FORMATION OF NAVIGATIONAL CHANNEL USING BANDAL-LIKE STRUCTURES

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The effectiveness of bandal-like structures (BLS) for the formation or restoration of navigational channel is tested. The basic feature of BLS in terms of flow and sediment control are clarified using simplified mobile bed experiments where a series of such structures are installed on both side banks. Based on the experimental results and flow visualization, simplified analytical model for the prediction of main channel degradation (as a measure of navigational channel formation or restoration) is developed and verified using experimental data. The model predicts the experimental results reasonably well.

Key Words : *bandal-like structure, navigational channel, mobile bed experiments, analytical model, prediction*

1. INTRODUCTION

Only 25% of the 24000 km of river network in Bangladesh are navigable due to insufficient water depth caused by huge sedimentation in the river systems. Scour-deposition and sediment transport processes, channel development, shifting and abandonment are very rapid in the floodplain rivers. As a result, navigational routes are often hampered and usually ships/boats are forced to travel longer distance on the way towards the destination, especially, during the dry season. Sometimes waterway vehicles cannot move inside rivers for several hours and even for several days because of the rapid unknown siltation in the navigational channels. In order to mitigate such undesirable situations in the navigational channels, dredging is often employed as an emergency measure. It is quite clear from the experiences of Bangladesh Inland Water Transport Authority (BIWTA) that dredging is very expensive and does not fit with the economical strength of Bangladesh. Moreover, it is a temporary method and not sustainable in long-term basis. As an alternative low cost method, bandal-like structures (BLS) are often used annually in order to maintain deep navigational channels during the dry season. From the recent analysis of the field data in some of the major river sites in Bangladesh[1)], it was found that the effect of BLS in order to create deeper navigational channel is quite uncertain. Probably, the underlying reason behind this kind of uncertainty is the lack of knowledge on the flow and sediment mechanism by BLS. If hydraulic functions of BLS are clarified, then its effective arrangements in terms of spacing, alignment and opening would be possible to design.

In an alluvial river, major portion of the sediment flow is concentrated within the lower half of the flow depth, while, the major part of water flows within the upper half. The essential characteristics of BLS 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

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

upper part should be about 50% of the flow depth 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 sides of BLS. The bottom flow is directed perpendicular to BLS 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 BLS is not sufficient to transport all the sediment coming towards this direction, resulting sedimentation over there (bank side). On the other hand, more water flows with little sediment move towards the main channel that develop deeper navigational channels over there (**Fig. 1**). This is merely the concept and never tested before at either laboratory or field level research. Therefore, in the present study, the features of BLS in terms of flow and sediment control are discussed on the basis of the results of simplified mobile bed experiments under clear-water scour condition.

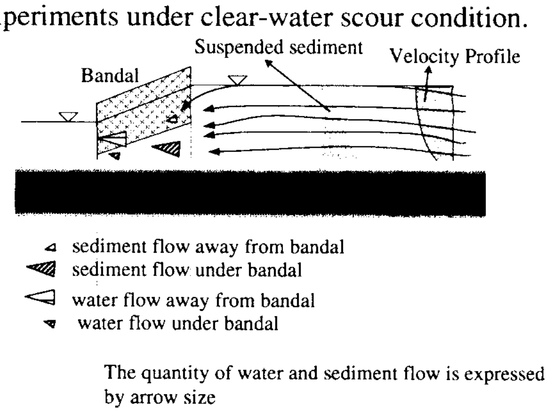


Fig. 1 Working principles of BLS.

Based on experimental facts and flow visualization, simplified analytical model for the prediction of main channel degradation (as a measure of navigational channel formation) is developed and compared with the experimental data.

2. HYDRAULIC EXPERIMENTS

(1) Experimental methods

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.

