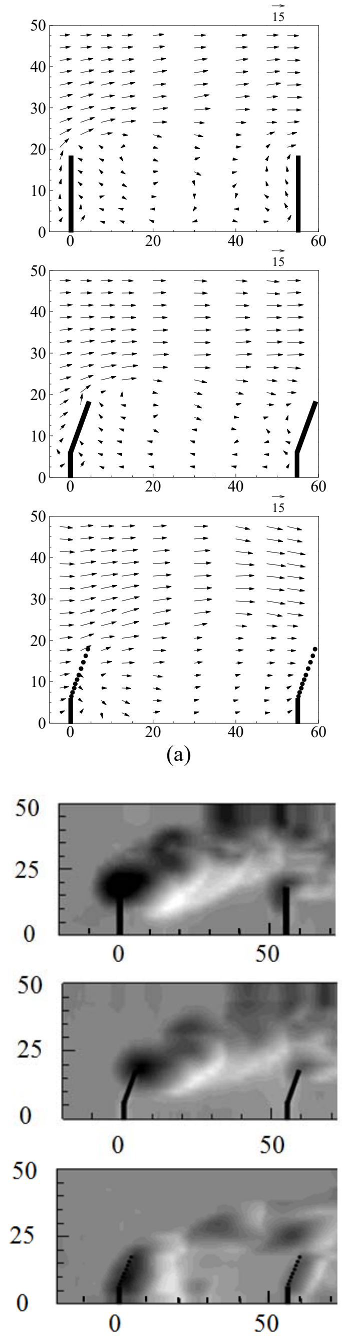

Fig. 5 (a) Flow fields and (b) bed topography due to spurs of different configuration

Based on a series of experiments conducted in the University of Auckland, New Zealand, some important formulae were proposed by Melville [38]-[40] for determining the equilibrium scour depth. An extension of this kind of researches is to taking into account the temporal variation of the local scour holes. Most of them are achieved by determining a function relating the time-dependent scour depth to the equilibrium scour depth [42]-[45]. Some of the equations in determining scour depth are listed below.

Lacey [46] proposed a formula for the prediction of the maximum scour depth around abutment-type structures as:

$$y_{s,max} = 0.47 y_1 K\,[Q/(f y_1^3)]^{1/3} - y_1 \quad (1)$$

with: $y_{s,max}$ = maximum scour depth measured from the water surface near head of structure, y_1 = mean water depth of contracted section before scour, Q = regime discharge (in m^3/s), $f = 56(d_{50})^{0.5}$ = sediment factor, d_{50} = sediment diameter (in m), K = coefficient depending on geometry (≈ 2 for rounded head to 4 for steep sloping head).

Inglish [47] developed the following formula for scour estimation,

$$y_s = k\left(\frac{Q}{f}\right)^{1/3} \quad (2)$$

k = function of approach conditions varying between 0.8 and 1.8.

In determining the depth of equilibrium scour near spurs, many researchers through laboratory experiments independently reached at similar expression which takes the form, $d(\infty) = K\,q^{2/3}$ [48]-[50]. The expression of Ahmed [51] as in [50] reads:

$$y_{s,e} + y_0 = K_A K'_A\left(\frac{q}{1-m}\right)^{2/3} \quad (3)$$

where: $y_{s,e}$ = equilibrium scour depth below initial depth, y_0 = initial water depth, $m = b/B$, b and B are the width of the dike and channel respectively, q = discharge intensity

$$K'_A = 2.14 g^{-1/3}\ (\cong 1.0\ m^{-1/3}s^{2/3}),\ K_A = 2K_p K_s K_\alpha K_\mu$$

K_p = correction factor for the influence of channel bend (inner = 0.85, outer = 1.1~1.4), K_s = for the shape of structure (vertical wall = 1.0, 1:1 sloped = 0.85), K_α = for the angle of attack (30^o to 150^o = 0.80 ~ 1.10), K_μ = for the influence of porosity (0.2 porosity = 1.0, 0.5 porosity = 0.9~0.6).

