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On the Formation of Stable River Course

Md. Munsur RAHMAN*, Hajime NAKAGAWA, A.T.M. KHALEDUZZAMAN**, Taisuke ISHIGAKI and Yasunori MUTO

* Institute of Water and Flood Management, Bangladesh University of Engineering and Technology, Bangladesh
** Sub Divisional Engineer, Bangladesh Water Development Board, Bangladesh

Synopsis

As an alternative low cost method that can be adaptive within local socio-economic and environmental condition, the possibility of use of bandals for the formation of stable river course is explored. The basic features of bandals in terms of flow and sediment control are clarified using simplified mobile bed experiments. Based on experimental results, simplified analytical models for the prediction of main channel degradation and local scouring around the structures are developed and verified using experimental data. The model predicts the experimental results reasonably well. Finally, the concept of gradual method for river course stabilization is discussed on long-term basis.

Keywords: stable, alluvial river, bandals, low cost, long-term

1. Introduction

Formation of stable river course discussed in the present study is to develop such a river that follows a designated path ensuring adequate protection to the river bank and forming deep navigational channel in the main stream preserving or restoring its natural environment. Revetments or a series of impermeable groins installed from single or either side banks are traditionally adopted to achieve those objectives. Formation of degraded main channel due to series of groins is often treated using the approach of long contraction (Laursen, 1964; Komura, 1966) with revetment considering only the effect of width contraction and ignoring the effect of local structures (Michiue et al., 1984) mostly because of the complex interactions between the local effect and contraction effect.

Due to flow separation at the groin head, return currents are developed towards the groin field area and often attack the riverbank. Owing to these difficulties, sometimes, permeable groins are used as a solution of the above problem (FAP 21, 2001). Flow passes through permeable groins towards the downstream oppose return currents develop at the end of the structure. The amount of flow diversion towards main channel and the amount of flow reduction towards bank side depends mainly on permeability of the structure.

Usually, river training structures are constructed during low flow period in order to get their function during the upcoming monsoon and onward. Changes related to local scours around structures and interaction between local scour and riverbed morphology are very rapid during the first monsoon due to rivers reaction against such interventions. Rivers need sufficient time to adjust with the modified condition towards the formation of stable courses. However, the scale of rivers responses against such human interventions depends on the scale of the imposed disturbances. In small rivers (in terms of channel width), the lateral length of impermeable or permeable groins would be reasonably manageable from the hydraulic viewpoints if the economic situations of the respective community can afford the required cost involved for the implementation of such projects. However, these kinds of structures are often extrapolated towards the larger rivers on the basis of the experiences in the smaller rivers (Klaassen et al., 2002). Very often, the extrapolated structures for large rivers are too expensive to implement along the entire river reaches in the developing countries like Bangladesh. Therefore, selection of priority sites (most vulnerable to erosion) are usually identified and recommended to protect first. Such kinds of intervention create local changes leading to changes in the entire river reach and in the long run, stabilized courses can never be formed. Rather intermittent local interventions would make the problem even more complex. In addition to these factors, it is already proved in some developed countries that the above conventional methods can never provide environmentally suitable solutions (Klaassen, 2002) even though these are proved to be effective against bank erosion and to some extent stream restoration (narrowing and deepening the base-flow-channels) in smaller rivers (Shields et al., 1995).

Owing to these difficulty of adopting the conventional methods for alluvial river course stabilization and restoration, alternative low cost methods are need to be developed that can be adaptive within local socio-economic condition and would be environmental suitable solution as well. Klaassen et al. (2002) discussed the need for the development of such approaches from their experiences at the Rhine River in the Netherlands and at three main large rivers in Bangladesh (Brahmaputra, Ganges and Meghna Rivers). To this extent, Rahman et al. (2003) discussed the preliminary idea on the possibility of use of bandals for the formation of stable river course. It would be a gradual method that allows the river enough time to adjust during each stages of small intervention using bandals instead of conventional intervention using groins or revetments at one time. Also, it would be a cost effective solutions for stabilizing macro scale sand bars along the major rivers in Bangladesh where about 600,000 people used to live (Sarker et al., 2003).

On the way towards the desired goal, the hydraulic functions of bandals need to be explored as a first step. Therefore, the basic features of bandals in terms of flow and sediment control are discussed from the results of simplified mobile bed experiments under clear-water scour using a series of such structures installed from both side-bank. Based on experimental facts and flow visualization, simplified analytical models for the prediction of main channel degradation and local scour depth around the structures are developed and verified using experimental data. Finally, the concept of gradual approach for the formation of stabilized river course and macro-scale sand bar is explained using bandals on long-term basis.

2. Functions of Bandals

Bandals are one of the local structures developed in the Indian Sub-Continents that obstruct flow near the water surface and allow it to pass near the riverbed. These are made of naturally available materials such as bamboos and woods that are regarded as inexpensive method over conventional structures and mostly applied for the improvement of navigational channels (Hanna, 2001) during the low flow season. Information available on bandals so far is from field experiences and features of flow and sediment transport around them are still unknown.

The sediment materials of an alluvial river are transported both as bed load and suspended load. Even in the case of suspended load, most of the sediment is transported near the bed. This feature of sediment transport is the key to use bandals. The working principles of bandals for the control of water and sediment flow are shown schematically in Figure 1 (Rahman et al., 2003a; 2003b). Within the lower half of the flow depth, major portion of the sediment flow is concentrated, while, the reverse is true for the water flow discharges. The essential characteristics of bandals are that they are positioned at an angle with main flow and there is an opening below it while the upper portion is blocked. As a thumb rule, the blockage of the flow section at upper part should be about 50% in order to maintain the flow acceleration. The surface flow is being forced to the upstream face creating significant pressure difference between the upstream and downstream side of bandal. The bottom flow is directed perpendicular to bandal resulting near bed sediment transport along the same direction. Therefore, much sediment is supplied towards the one side of channel and relatively much water is transported to the other side. The reduced flow passing through the opening of bandals are not sufficient to transport all the sediment coming towards this direction, resulting

Table 1 Experimental condition

Q (l/s)	h (cm)	b/h	S/b	u (cm/s)	I	d_{50} (mm)	u_*/u_{*c}	Re_*	Re	Fr
10.52	4.56	3.3	4	23.30	1/3000	0.19	0.83	2.33	10,678	0.35

Here, Q = flow discharge; h = water depth at uniform flow condition before the installation of bandals or groins; u = approach flow velocity; I = channel slope; d_{50} = sediment diameter of 50% finer; u_* = approach shear velocity; u_{*c} = critical shear velocity for sediment transport; b = projected length of bandals or groins measured perpendicular to flow; S = center to center spacing between bandals or groins; Re_* = particle Reynolds number; Re = Reynolds number and Fr = Froude number;