Here, Q = flow discharge; h = water depth at uniform flow condition before the installation of BLS; b (cm) = projected length of BLS measured perpendicular to flow; 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; S (cm) = center to center spacing between BLS; Re_* = particle Reynolds number; Re = Reynolds number and Fr = Froude number;

Mobile bed experiments with a series of BLS were carried out under the above hydraulic condition. After several trials 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. Two kinds of structures were adopted for each of the experiments. For simple BLS, 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 and

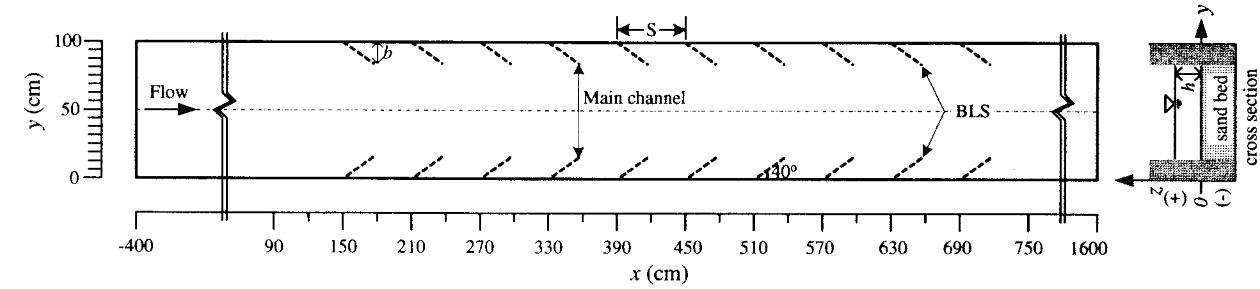


Fig. 2 Experimental arrangements.

allowed the flow to pass towards the downstream direction. For modified BLS, bended plate was used at the upper half to get more flow diversion towards the main channel and less flow towards the downstream as compared with simple BLS. 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 (**Fig. 3**). 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.

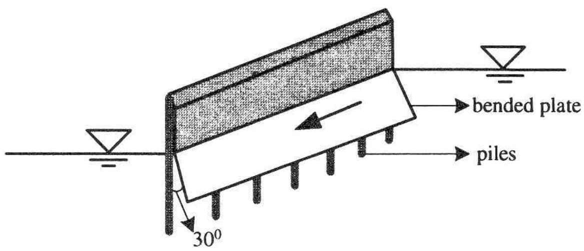


Fig. 3 Modification of simple BLS.

3-D flow velocities were measured at different horizontal plane in the equilibrium state using electro-magnetic velocimeter (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 (Model: LK-2500). It is important to note that experiments were carried out under non-submerged condition and no sediment supply was made from the upstream approach flow.

(2) Experimental results

From the bed contours at the final stage (**Fig. 4**), it can be seen that main channel degradation in both of the experiments is more or less similar. Moreover, near bank sediment deposition is clearer in modified BLS as compared with the simple BLS case because of the additional flow reduction towards the downstream due to piles in the lower half and bended bandal plate in the upper half.

Due to bandal effect, the flow velocity towards the main channel is increased and near the bank line is decreased (**Fig. 5**). However, the depth average velocity near the bank line are found to be more reduced in the case of modified BLS as compared with the simple one. Therefore, near bank deposition is found to be clearer in the modified case.

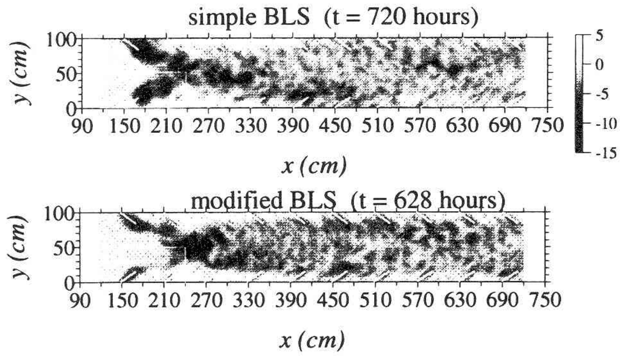


Fig. 4 Bed contour for simple BLS and modified BLS (bed level unit: cm).

