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Design of groynes modified with both alignment and permeability for lowland river problems

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A groyne is an important river restoration structure. Although its history is for long and widespread use, optimized design of new groynes is not attempted much, which is very important to treat the highly unstable lowland river channels. A completely blocked impermeable groyne suffers from instability of the structure itself; whereas, fully permeable structure can not divert the flow rightly. Considering the present demands, four different groyne structures including modified combined and bandal-structures are examined in the laboratory channel to recognize their fluvial responses, incorporation with some field information. The performance of a groyne is confirmed through three key features: scour near groynes (structure stability), deposition in the groyne field (bank stability) and erosion in channel bed (navigability). Analyses of data show that the combined groynes cause gradual deceleration of flow towards the land and minimize local scour compared with the conventional impermeable ones. Also two other important features: deposition near bank and channel erosion, are better responded from modified bandal-structures and modified combined groyne.

Key Words: *combined groynes, bandal-structures, local scour, erosion, deposition*

1. Present State of Work and Problem Definition

The rivers through flat delta lands of Bangladesh, especially Jamuna, one of the largest rivers in the world, with fine-grained non-cohesive sediments on banks cause severe erosion with high frequency at high flood time and the river persistently widens rather than deepens the bed. This destroys huge farmlands, homestead lands, and so on; on the other hand, inland waterways frequently lose navigability due to rapid sedimentation at low flow time and disrupt very important transport-system there. So far, numbers of studies have been conducted to understand the dynamism of the river, and to develop and improve the techniques in stabilizing the channels [1-5)]. Based on the findings of the studies, groynes are practiced including revetments and repeated dredging to overcome these problems; however the suitability of the existing measures yet to be accepted [6-8)].

In the cases of fully blocked impermeable groynes, there are many chances of strong recirculation of flow downstream of the structures[9-11)] which can attack the bank back again where the structures installed; this may spoil one of the major targets, where deposited riverine landscape could serve improved environments through vegetation, and so on, in addition to protection of floodplain area. Moreover, instability of the structures due to local scour is an endemic problem, which can lose the huge investment for them, and also there are destructive consequences due to hydraulic actions after their failures at downstream region, planned to be protected. Sudden and big responses from these structures, in one way, leave behind strong eddies near the groyne-head causing scour holes responsible for this instability; furthermore, these affect other regions such as islands where numbers of people are living or other bank, and so on, and make them unstable. Besides, the desired channel for navigation is not estsblished rightly, for which waterway transports are greatly interrupted at low flow period. Thus, the stable river course is not established.

Although some studies have been conducted with bandal-structures, as practiced at low flow or in sub-channels for both bank protection and maintenance of navigation depth[7), 8), 12)], their large-scale use at varying flow condition are not evident yet. This structure, modified with straight impermeable part adjacent to the bank to develop more stagnant region of flow there, without influencing strong return currents at high flood, yet to be tested for seeking its extensive use for lowland river problems. Besides, a combined (impermeable and permeable) groyne-structure varying its permeability from higher to lower value and then near bank impermeable part could affect flow patterns more natural way so as to prevent flow separation as impermeable groynes do, and to achieve a gradual deceleration of flow velocities towards the bank. To ensure optimum functions of the structure, its alignment could be modified as in optimum configuration of a groyne to improve navigability [13]. Thus the disadvantages of impermeable groynes can be minimized replacing some length with permeable ones which have form drag against flow and favour rapid deposition by slow flow through them; particularly, in lowland rivers with high sediment load.

All complex flow phenomena persistent to alluvial channels like turbulent flow, secondary flow, sediment transport, and so on, must be treated rightly prior to applying any engineering interventions in the course to get some defined benefits. In order to design a suitable engineering structure for addressing the aforementioned problems, channel responses from the interventions could be analyzed by computational or experimental tools. In the present study, thorough investigations in the laboratory for different combinations in groyne structures are attempted to recognize modifications of fluvial processes by the structures to reach the desired goals, incorporation with some field evidences. Thus this paper presents the channel responses against four different groyne-structures: impermeable, combined, modified combined and bandal-like structure modified with straight impermeable (near bank) portion and alignment, as that of modified combined one. To compare the performance of the groynes, three key features: depth of scour near groynes, deposition near bank, and erosion in the main channel are explored including the flow dynamics responsible for these morphological changes, all aiming at improving the understanding in stabilization of lowland river channels.