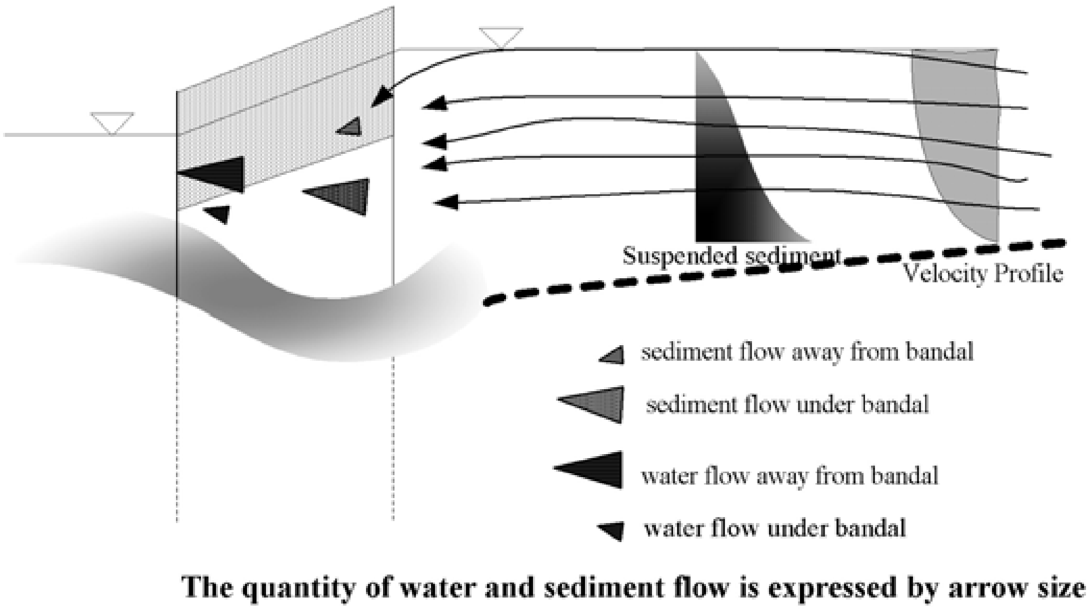


Fig. 1 Working principles of bandals

sedimentation over there (bank side). On the other hand, more water flows with little sediment moves towards the main channel that develop deeper navigational channels over there.

3. Hydraulic Experiments

3.1 Experimental method

Experiments were performed in a re-circulated straight flume that is 20 m long, 1 m wide and 28 cm deep at Ujigawa Open Laboratory, Disaster Prevention Research Institute, Kyoto University (Fig. 2). The hydraulic conditions for the experiments are shown in Table 1.

Mobile bed experiments with a series of impermeable groins and bandals were carried out under the above hydraulic condition. After several trial values of approach u_*/u_{*c} ratio, such lower u_*/u_{*c} (= 0.83) was adopted in order to avoid bed forms in the approach flow upstream of the control reach. However, in the downstream of control reach, bed forms and then sediment transport was occurred resulting bed level lowering over there. Therefore, the average bed level lowering in the downstream reaches was subtracted

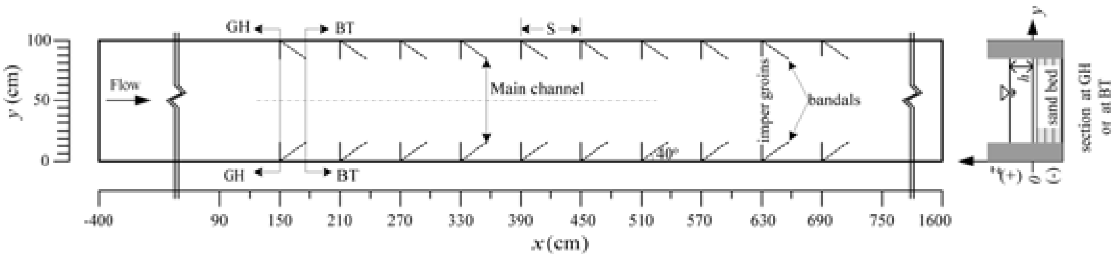


Fig. 2 Experimental arrangements

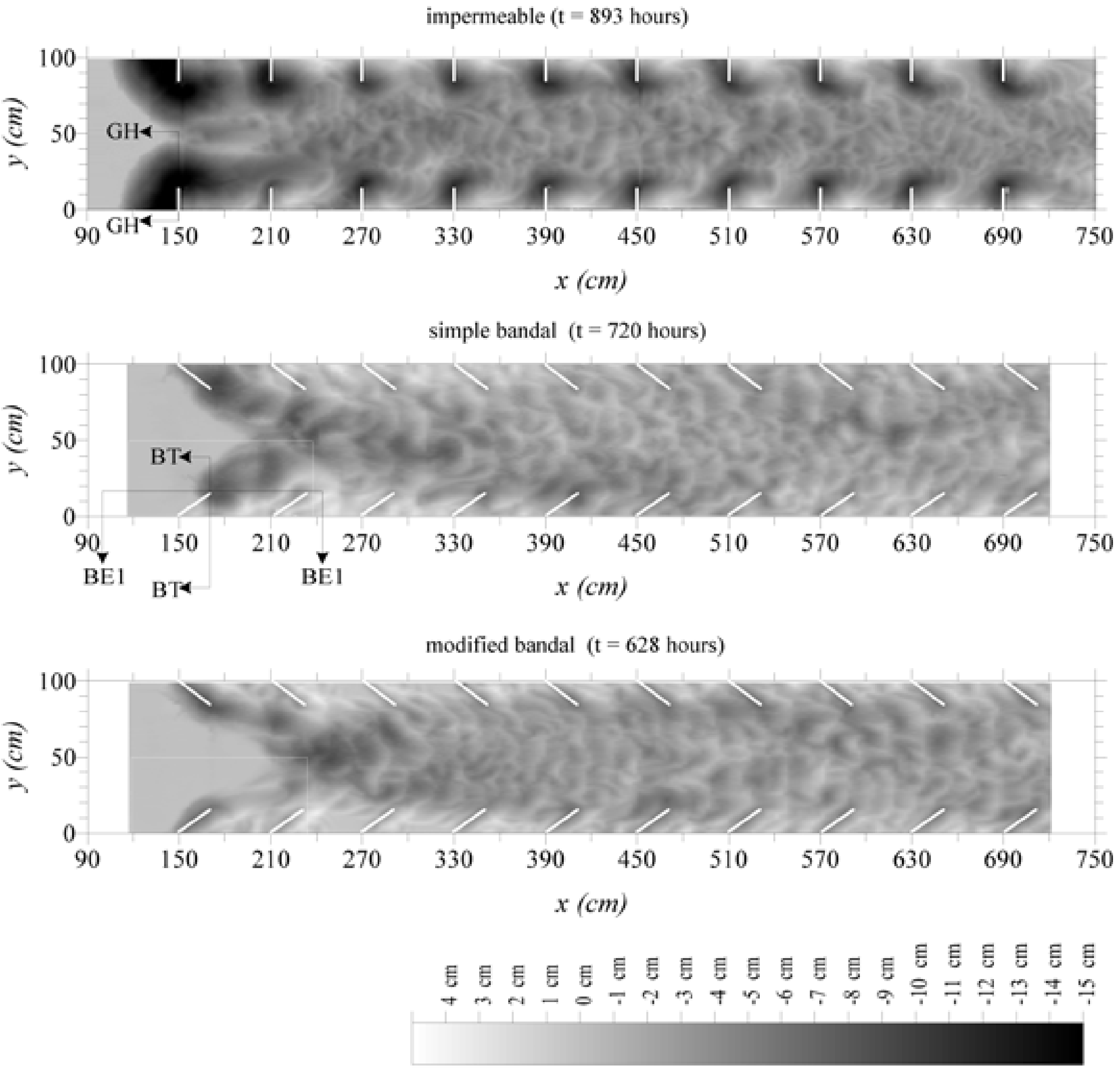


Fig. 3 Final bed shape for impermeable groins, simple bandals and modified bandals

from gross values of main channel degradation and local scour depths to get their net values. For impermeable groins, 10 pairs of wooden plates were installed from both side of channel wall perpendicular to flow and run time was 893 hours until the equilibrium condition was reached. In the case of bandal experiments, two kinds of structures were adopted. For simple bandals, the upper half of the flow depth was blocked by bandal plate made of plastic board and the lower half of the flow depth was free that allowed the flow to pass towards the downstream direction. For modified bandals, bended plate was used