Considering the length of spur and Froude number, Liu et al. [52] proposed an expression for scour estimation as,

$$y_s = y + 1.1y(L/y)^{0.4} Fr^{1/3} \quad \text{for } L/y \le 25$$

$$y_s = y + 4.0y\,Fr^{1/3} \quad \text{for } L/y > 25 \quad (4)$$

where, L = effective length of spur, F_r = Froude number, and y = average depth in unconstructed section.

According to Blench [53], scour can be estimated as,

$$y_s = k\left(\frac{q^2}{F_r}\right)^{1/3} \quad (5)$$

where, k varies between 2.0 and 2.75.

Gill [48] introduced the channel constriction and the effect of sediment size in estimating the scour depth as,

$$y_s = 8.375y(d_{50}/y)^{0.25}(B_1/B_2)^{0.83} \quad (6)$$

where, B_1 = original channel width, B_2 = constricted channel width.

Based on laboratory experiments with spurs with vertical noses, scour depth at the nose of the spur can be estimated with the Neill formula [54] as,

$$H' = \frac{2.1}{y}\left(\frac{2.5q^2}{d^{0.318}}\right)^{0.333} \text{ to } H' = \frac{2.75}{y}\left(\frac{2.5q^2}{d^{0.318}}\right)^{0.333} \quad (7)$$

where, $0.1 \le d_{50} \le 200$mm, H' = relative maximum scoured depth, mm; y = flow depth before scour, mm; z = depth of scour below y, mm; d = size of bed materials, mm.

Suzuki et al. [55], showed through laboratory experiments, that the local scour depth around a spur located far downstream in a series of spurs is a function of the spacing (S) to length (L) ratio, and it could be expressed roughly in the following form:

$$\frac{Z_{s,DS}}{Z_{s,1}} = 0.07\frac{S}{L} + 0.14 \quad \text{for } 2 < \frac{S}{L} < 10 \quad (8)$$

where: $Z_{s,DS}$ = scour depth around any spur far downstream, $Z_{s,1}$ = scour depth around the first spur which is similar to the scour depth near a single spur.

When (S/L) >12, i.e. the spurs are very far apart, the group action vanishes and the scour depth near any spur is nearly the same as that of a single spur.

Klaassen and Vemeer [56] developed a formula for calculating scour depth in the Jamuna River. Their study was specially based on the feasibility study of the Jamuna Bridge. The equation is as

$$\frac{y_{cs}}{y} = 1.292 + 0.037\theta \quad (9)$$

where, y_{CS} = confluence scour depth, θ = junction angle.

Wang & Yanapirut [57] analytically derived the static equilibrium bed degradation formula as,

$$\frac{y_2}{y_1} = \left(\frac{B_1}{B_2}\right)^{6/7} \quad (10)$$

where, y_1, y_2 = depth of flow before and after constrictions, respectively. Further, they extended the formulation through dimensional analysis and dimensionless plots to include the ratio (S/L) that reads:

$$\frac{y_2}{y_1} = \left(\frac{B_1}{B_2}\right)^{6/7}\left(\frac{S}{L}\right)^{-1/7} \quad (11)$$

Analyzing field data from rivers, the following expression was proposed for calculation of depth of scour [50]:

$$y_{s,max} = \alpha[q_o/(1-m)]^{2/3} - y_1 \quad (12)$$

with: α = coefficient depending on geometry (≈1 to 2 for straight channel and spur normal to bank), q_o = discharge per unit width at upstream of contracted section (in m^2/s), $m = L/B$ = blocking coefficient.

Rahman and Haque [58], taking the structure length into account, modified the Lacey's equation [39] into:

$$d_{s,max} = 0.47y_1 M^{1/3}[1+1.5L/y_1]^{1/3} - y_1 \quad (13)$$

with: $M = Q/(fy_1^3)$ = discharge coefficient. They also presented field data of scour depths near abutment-type structures along the Jamuna River. The relative scour depth values ($y_{s,max}/y_1$) are found in the range of 0.5 to 2 for a length scale of about L/y_1 = 7 to 12 and about 1 for L/y_1 = 40.