2. Methodology

2.1 Experimental Setup

(1) Model channel and structures

The experiments are performed in a tiltable open-channel flume located in the Hydraulic Engineering Laboratory of Nagoya University. The flume is straight and of rectangular cross-section, 20.0 m long, 0.5 m wide, 0.3 m deep and is capable of a discharge not exceeding 50.0 m^3/hr. The side walls of the flume are made of a transparent weather-resistant acrylic sheet, thereby allowing visualization of the flow and the scour process during an experimental run. Its bed at both upstream and downstream regions is made rigid with wooden planks, and extended by 5.5 m and 4.5 m from the inlet tank and discharge tank, respectively. Relatively fine and uniform sands with a median size d_{50} = 0.13 mm covered the remaining area of the channel with a thickness of 16 cm.

Four different model-structures are considered in this study varying both alignment and permeability, where one of them is impermeable and other three are combined. First model (M1) is straight impermeable; second one (M2) is also straight, but first one-third portion is impermeable and rest part is made permeable with round sticks, and permeability is varied along the length changing blockage percentage from 67% near impermeable part to 50% at far-end, i.e., first-half of permeable portion is of 67% blockage and rest portion is of 50%. First one-third part of third model (M3) is perpendicular to the side wall and later part is aligned towards 20^0 downstream, i.e., 70^0 to the direction of flow at upstream; permeability is similar to M2. Fourth one (M4) is of same alignment as in M3, except that permeability of downstream-aligned part is varied vertically: upper portion is blocked and lower portion is kept open, i.e., bandal-structure, such that its projected area is similar to other combined model structures (M2 and M3). The projected length of all groyne models (L_g) is 18.0 cm. A set of six numbers of each model-structure are placed on right side of the channel perpendicular to the side, as the groynes should preferably be installed in a series to protect a certain reach of a bank of a wide alluvial river, also to favour in formation of navigation channel. **Figs. 1(a-c)** depict a schematic representation of experiment setup including side view and top view of model channel, top view of groyne models, and channel cross-section, respectively. The center of the first structure is at 10.0 m away from the inlet boundary, which is theoretically sufficient to achieve a fully developed turbulent flow in control region. The model structures are installed with an interval S_g = 0.55 m, i.e., aspect ratio $S_g/L_g \approx 3.0$ and cover the total distance 2.75 m by five embayments.

The x-axis is the downstream direction with x = 0 at center of the first groyne; y-axis is pointing towards the left side in the transverse direction with y = 0 at the right-side where the groynes are placed; and z starts from the initial loose bed-level with upward positive. The velocity components u and v are corresponding to their directions x and y, respectively.

(2) Experimental conditions

The flow condition in the channel is adjusted by a control valve and a tail gate so that a bed shear velocity