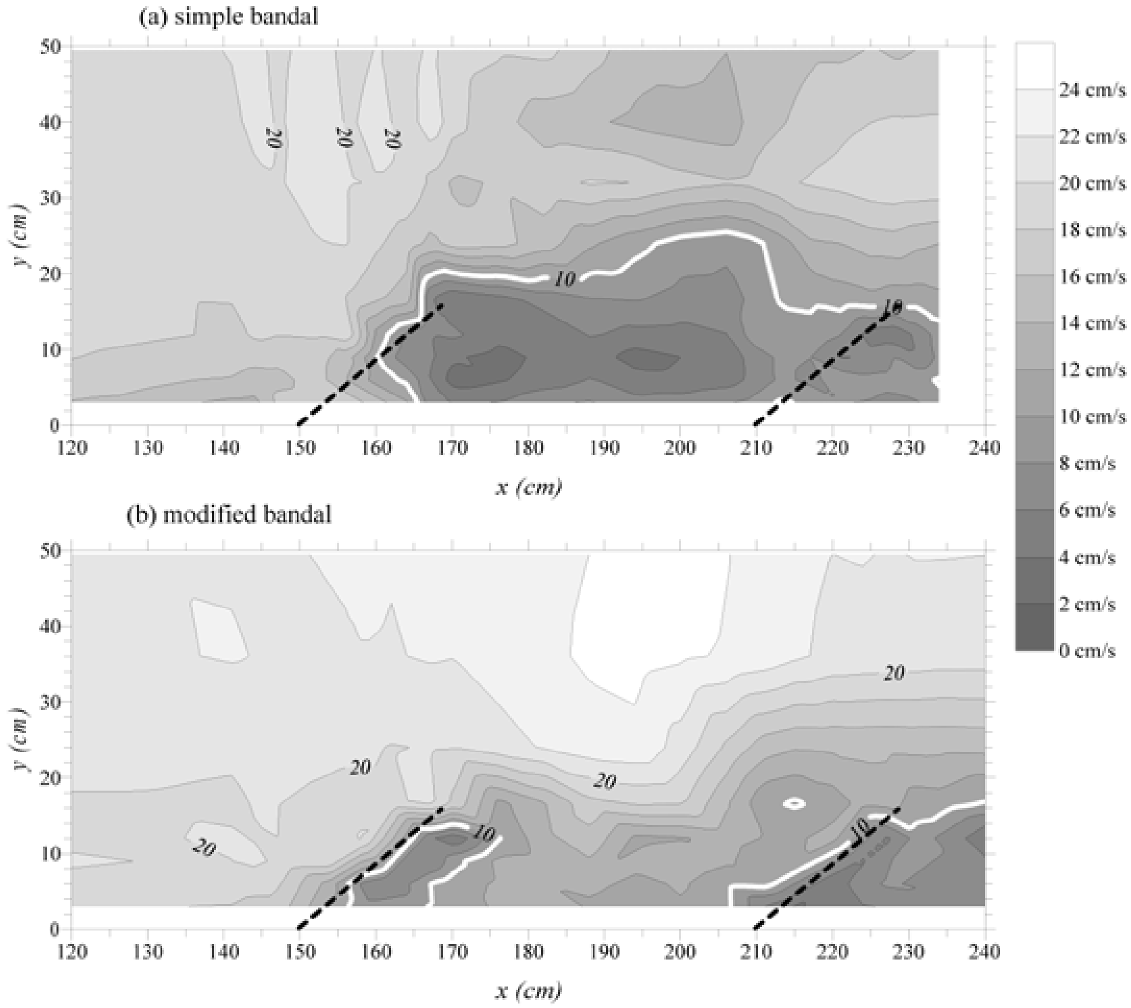


Fig. 4 Depth average isovels (u_x, u_y, u_z) around bandal fields and main channel for both simple and modified bandals

at the upper half to get more effective blockage and flow diversion towards the main channel instead of flat plate used in simple bandal. In order to strengthen this effect, piles in the form of permeable groins were installed at the lower part of the flow depth. The bandal plates were fixed on wooden-sticks at both ends. A total 10 pairs of models were set up from both wall inclined by 40° towards the downstream direction. Total run time for simple and modified bandal cases were 720 hours and 628 hours, respectively. It is important to note that the projected obstructions towards the lateral direction during each of the experiments were same.

3-D flow velocities were measured at different horizontal plane in the equilibrium state using electro-magnetic velocity meter (Model: ACM250-A, 'I' and 'L' probes). After the velocity measurement, flow visualization was made using dye injection around the scour holes and in between bandal fields. At the end of the experiments, bed levels at dry bed were measured using a laser sensor (LK-2500).

3.2 Experimental results

Detailed of the bed features and flow characteristics around impermeable groins are not discussed here as these issues have been explored in many previous researches (Laursen, 1964; Komura, 1966; Michiue et al., 1984; Rahman and Muramoto, 1999). Only, some specific parameters in terms of main channel degradation, local scour depth and flow concentration around the scour holes are compared with the results of bandal experiments. From the bed contours at the final stage (Fig. 3), it can be seen that main channel degradation in impermeable groins and both of the bandal experiments is more or less similar. But near