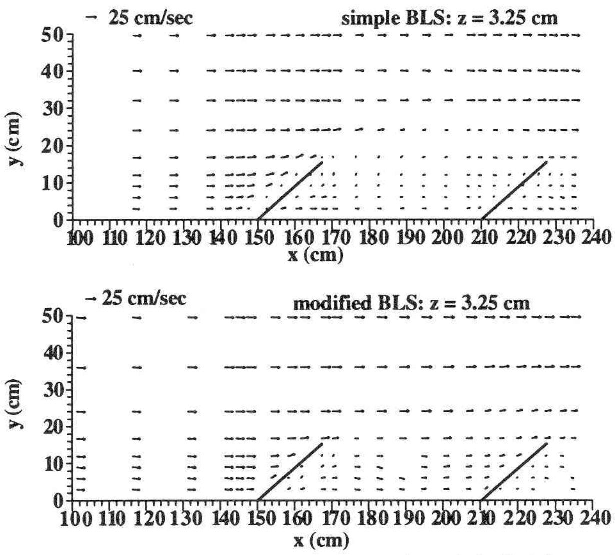
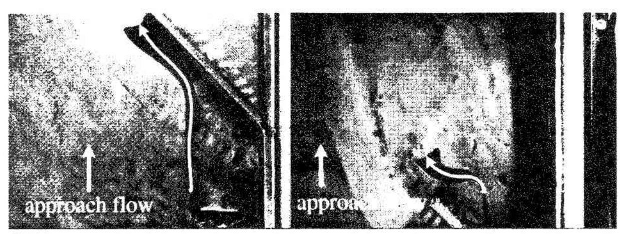


Fig. 5 Velocity vectors around bandal fields and main channel for both simple and modified BLS.



(a) flow diversion towards main channel from upstream side

(b) flow diversion towards main channel from downstream side

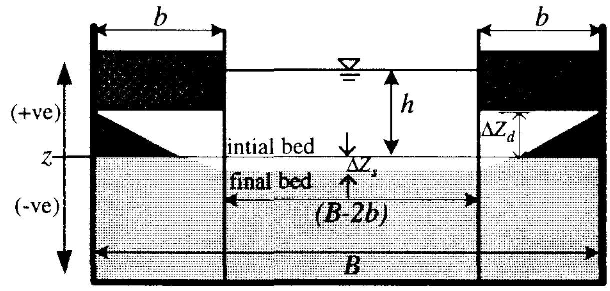
Fig. 6 Flow diversions towards the main channel from the upstream and the downstream of the first structure.

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. Now, part of the flow from the downstream of the structure moves towards the main channel due to lateral flow acceleration away from the bank side. These features are strongly supported by flow visualization at the upstream and downstream of the structure (**Fig. 6**). The downstream lateral flow components towards the main channel opposes the separate flow generated from the head of the BLS towards the bank line that is usually observed in conventional structures like impermeable groins. Therefore, BLS produces flow diversion towards the main channels both from the upstream and downstream of the structure.

3. PREDICTION OF BED DEGRADATION

(1) Model development

Due to 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.



Main channel degradation

Fig. 7 Definition sketch for bed degradation model.

The definition sketch of the model is shown in **Fig. 7**. It is assumed that the discharge fluxes and water level in the main channel region would remain same at the initial and equilibrium condition after the installation of BLS. 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; Q_m = discharge within the main channel in the flat bed (fixed) and equilibrium bed; u_m and u_{me} = depth averaged flow velocities in the main channel at flat (fixed) bed and equilibrium bed, respectively; B = approach channel width; b = projected lengths of BLS measured perpendicular to the flow (for both side = $2b$); h = approach flow depth; ΔZ_s = main channel degradation below the original bed level, and ΔZ_d = maximum deposition at the channel bank above the initial bed.

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 power-law of 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 velocities 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 [2)]; k_s is the roughness height at the approach section and is assumed that $k_s = 3d_{90}$ [3)], d_{90} = sediment size of 90% finer; 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 static equilibrium state of bed degradation, $u_{*me} \approx u_{*c}$ 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[2), 4)], Eq. (8) can be written as:

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

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

(2) Estimation of model parameter (λ)

In a wide open channel, the vertical velocity distribution function can be expressed as the power-function of point flow velocities by Eq. (10).

$$\frac{u(z)}{u_*} = m(p+1)\left(\frac{z}{k_s}\right)^p \tag{10}$$

Where z is the vertical distance measure from channel bottom.

Integrating Eq. (10) within the upper half of flow depth, the average flow velocities within the upper half can be obtained as:

$$u_{up} = \left(2 - 2^{-p}\right) u \qquad (11)$$

where, depth average approach velocity, $u = mu_*(h/k_s)^p$.

Therefore, the discharge flux within the upper half of flow depth can be expressed as:

$$q_{up} = \frac{1}{2} u_{up} h = \frac{1}{2}\left(2 - 2^{-p}\right) uh \qquad (12)$$

where q_{up} is the flow within the upper half that is diverted towards the main channel.