According to [34], the maximum scour depth, y_S, is the dependent variable and can be expressed as a function of other independent variables as,

$$y_S = f(g, \rho, v, H, V, V_C, B, b, \phi, S, L_{up}, L_{down}) \quad (14)$$

where, g = gravitational acceleration, ρ = fluid density, v = kinematic viscosity, H = depth of approach flow upstream of the piles, V = mean flow velocity, V_C = critical flow velocity, b = length of obstruction, ϕ = angle of attack, S = shape factor, L_{up} = length of scour upstream the spur, L_{down} = length of scour downstream the spur.

Dawood [59] conducted laboratory experiments in a straight channel with impermeable spurs of three different shapes: straight, T-head and L-head. He utilised non-submerged spurs of three different numbers: 1, 2, and 3 in the runs. It was found indirect relationship between the effect of spur numbers and shape of spurs on the maximum depth of scour. In case of multiple spurs in the experiments, the distance between the spurs was 1, 1.5, and 2 times the length of spurs. This could be noted that the depth of scour was increased by around 20% with increasing the distance of spurs by 0.5 times the length of spur. This is very important to provide series arrangement of spurs to have desired results. However, in the group of spurs, first one is affected highly, and special care should be taken for this. Karami and Ardeshir [60] performed experiments on spurs placed in a series and introduced a spur to reduce the scouring of the downstream spurs which was called a protective spur. The effect of each spur had on other spurs of the series was investigated experimentally, with an emphasis on the influence of the protective spur in reducing the scour around other spurs. The incorporated protective spur was shown to effectively decrease the scour around the spurs placed sequentially. Nevertheless, it was left susceptible to scour potential which diminished its functionality. Jourabi et al. [61] proposed to introduce another spur called sacrificial spur to decrease the scour potential around a protective spur as the main focus, and the sequential spurs as well.

The equations presented above are in very brief. The mentioned references should be checked for detailed information. There may have wide variations in the prediction of local scour. Their applicability should be checked carefully with physical model studies.

V. Environmental Effects

Other than land reclamation, aquatic habitats in alluvial rivers can be restored installing in-stream structures like spurs to enhance channel diversities in terms of flow patterns, bed topographies and substrate compositions. Variety in flow pattern developed by the structures play essential roles in the life cycles of many aquatic species such as fishes and macroinvertebrates, and is recognized as the important habitat suitability in the riverine area [62]-[65].

As found from field survey by Uddin and Rahman [66], after installation of spurs, some *char* lands are formed at various locations along the bank and inside the river as well. Due to low water and backward water flow simultaneously, different types of fish populations dwell there. However, it is very uncertain to maintain in-stream flow requirements in the channels at low flow season that is very important for maintaining aquatic habitat necessary for the healthy life cycle and the river ecology. Also, at high flow season, different flow velocities made at different zones by the installed spurs are favorable for various species of aquatic lives. So that these variety of flow conditions are important to establish with the provision of stable spurs. Otherwise, certain species of aquatic life grown up in the area cannot survive anymore because of unfavorable flow environment.

VI. Conclusions

This study aimed at reviewing the literature on the effect of spurs to explore their design criteria for proper functioning. Specific discharge in the main channel outside the spur field is increased due to constriction made by the spurs. In the spur field, almost a stagnant region is developed, except intermittent vortices and large eddy, single or multi, based on spur ratio are formed.

Spurs should be oriented in such a way to function efficiently at high flow and low flow both for bank protection and navigation respectively. Strong vortices due to perpendicular and impermeable spurs are minimized when alignment of spur is modified with downstream aligned part in the far end from the bank. However, the chance of return current to attack the bank is increased, and this can be minimized by making that portion permeable. The crest of spurs can also be sloped from bank to channel to serve this function.

A series arrangement of spurs is important to have desired results. First spur in a group is affected highly, so that special care should be taken for this. Additional spurs could also be used at upstream to provide safety to the spurs of critical zone. Spacing of spurs should be fixed considering all related factors including high flow and low flow conditions when spur ratio may vary significantly, and flow has sufficient strength to cause huge scour. Scour is more pronounced for impermeable perpendicular spurs.

Several equations have been presented in the paper for estimation of scour depth. There may have wide variations in the prediction. Their applicability should be checked carefully with physical model studies. Different flow environments developed by spurs are important for various aquatic species. However, stable flow condition, especially minimum required flow at low flow and nearly a stable environment with stable spurs at high flow are required to maintain.

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