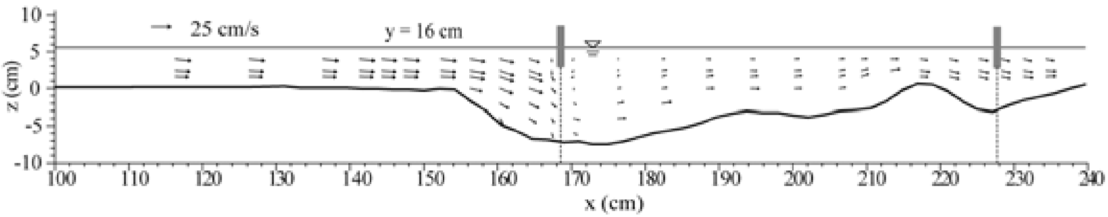


Fig. 5 Vectors (u_x, u_z) along BE1-BE1 in figure 3 for simple bandals

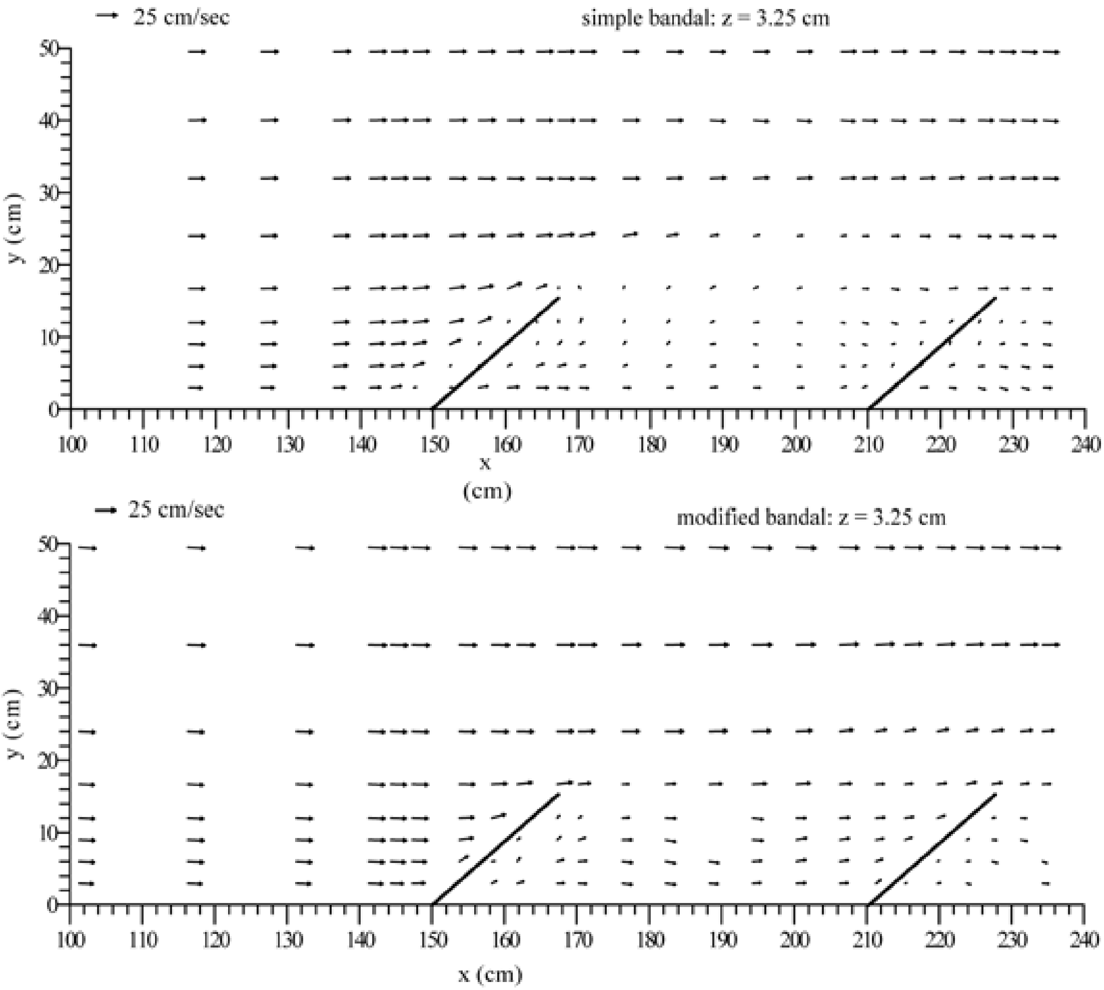
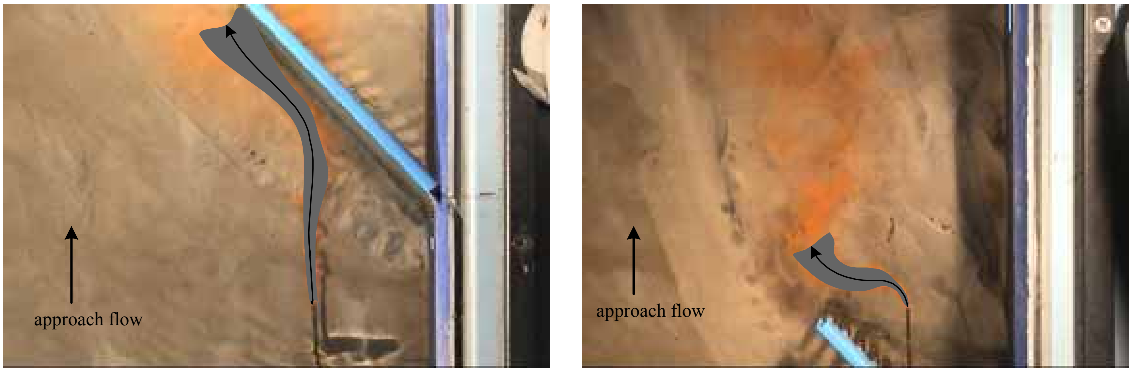


Fig. 6 Velocity vectors (u_x, u_y) near the water surface around first two structures for both the simple and modified bandal cases

bank sediment deposition is clearer in modified bandals as compared with the impermeable groins and simple bandal case. Because of the additional flow reduction at the downstream of the bandals due to piles in the lower half and bended bandal plate in the upper half over the simple bandal case. In the case of impermeable groins, near bank deposition is almost absent because of strong return currents developed towards the bank line. It can be expected that the required degradation of main channel and deposition along the bankline can be obtained by adjusting bandal opening and permeability of the bottom piles for a specified hydraulic condition.

Due to the flow bandal effect, the flow velocities towards the main channel is increased and near the bank line is decreased (Fig. 4). However, the depth average velocities near the bank line are found to be



(a) flow diversion towards main channel from upstream side

(b) flow diversion towards main channel from downstream side

Fig. 7 Flow diversions towards the main channel from the upstream and the downstream of the first structure (modified bandal)

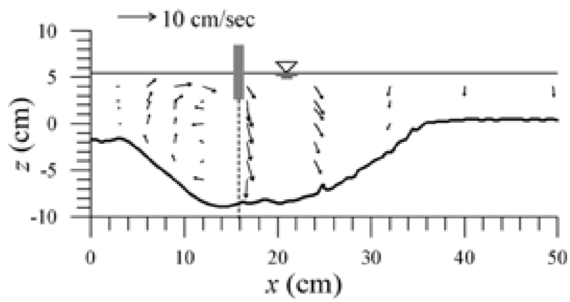


Fig. 8 Velocity vectors (u_y, u_z) at the end of the first bandal (section BT-BT of figure 3): simple bandal case