Similarly, the average velocity within the lower half can be obtained as:

$$u_l = 2^{-p} u \qquad (13)$$

and the discharge flux within the lower half of flow depth can be expressed as:

$$q_l = \frac{1}{2} u_l h = \frac{1}{2} 2^{-p} uh \qquad (14)$$

where q_l is the flow within the lower half that moves downstream of the first structure in the case of simple BLS.

It is assumed that, in a series of such structures, the amount of flow that comes downstream of the first structure [Eq. (14)] would be redistributed towards the vertical direction (over the vertical depth h) by mixing processes and the velocity distribution would take the form of power function [expressed in Eq. (10)] before approaching to the second structure and the process would be repeated.

If piles in the form of permeable groins are installed in the lower half of simple BLS, then additional flow diversion would be obtained towards the main channel and subsequently, reduced flow would be obtained at the downstream of the first structure. The reduced flow velocities towards the downstream can be expressed as[5]:

$$u_{ld} = u_l \delta^{1/2} = 2^{-p} u \delta^{1/2} \qquad (15)$$

where u_{ld} = flow velocities downstream of the first structure (within the lower half) in the case of modified BLS and δ can be expressed as:

$$\delta = 1 - \frac{1}{2} C_D \frac{A_p}{A_g \cos\gamma} \qquad (16)$$

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. (15) more that three times.

Therefore, flow towards the main channel due to piles of the 1st structure can be written as

$$Q_{1p} = \frac{1}{2} 2^{-p} bhu\left[1 - \delta^{1/2}\right] \qquad (17)$$

Again, flow towards the main channel due to the bandal plate of the first structure can be expressed as:

$$Q_{1b} = \frac{1}{2}\left(2 - 2^{-p}\right) bhu \qquad (18)$$

For the structures installed from both side bank, Eq. (17) and Eq. (18) can be expressed as:

$$Q_{1-2p} = 2^{-(p+1)} 2bhu\left[1 - \delta^{1/2}\right] \qquad (19)$$

$$Q_{1-2b} = \left(1 - 2^{-(p+1)}\right) 2bhu \qquad (20)$$

In the generalized form, Eq. (19) and Eq. (20) can be expressed for flow diversion towards the main channel from any structure (n-th structure) of modified BLS as below:

$$Q_{n-2p} = \left[2^{-(p+1)}\right]^n 2bhu\delta^{\frac{n-1}{2}}\left[1 - \delta^{1/2}\right] \qquad (21)$$

$$Q_{n-2b} = \left(1 - 2^{-(p+1)}\right)\left[2^{-(p+1)}\right]^{n-1} 2bhu\delta^{\frac{n-1}{2}} \qquad (22)$$

In the case of simple BLS, Eq. (21) and Eq. (22) can be expressed as:

$$Q_{n-2p} = 0 \qquad (23)$$

$$Q_{n-2b} = \left(1 - 2^{-(p+1)}\right)\left[2^{-(p+1)}\right]^{n-1} 2bhu \qquad (24)$$

It is important to note that due to the flow diversion towards the main channel, flow velocity would be increased in addition to the approach flow leading to degradation within the main channel area until equilibrium is reached. The increase of flow velocity over the approach flow within the main channel can be expressed for modified BLS as below.

Effect of piles below the bandal plate at each of the structures:

$$u'_p = u_p / u = \frac{Q_{n-2p}}{(B - 2b)uh} = \left[2^{-(p+1)}\right]^n \delta^{\frac{n-1}{2}}\left[1 - \delta^{1/2}\right]\frac{2b}{B - 2b}$$

.... (25)

Effect of the bandal plate at each of the structures:

$$u'_b = u_b / u = \frac{Q_{n-2b}}{(B - 2b)uh} = \left(1 - 2^{-(p+1)}\right)\left[2^{-(p+1)}\right]^{n-1} \delta^{\frac{n-1}{2}} \frac{2b}{B - 2b}$$

.... (26)

It is important to note that the increase of flow velocity due to bandal plate and permeable piles would be cumulative towards the downstream direction and the effect should be considered up to 3rd structures[4].