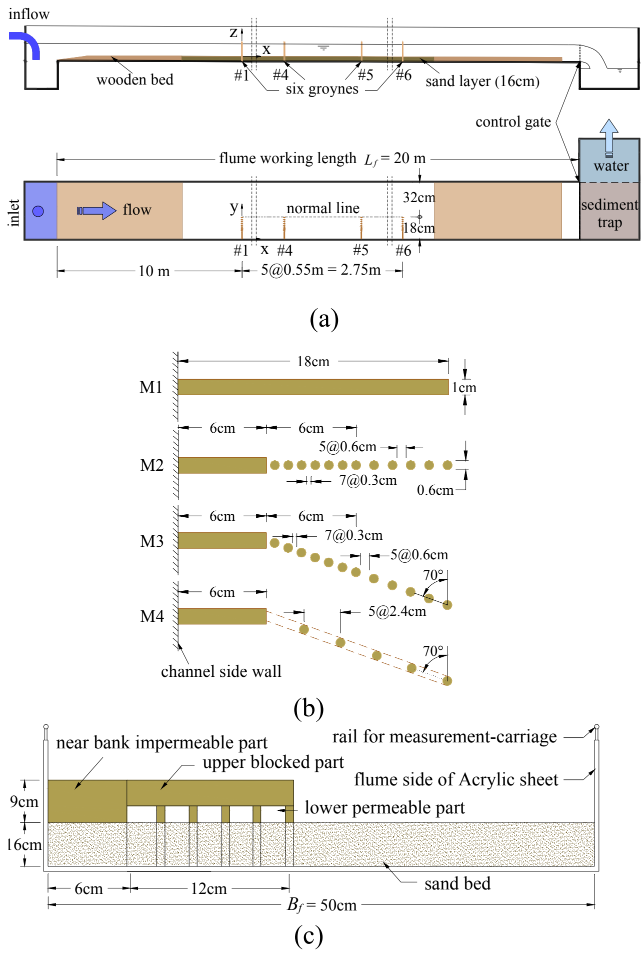


Fig. 1 Experimental setup: (a) side (top) and plan view (bottom) of model channel; (b) groyne models (plan view); and (c) flume cross-section with modified bandal-structure.

Table 1. Experimental conditions for the entire test runs.

Parameters	Groyne type	
	Impermeable	Combined
Flow Q (m^3/hr)	12.5	16.5
Flow depth h (cm)	5.0	5.5
Mean velocity U (cm/s)	13.9	16.7
Sediment size d_{50} (mm)	0.13	0.13
u_*/u_{*c}	0.88	0.92
Froude number Fr	0.20	0.23
Reynolds number Re	6944	9167

(u_*) does not exceed the critical shear velocity for initiation of motion of the bed sediment (u_{*c}) for the approach flow to avoid bed-forms at upstream of the control reach. This has been decided after some trials such that except control sections, the channel bed has been remained unchanged, i.e., the condition of clear water scour. Flow uniformity is verified by comparing the free-surface slope and the flume's bed slope. Two different flow discharges and approach depths are maintained for two types of groynes: impermeable and permeable to establish similar mean velocity in the control region considering blockage area of the structures.

In all tests, the groynes are emerged and the Froude number ($Fr = U/\sqrt{gh}$) is small enough to ensure sub-critical flow and the Reynolds number ($Re = Uh/\nu$) is high enough to ensure fully developed turbulent flow in the control section. The details of the tests undertaken, including the hydraulic and sediment transport conditions are presented in **Table 1.**

2.2 Procedure

Before starting the flow in the flume, after placing one set of model structures on one side, the loose bed surface of fine sediment in the working area is leveled with a scraper wooden plate mounted on a moving carriage, which can ride over the steel frames on both sides of the channel. After that, the flow is allowed to enter gently in the flume; when the bed is completely wetted, then it is drained and a profile of this bed surface is collected as an initial bed. The flume is then filled slowly with water and the specific flow in consideration of clear-water scour as defined in the previous section is allowed to run. A control gate at the end of the flume is adjusted along with bed slope while allowing final flow to run to ensure uniform subcritical flow and clear-water scour condition. Then, the change of bed topography, especially the depth of local scour near the first structure is monitored by a CMOS (complementary metal-oxide semiconductor) laser sensor (a sensor head IL-300 with an amplifier unit IL-1000, KEYENCE Corp.) to identify the equilibrium condition when the rate of change decreases considerably. Then all the measurements, such as flow depth, velocity fields, final bed topographies, and so on, are collected along some selected sections.