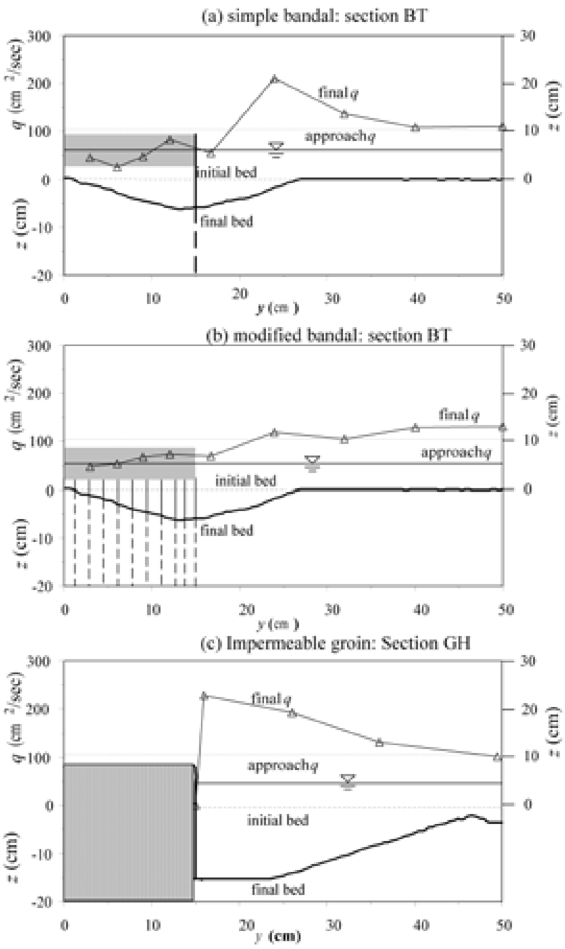
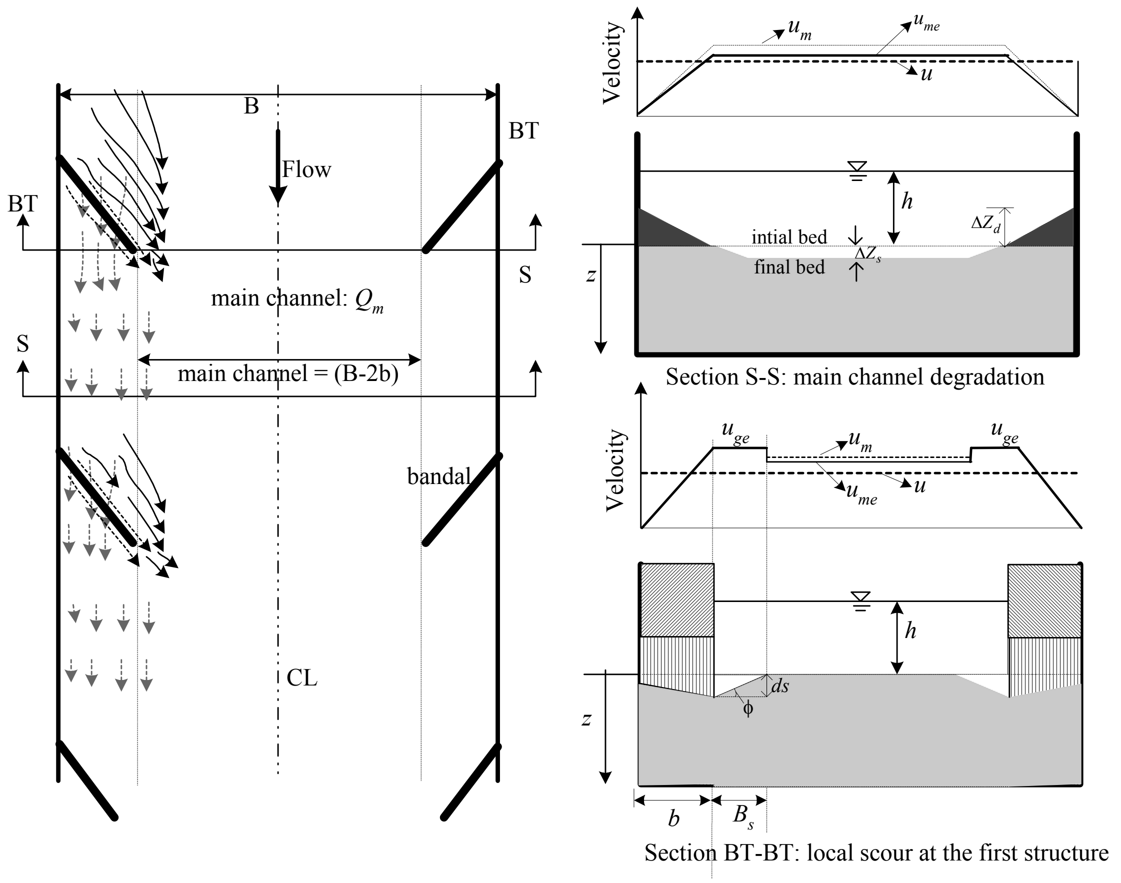


Fig. 9 Lateral distribution of unit discharges and bed profiles: (a) at section BT-BT of simple bandal, (b) at section BT-BT of modified bandal and (c) at section GT-GT of impermeable groins

more reduced in the case of modified bandals as compared with the simple one. Consequently, near bank deposition is found to be clearer in the modified case.

When flow comes close to bandals plate, major part of the obstructed flow diverts towards the main channel while rest of the flow goes towards the downstream through the bottom opening due to vertical acceleration of flow passing the bandals (Fig. 5). Now, the flow from the downstream of the structure moves towards the main channel due to lateral flow acceleration away from the bank side (Fig. 6). These features are more strongly supported by flow visualization at the downstream of the structure (Fig. 7). Such lateral flow components towards the main channel opposes the return current towards the bank line that is usually observed in conventional structures like impermeable groins. Therefore, bandals produce flow diversion towards the main channel both at the upstream and downstream of the structure that cannot be found in other known structures. As a result, flow passing



Notes: ΔZ_d = depth of sedimentation near the bank line

⟶ flow diversion towards main channel from the upstream of the structure

⇢ flow diversion by bandals at the downstream and by piles at upstream towards main channel

⇢ Flow towards the bandal field after passing below the bandal plate

Fig. 10 Definition sketch for bed degradation and local scour model

a bandal has always a tendency to move towards the main channel and away from the bank line as shown in Figure 8. The distribution of unit discharges and profile of scour hole (Fig. 9a and 9b) towards the lateral direction just downstream of the first bandal (at section BT-BT of figure 3) strongly support the above phenomenon. However, such effects are clearer in the modified bandal case (Fig. 9b) as a result of additional effect on flow diversion by submerged piles. In contrast, the flow discharges are concentrated within the scour holes around impermeable groins (Fig. 9c) rather than flow diversions towards the main channel. This kind of flow concentration was also observed in previous studies (Tuchiya and Ishizaki, 1966; Lim, 1997; Rahman and Muramoto, 1999 and many others). The big local scour holes around impermeable groins attracts the flow towards the structure and consequently, strong return currents are developed towards the bankline at the downstream reaches. Therefore, effectiveness of this kind of structure towards the formation of desired stable river courses remains questionable. Also, the formation of big scour holes as a result of strong impact of impermeable groins on river bed variation is not suitable for aquatic habitats. Rather gentle effects by structures like bandals on local scour development and riverbed variation would be suitable for river environment.

4. Model Development

4.1 Main channel degradation model

Due to the flow diversion, the shear stresses are amplified towards the main channel. As a result, the river bed along the main channel degrades in the process of deeper main channel formation until the bed shear stresses becomes equal to or less than the critical shear stresses for bed sediment transport. This phenomenon is termed as static equilibrium of clear-water scour. The definition sketch of the model summarizing the above phenomenon of flow diversion towards the main channel is shown in Figure 10. It is assumed that the flow intensity and water level in the main channel region would remain same at the initial and equilibrium condition after the installation of bandals. Based on the above assumptions, the following set of discharge continuity equations can be written in the main channel at initial and equilibrium condition.

at $t = 0$, $$Q_m = u_m(B - 2b)h \tag{1}$$

at $t = t_e$, $$Q_m = u_{me}(B - 2b)(h + \Delta Z_s) \tag{2}$$

Here $t = 0$ and t_e represent elapsed time at initial and equilibrium condition, respectively; ΔZ_d = maximum deposition at the channel bank above the initial bed; Q_m = discharge within the main channel in the flat bed (fixed) and equilibrium bed; u_m and u_{me} = depth averaged flow velocity in the main channel at flat (fixed) bed and equilibrium bed, respectively; B = approach channel width; b = projected lengths of groins or bandals measured perpendicular to the flow (for both side = $2b$); h = approach flow depth; ΔZ_s = main channel degradation below the original bed level.

Equating, Eq. (1) and Eq. (2):

$$1 + \frac{\Delta Z_s}{h} = \frac{u_m}{u_{me}} \tag{3}$$

For the wide alluvial channel, the logarithmic velocity profile can be approximated for the fully rough flow (Lim, 1997) in the main channel region as:

at $t = 0$, $$\frac{u_m}{u_{*m}} = m\left(\frac{h}{k_s}\right)^p \tag{4}$$

at $t = t_e$, $$\frac{u_{me}}{u_{*me}} = m\left(\frac{h + \Delta Z_s}{k_{sm}}\right)^p \tag{5}$$

Here u_{*m} and u_{*me} = shear velocity at flat bed and equilibrium bed within the main channel region; m and p are co-efficient and exponent, respectively, which depends on the type of bed form and p is usually taken as 1/6 (Lim, 1997); k_s = roughness height at the approach section = $3d_{90}$ (van Rijn, 1984), d_{90} = sediment size finer than 90%; k_{sm} = roughness height in the main channel after bed degradation.