Therefore, the flow velocities in the main channel can be expressed as:

$$u_m / u = \left(1 + \sum_{n=1}^{n} u_b' + \sum_{n=1}^{n} u_p'\right) \tag{27}$$

Using the power-law in the approach flow velocities, the depth averaged velocity can be expressed as:

$$\frac{u}{u_*} = m\left(\frac{h}{k_s}\right)^p \tag{28}$$

From (4) and (28):

$$\frac{u_m}{u} = \frac{u_{*m}}{u_*} \tag{29}$$

From (27) and (29):

$$u_{*m} = \left(1 + \sum_{n=1}^{n} u_b' + \sum_{n=1}^{n} u_p'\right) u_* = \lambda u_* \tag{30}$$

where $\lambda = \left(1 + \sum_{n=1}^{n} u_b' + \sum_{n=1}^{n} u_p'\right)$

Here n = 1 to 3.

In the case of simple BLS,

$$u_p' = 0 \tag{31}$$

$$u_b' = u_b / u = \frac{Q_{n-2b}}{(B-2b)uh} = \left(1 - 2^{-(p+1)}\right)\left[2^{-(p+1)}\right]^{n-1} \frac{2b}{B-2b}$$

.... (32)

In above relation, *2b/(B-2b)* can be expressed as *(1-M)/M* where *M* is the contraction ratio expressed as *(B-2b)/B*.

(3) Model application

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 the critical condition of approach flow (**Fig. 8**). To estimate the λ value using Eq. (30), the values of u_p' and u_b' for modified BLS are estimated from Eq. (25) and Eq. (26), whereas, the same values were estimated for simple BLS using Eq. (31) and Eq. (32). It can be seen that modified BLS (λ = 1.41) as compared with simple BLS (λ = 1.33) predicts higher values of bed degradation. The experimental results of main channel degradation averaged at each of the BLS sections are plotted and found that in average, the model predicts the experimental values reasonably well, although, data points vary within a wide range for each of the sections. However, more data are required to test the general applicability of Eq. (9).

5. CONCLUSIONS

BLS 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 sediment deposition. The features of BLS in terms of flow and sediment control are clarified under clear-water condition only. Simplified models developed for the prediction of main channel degradation, predict 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 for their general applicability. Moreover, pilot projects in the field are very important to execute before applying such method for the formation/restoration of navigational channels in alluvial river.

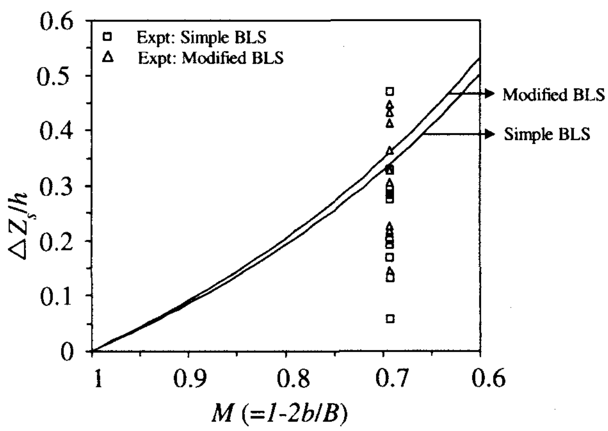


Fig. 8 Comparison of main channel degradation.

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REFERENCES

1) Rahman, M.M., Nakagawa, H., Khaleduzzaman, A.T.M. and Ishigaki, T.b: Flow and scour-deposition around bandals, Proc. Fifth International Summer Symposium, JSCE, pp. 177-180, 2003.
2) Lim, S.Y.: Equilibrium clear-water scour around an abutment, Journal of Hydraulic Division, ASCE, Vol. 123(3), pp. 237-243, 1997.
3) van Rijn, Leo C.: Sediment transport, part III: bed forms and alluvial roughness, Journal of Hydraulic Division, ASCE, Vol. 110, No. 12, pp. 1733-1754, 1984.
4) Komura, S.: Equilibrium depth of scour in long constrictions, Journal of Hydraulic Division, ASCE, Vol.92, No.Hy5, pp.17-37, 1966.
5) FAP 21: Guidelines and Design Manual for Standardized Bank Protection Structures, Bank Protection Pilot Project, Govt. of Bangladesh, December, pp. 1.1-4.21, 2001.

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