Measured data are then analyzed to extract some typical features to recognize the modification of fluvial responses. To determine the performance of groyne structures, three typical features are investigated critically: depth of scour near groynes (ΔZ_g), deposition of sediment in the groyne field (ΔZ_{gf}), and erosion in the main channel (ΔZ_{ch}) (**Fig. 2**), where the first one signifies the stability of the groyne-structures, the second one the protection of bank from erosion, and the

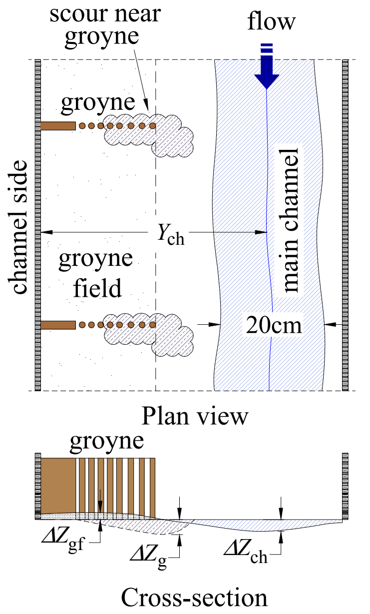


Fig. 2 Definition sketch of key features of groynes to evaluate performance.

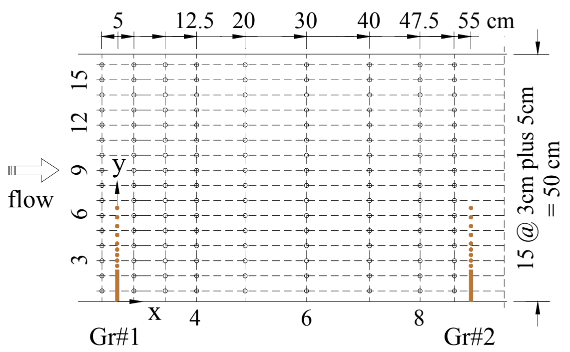


Fig. 3 Measuring points and sections for velocity measurements.

third one the maintenance of navigation channel, respectively. Here, the values of the parameters for erosion in main channel and deposition in groyne field are averaged over the area between second and fifth groynes for combined case, and second and fourth groynes for impermeable case, to avoid the effect of reflected flow. However, local scour is the maximum scour depth near the first groyne.

3. Measurements

Bed level measurements are taken in the test area before the start of each test for reference and at the end of the tests, respectively; velocity measurements are taken once in every test case at equilibrium state of flow. After continuous running the flow, when the channel bed seemed to be unchanged, then that state can be assumed to be reached equilibrium state and it is considered 9.0 hrs in the tests. One test case is, however, conducted first for 18.0 hrs to recognize this time length, after which the change in bed level is found insignificant.

3.1 Velocity Fields

Two-dimensional velocity components are collected with an electromagnetic velocimeter (VM-602HT, KENEK Co.,LTD.) under dynamic flow conditions utilizing I-shape sensor, which is attached to a moveable platform. The measuring devices recorded a signal in *x*- and *y*-directions simultaneously, which later converted into velocities in cm/s. Three measurements are taken at each point to have average value, and the area between first and second groynes is chosen for the measurements to inspect the modification of flow patterns by the individual structure after coming the flow from uninterrupted area. To grasp the velocity fields rightly, these measurements are taken along 9 transverse transects, from 2.5 cm upstream of first groyne to 2.5 cm upstream of the subsequent groyne, and 16 longitudinal transects with 3.0 cm intervals starting at 2.5 cm from the side. The measurements are made at approximately 60% of the water depth, measured from the water surface. It is assumed that the magnitude of the velocity at this depth equals the magnitude of the depth-averaged velocity. The locations of the measuring sections and points are shown in **Fig. 3**.

3.2 Bed Levels

After the velocity measurements, the flow is gradually decreased in such a way as to cause minimal disturbance to the bed. The channel is drained and after the bed is dry, typically after one day of the run, the elevation of the bed is measured in the control area using a computer aided laser sensor. Bed levels are measured in all the groyne area along 18 longitudinal transects with 2.5 cm intervals. Three sensors are attached to a moving carriage to cover three transects at each sweep that travels over a steel frame on both sides of the channel.

4. Analyses of Data

As the main two purposes of installing groynes are bank protection through deposition of fine sediment near the bank and maintenance of thalweg for navigation channel accompanying with structural safety, three typical features such as scour depth near groynes, height of deposition of sediment in the groyne field and depth of erosion in the main channel, are considered to confirm the performance of groynes. Velocity distributions and bed topographies measured with available setup in the selected sections are presented in this section to understand the modification of flow patterns and to explore all the features influenced by the structures, respectively.