From Eq. (4) and Eq. (5):

$$\frac{u_m}{u_{me}} = \frac{u_{*m}}{u_{*me}}\left(\frac{k_{sm}}{k_s}\right)^p\left(\frac{h}{h + \Delta Z_s}\right)^p \tag{6}$$

From Eq. (3) and (6) and Solving for $\Delta Z_s / h$:

$$\frac{\Delta Z_s}{h} = \left(\frac{u_{*m}}{u_{*me}}\right)^{\frac{1}{1+p}}\left(\frac{k_{sm}}{k_s}\right)^{\frac{p}{1+p}} - 1 \tag{7}$$

At the equilibrium state of bed degradation under clear-water scour, $u_{*me} = u_{*c}$ and Eq. (7) becomes:

$$\frac{\Delta Z_s}{h} = \left(\frac{u_{*m}}{u_{*c}}\right)^{\frac{1}{1+p}}\left(\frac{k_{sm}}{k_s}\right)^{\frac{p}{1+p}} - 1 \tag{8}$$

putting the value of p = 1/6, Eq. (8) can be written as:

$$\frac{\Delta Z_s}{h} = \left(\frac{u_{*m}}{u_{*c}}\right)^{\frac{6}{7}}\left(\frac{k_{sm}}{k_s}\right)^{\frac{1}{7}} - 1 = \left(\frac{\lambda u_*}{u_{*c}}\right)^{\frac{6}{7}}\left(\frac{k_{sm}}{k_s}\right)^{\frac{1}{7}} - 1 \tag{9}$$

where λ is the flow amplification parameter towards the main channel that is expressed as u_{*m}/u_*.

4.2 Estimation of model parameters

(a) λ parameter

In a wide open channel, discharge flux within the upper half can be approximated as $2uh/3$ and at the lower half as $uh/3$ considering triangular distribution of vertical velocity profiles. Therefore, average velocities within the upper half and lower half would be $4u/3$ and $2u/3$, respectively. From the experimental facts, it can be safely assumed that the obstructed flow within bandal plate would divert towards the main channel because a portion of flow passes below the bandal plate also moves towards the main channel from the downstream that opposes the return current to come inside the bandal field. Therefore, re-circulating flow (or return current) from the bandal head towards the bandal field is almost absent.

The amplification of the main channel shear velocity u_{*m} in the flat (fixed) bed condition in terms of approach shear velocity u_* can be expressed as Eq. (10).

$$u_{*m} = u_* \left(1 + \sum_{n=1}^{n} \lambda_b + \sum_{n=1}^{n} \lambda_p \right) = u_* \lambda \tag{10}$$

Here n instance for the structure number = 1 for the first structure and 3 for the 3rd structure in a series of structures; λ_b and λ_p are the amplification factor for main channel shear velocity due to bandal at the upper half and due to piles at the bottom half, respectively. The expressions for λ_b and λ_p at n-th structure can be written as:

$$\lambda_b = \frac{1-M}{M}\left[\frac{2}{3}\left(\frac{1}{3}\right)^{n-1} \delta^{\frac{n-1}{2}}\right] \tag{11}$$

$$\lambda_p = \frac{1-M}{M}\left[\left(\frac{1}{3}\right)^{n} \delta^{\frac{n-1}{2}} \left(1-\delta^{1/2}\right)\right] \tag{12}$$

Here M $(=1-2b/B)$ is the opening ratio at the contracted section (projected lateral contraction) that can be expressed as the ratio of contracted width and un-contracted approach width; δ = flow reduction parameter due to permeable groins at the bottom part and it can be expressed as (FAP 21, 2001):

$$\delta = \left(1 - \frac{1}{2} C_D \frac{A_p}{A_g \cos\gamma}\right)^{\frac{1}{2}} \tag{13}$$

Here C_D = drag coefficient = 2.0, for rough closely spaced piles in moderate flows; A_p = cross sectional area of piles at the lower half (blocked area by piles); A_g = upstream cross sectional area in the permeable groin field below the lower half; γ = direction of the separation flow line = 0° (as no flow separation). Optimum estimates of velocity reduction can be obtained for three times and it is not recommended to apply Eq. (13) more that three times and therefore, the value of n can be considered up to 3 in Eq. (10) even though the number of structures are more than three in reality.

In the case of simple bandal, λ_p in Eq. (10) and δ in Eq. (11) would vanish and λ_b can be expressed as

$$\lambda_b = \frac{1-M}{M}\left[\frac{2}{3}\left(\frac{1}{3}\right)^{n-1}\right] \tag{14}$$

For impermeable groins, the value of λ can be estimated as $1/M$ from the available researches (Laursen, 1964; Komura, 1966; Gill, 1972).

(b) k_{sm}/k_s parameter

Due to the increase of main channel shear velocity, the sediment transport would start when its value exceeds the critical shear velocity for the sediment transport. Owing to such sediment transport in the contracted region, bed forms like ripples, dunes would form and bed roughness would be increased.

According to van Rijn (1984), the bedform height in alluvial channels can be estimated as:

$$\frac{h_b}{h} = 0.11\left(\frac{d_{50}}{h}\right)^{0.3}\left(1-e^{-0.5T}\right)(25-T) \tag{15}$$

$$\frac{h_b}{L} = 0.015\left(\frac{d_{50}}{h}\right)^{0.3}\left(1-e^{-0.5T}\right)(25-T) \tag{16}$$

Eq. (15) and Eq. (16) is valid for $0 \le T \le 25$.

Here h_b = bedform height above the average bed level; L = wavelength of the bedform = $7.3h$ (van Rijn, 1984); T is the transport stage parameter that can be expressed as:

$$T = \frac{{u_*}^2 - {u_{*c}}^2}{{u_{*c}}^2} = \left(\frac{{u_*}^2}{{u_{*c}}^2} - 1\right) \tag{17}$$

In the case of clear-water scour, $u_* \le u_{*c}$ and $T \le 0$ in Eq. (17). But as the approach flow comes close to the bandal or groin field, the shear velocity in the main channel becomes amplified as expressed in Eq. (10). Now, from Eq. (10) and Eq. (17), the expression for stage parameter, T in the main channel region after installation of bandals or groins can be written as:

$$T = \left(\frac{\lambda u_*}{u_{*c}}\right)^2 - 1 \tag{18}$$

For the critical condition of approach flow, Eq. (18) can be written simply as:

$$T = \lambda^2 - 1 \tag{19}$$

Due to the bed form height, the bed roughness would be increased over the grain roughness. The equivalent roughness due to bed form can be expressed (van Rijn, 1984) as:

$$k_{s,form} = 1.1h_b\left(1 - e^{-25\psi}\right) \tag{20}$$

where, $\psi = h_b / L$ = bed form steepness obtained from Eq. (16).

Again, the roughness in flat bed due to grain only can be expressed as (van Rijn, 1984):

$$k_s = 3d_{90} \tag{21}$$

From Eq. (20) and Eq. (21), total roughness in the deformed bed can be estimated as:

$$\begin{aligned} k_{sm} &= k_{s,form} + k_s \\ &= 1.1h_b\left(1 - e^{-25\psi}\right) + 3d_{90} \end{aligned} \tag{22}$$

Finally, the ratio of k_{sm}/k_s can be expressed as:

$$k_{sm} / k_s = 1 + 0.37\left(\frac{h_b}{d_{90}}\right)\left(1 - e^{-25\psi}\right) \tag{23}$$

In the case of impermeable groins, the value of k_{sm}/k_s = 1 was assumed by previous researchers (Laursen, 1964; Komura, 1966; Gill, 1972). For the live-bed scour, the above assumption is reasonable. But in the case clear-water scour with ripple forming sediment (d_{50} < 0.5 mm), the ratio of k_{sm}/k_s would be greater than unity.

4.3 Local scour model

It is very important to predict the maximum local scour depth in order to provide adequate safety protection at the structure. The definition sketch of the local scour model is also shown in Figure 10. The diverted flow towards the main channel at the *n*-th structure (single side) can be expressed by $bhu\varepsilon$, when ε can be written as:

$$\varepsilon = \left[\frac{2}{3}\left(\frac{1}{3}\right)^{n-1} \delta^{\frac{n-1}{2}} + \left(\frac{1}{3}\right)^{n} \delta^{\frac{n-1}{2}}\left(1 - \delta^{1/2}\right)\right] \tag{24}$$

The first part of Eq. (24) within the third bracket is the effect due to bandal plate and the second part is due to permeable piles below the solid plate. That much of obstructed flow together with the approach flow passes within B_s outside the structure while going towards the main channel. Therefore, local scouring within that region would be developed. It is assumed that the flow passing through B_s would remain same at initial and equilibrium condition.

Discharge passing through B_s at $t = 0$

$$Q_s = buh\varepsilon + B_s uh \tag{25}$$

Discharge passing through B_s at $t = t_e$

$$Q_s = B_s\left(h + d_s/2\right)u_{ge} \tag{26}$$

Here B_s = lateral width of the local scour hole; $buh\varepsilon$ = diverted flow by the structure; $B_s uh$ = approach flow within B_s; d_s = local scour depth below the initial bed; u_{ge} = depth average velocity in the local scour at equilibrium.

Equating Eq. (25) and Eq. (26):

$$1 + \frac{d_s}{2h} = \frac{u}{u_{ge}}\left(1 + \varepsilon\frac{b}{B_s}\right) \tag{27}$$

Using the power law of velocity functions and $B_s = d_s/\tan\phi$, Eq. (27) can be expressed as:

$$\frac{d_s}{h}\left(1 + \frac{d_s}{2h}\right)^{1+p} = \frac{u_*}{u_{*ge}}\left(\frac{d_s}{h} + \varepsilon\frac{b}{h}\tan\phi\right) \tag{28}$$

Here ϕ = angle of repose of bed sediment; u_{*ge} = shear velocity in the local scour at equilibrium;

Assuming $1+p \approx 1$ for small value of p (= 1/6), Eq. (28) can be written as:

$$\frac{d_s}{h}\left(1 + \frac{d_s}{2h}\right) = \frac{u_*}{u_{*ge}}\left(\frac{d_s}{h} + \varepsilon\frac{b}{h}\tan\phi\right) \tag{29}$$

d_s/h can be expressed in the form of quadratic equation at the equilibrium condition ($u_{*ge} = u_{*c}$):

$$\left(\frac{d_s}{h}\right)^2 + 2\left(\frac{d_s}{h}\right)\left(1 - \frac{u_*}{u_{*c}}\right) - 2\varepsilon\frac{u_*}{u_{*c}}\frac{b}{h}\tan\phi = 0 \tag{30}$$

Solving Eq. (30) for d_s/h:

$$\frac{d_s}{h} = -\left(1 - \frac{u_*}{u_{*c}}\right) + \left\{\left(1 - \frac{u_*}{u_{*c}}\right)^2 + 2\varepsilon\frac{u_*}{u_{*c}}\frac{b}{h}\tan\phi\right\}^{1/2} \tag{31}$$

At the critical condition of approach flow, Eq. (31) can be written as:

$$\frac{d_s}{h} = \sqrt{\left(2\varepsilon\frac{b}{h}\tan\phi\right)} \tag{32}$$

Using Eq. (32), the maximum scour depth at any structure in a series can be computed having the value of ε. It is obvious that the maximum scour depth could be obtained around the first structure and with a gradually less value towards the downstream direction. The value of ε can be expressed for simple bandal (no piles at the lower half) as:

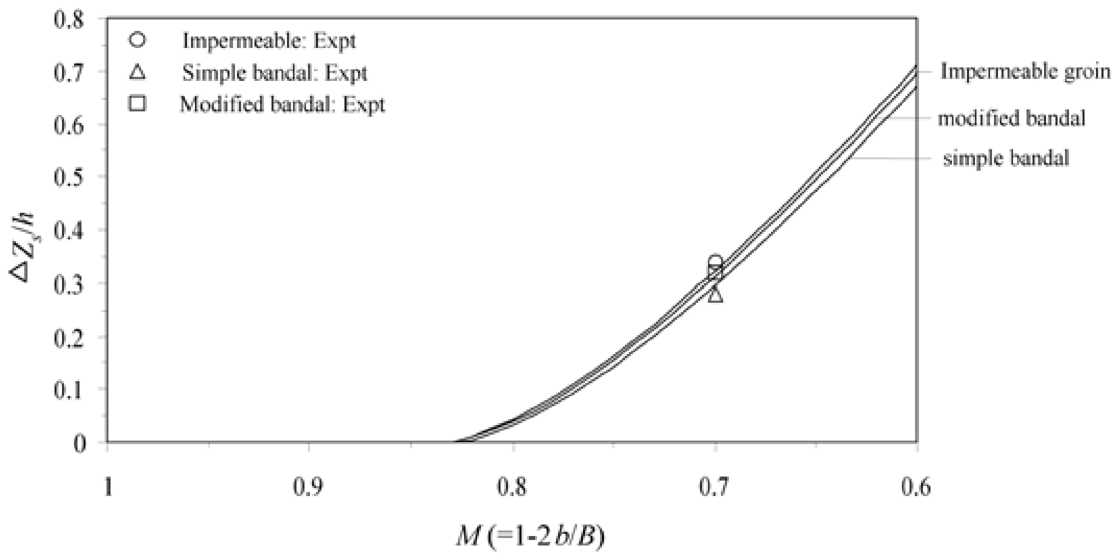


Fig. 11 Comparison of main channel degradation for impermeable groins and bandals (both prediction lines and experimental data are for $u_*/u_{*c} = 0.83$)

$$\varepsilon = \frac{2}{3}\left(\frac{1}{3}\right)^{n-1} \quad (33)$$

In the case of single impermeable groin that can be treated as the first one from the upstream, the value of ε can be approximated as 2.0 (Rahman and Muramoto, 1999). It is important to note that the effect of groin alignment on the local scour depth is relatively insignificant (Melville, 1992). Therefore, groin alignment factor in Eq. (32) is ignored and local scour depth around bandals and impermeable groins are compared on the basis of projected length only.

5. Model Application

5.1 Main channel degradation model

The average main channel degradation ($\Delta Z_s / h$) below the initial bed level is predicted as a function of M using Eq. (9) at $u_*/u_{*c} = 0.83$ (Fig. 11) for impermeable groins and bandals. To estimate the λ value for modified and simple bandals, Eq. (10) and Eq. (14), respectively, are used. In the case of impermeable groins, λ is taken as $1/M$. Using the respective λ value for each of the cases, the transport stage parameter (T) in the main channel is estimated by Eq. (18). The ratio k_{sm}/k_s is then calculated using Eq. (23) with the aid of Eq. (15) and Eq. (16). It can be seen that impermeable groins predict the maximum value followed by modified bandals and simple bandals. However, the differences in predicted values by each of the structures are very small. On the other hand, the bank side deposition in the bandal cases are clearer than in the case of impermeable groins (see figure 3). Also, it is found that the model predicts the experimental values of main channel degradation reasonably well. However, more experimental data are required to test the general applicability of Eq. (9).