4.1 Flow Fields

Fig. 4 depicts the transverse distributions of streamwise velocities non-dimensioned by mean velocity in impermeable case (U_{imp}) from the four models at 7.5 cm downstream of first structure to compare the flow patterns affected by varioust groynes. From the average trend of transverse distributions of streamwise velocity for combined groynes, it can be recognized that velocity reduces gradually towards the channel boundary the groynes installed, not sudden reduction at the end of the structure, or at the end of the impermeable part, what impermeable structures do leaving strong eddies. This modification of flow-patterns can be attributed to the permeable components of the structures and gradual reduction of permeability along the length of groynes towards the side wall.

Depth-averaged flow fields in the first groyne area influenced by the model structures are presented in **Fig. 5(a)**. It can be seen here that the magnitude of velocity vectors in the groyne field near bank for combined groynes (M2, M3, M4) are appreciably decreased and no strong recirculation of flow be marked except a smaller one from M4 behind the impermeable portion, as compared to the case of impermeable groyne (M1). These return currents, if groynes are not closely spaced, are sometimes dangerous at high flood time to cause scour near bank and hence bank recession, rather than forming sustainable riverine landscape. However, this inherently causes strong eddies and hence huge scour near groyne-tip to hamper stability of the structure itself; as evident in Jamuna, several failures of RCC spurs due to separation of flow are reported [14].

4.2 Bed Topographies

The important key features to evaluate the performance of groynes such as: scour near groynes, deposition in the groyne field, and erosion in the main channel induced by the structures can be extracted from the bed topographies depicted in **Fig. 5(b)**, where (relatively) higher impact near the first structure causing deeper scour as well as higher erosion in the channel bed can be marked. Dimensionless transverse distributions of erosion and deposition averaged over the area between second and fourth groynes for impermeable case and second and fifth groynes for combined case are shown in **Fig. 6**, to recognize the

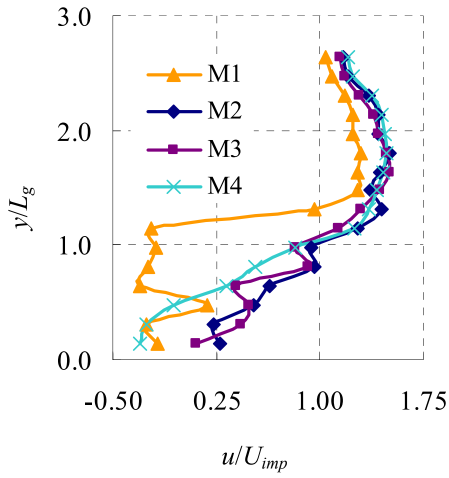


Fig. 4 Depth-averaged streamwise velocity (dimensionless) distributions across the channel at 7.5 cm downstream of first structure.

influence of various structures in the main channel and groyne field, respectively. Here, depth of flow in impermeable case (h_{imp}) is considered to make the parameters dimensionless. In averaging the feature values different distances are considered here, as the downstream embayments are affected by the reflected flow from the opposite wall in the case of impermeable structures. As the flow velocity decreases significantly in the embayments, sediment settles there with different mechanisms of material transports for impermeable and combined groynes, respectively.

Channel ripples of various dimensions are observed in the control area with larger dimension in the main channel and smaller extent in the groyne field, not in the upstream part of the area. As local scour around the first groyne was significantly more pronounced, so this can be explained from the fact that the first groyne is exposed to the strongest current, which results in an increased erosion rate. However, in impermeable case, the flow is highly diverted, so that it is reflected from the opposite wall of the channel and turned back to attack the downstream embayments causing much scour near groynes there. It is surprising to notice here that the impact by the back flow can even be higher than that occurred near the first structure, depending on the intensity of oblique flow. In the region behind the last groyne, as the channel becomes wider, consequently, deposition took place due to the decreased velocity.