5.2 Local scour model

The local scour depth (Eq. (31)) around the most upstream structure (n = 1) for impermeable groins and bandals are compared in Figure 12 at $u_*/u_{*c} = 0.83$. ε is estimated using Eq. (24) and Eq. (33) for modified bandals and simple bandals, respectively, whereas, ε = 2.0 is taken for impermeable case. It can be seen that the maximum local scour depths around impermeable groins are much bigger as compared with bandals. The observed scour depths are also compared with the predicted values and found that model predicts the experimental results of bandals reasonably well. Previously, Rahman and Muramoto model (1999) with ε = 2.0 was compared with a number of experimental and field data (Rahman, et al., 2003; Rahman and Haque, 2004) for the prediction of local scour depth around impermeable groins. Therefore, with the present state of knowledge, the maximum local scour depth

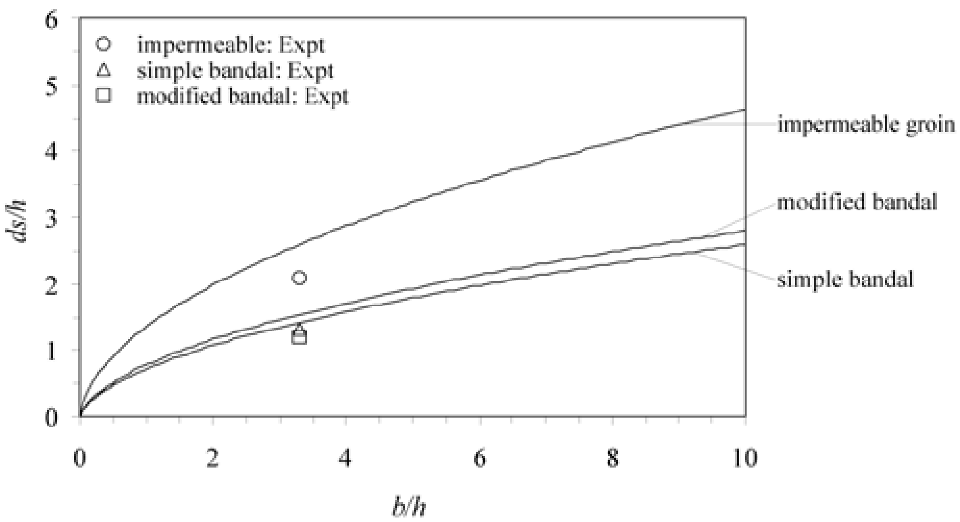


Fig. 12 Prediction of local scour depth

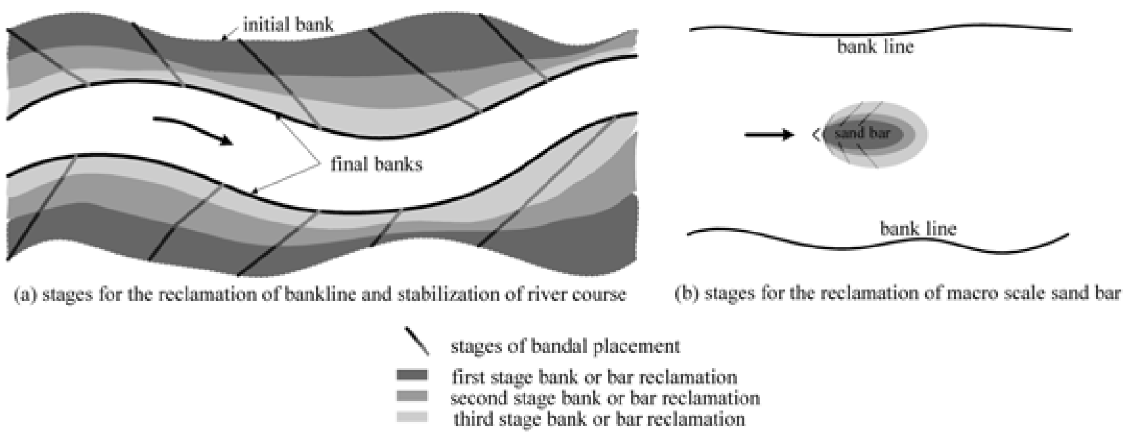


Fig. 13 Schematic sketch for river course and sand bar stabilization using bandals

around impermeable groins can be predicted with enough confidence. However, more experimental and field data around bandals are required to test the general applicability of the present model for the prediction of local scour depth around bandals.

6. Gradual Method for Formation of Stabilized River Course

From experimental and theoretical analyses, it is found that bandals are capable for flow diversion towards the main channel leading to deep navigational channel formation. On the other hand, flow velocities are reduced near the bank lines that ensure bank protection. In addition to this, the local scours around these structures are much less than it is in the case of impermeable groins. Therefore, would be less expensive solution over conventional methods. Another important feature of bandals is that the lateral intervention can be extended gradually that cannot be possible using conventional structures such as groins, revetments. During each stage of small intervention enough time would be allowed so that its flow and bed topography can adjust with the changed environment. At each of the small-scale interventions, river responses such as scour-deposition would be smaller as compared with the large-scale sudden interventions by impermeable groins or revetments. The gradual encroachment towards the lateral direction using bandals creates fewer disturbances to the river and the river can get sufficient time for its adjustment and new main channel and bankline development through scour-deposition processes. The river response against such small intervention will be comparatively less. The stabilized channel development using bandals are schematically shown in Figure 13. The above method would be more suitable than conventional methods for the restoration of stream channel where deep and narrow main channels are required (Shields et al., 1995). In addition to this, the cost effective solutions for the stabilization of macro scale sand bars where many people used to live (Sarker et al., 2003) in big alluvial rivers may be obtained through this gradual process using bandals.

7. Conclusions

Bandals are capable for flow diversion towards the main channel leading to deep navigational channel formation. On the other hand, flow velocities are reduced near the bank lines that ensure bank protection. The gradual encroachment towards the lateral direction using bandals creates fewer disturbances to the river and the river can get sufficient time for its adjustment and new main channel and bankline development. Therefore, it can be expected that bandals would be capable in forming stable river course that would ensure deep navigational channel and bank protection as well. Also, the local scour depth is significantly smaller as compared with the conventional structures such as impermeable groins, and bandals would be less expensive and suitable for preserving or restoring river environment.

The basic features of bandals in terms of flow and sediment control are clarified under clear-water scour only. Simplified models developed for the prediction of main channel degradation and local scour depths, predicts such experimental data reasonably well. But more experimental data with different bandal spacing and alignment under both clear-water and live-bed condition are required to test their general applicability. Moreover, pilot projects in the field are very important to execute before applying this method for the stabilization of alluvial river courses.

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安定流路の形成に関する研究

Md. Munsur RAHMAN*・中川　一・A.T.M. KHALEDUZZAMAN**・石垣泰輔・武藤裕則

*バングラデシュ工科大学水・洪水管理研究所（現JSPS外国人特別研究員）
****バングラデシュ国水資源開発局（元京都大学大学院工学研究科）

要旨

発展途上諸国においては社会経済や河川環境の観点から、現地調達可能でかつ安価な材料を用いた河道の安定化工法が好ましい。本報告では、その方策の一つとしてバンダルをとりあげ、その機能評価を行った。すなわち、移動床模型水路を用いてバンダル上部工（不透過型水制）の水刎ね効果による澪筋の形成およびバンダル下部工（透過型水制）の土砂制御効果による側岸への土砂堆積について検討するとともに、バンダル周辺部での局所洗掘および澪筋部の河床低下を評価し得る解析モデルを開発し、水理実験結果をもとにモデルの妥当性を検討した。その結果、本解析モデルにより、実験結果が比較的良好に説明し得ることが判明した。なお、比較のため、不透過型水制および下部工を有しないバンダルについても検討している。さらに、バンダルを長期的に用いることにより安定河道を形成する方法についても概念的に検討している。

キーワード：安定流路，バンダル，水理実験，モデル，長期的