5. Performance of Model-Structures

The performance of a groyne is evaluated through three key features: scour near the groyne, deposition in

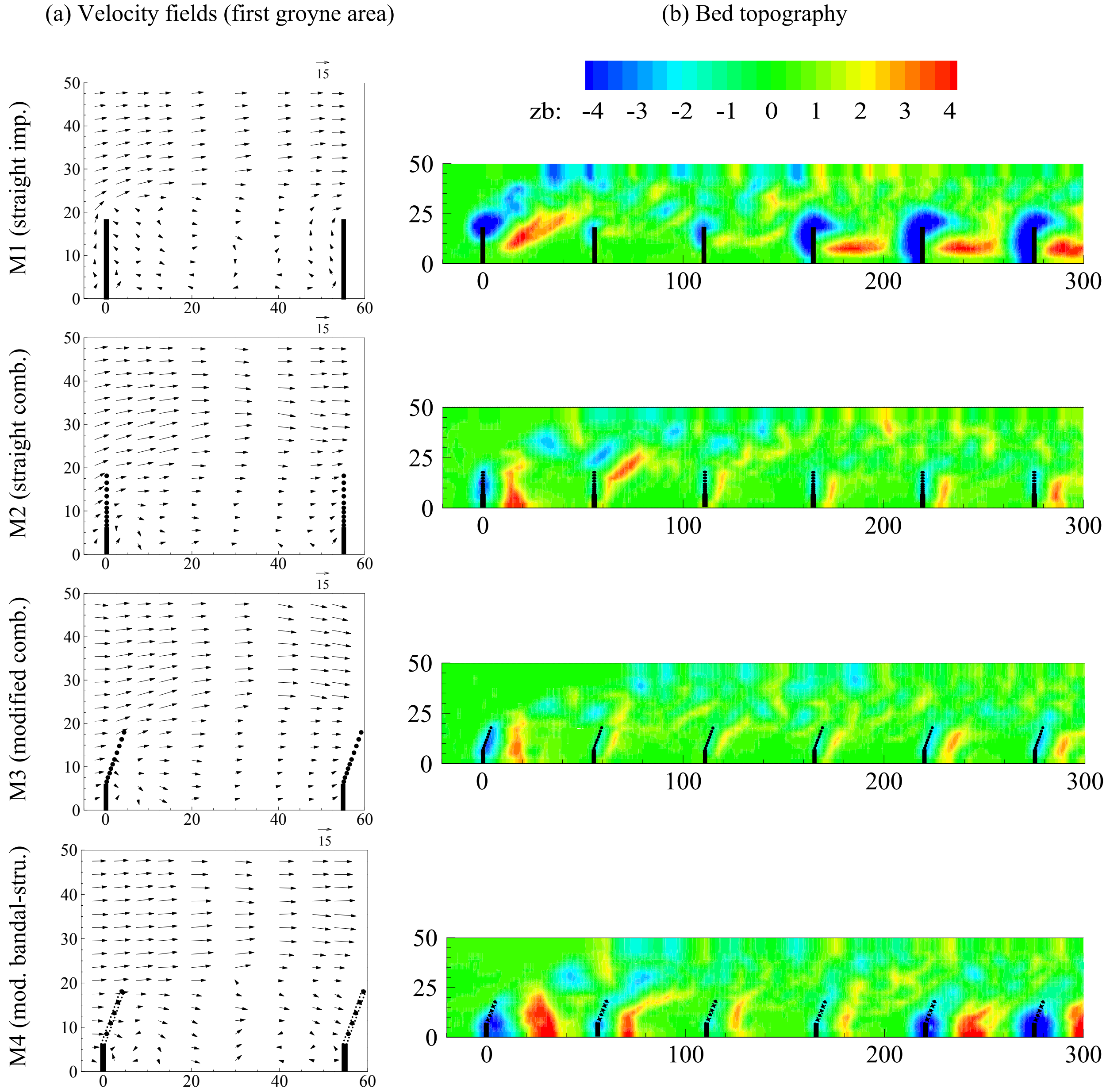


Fig. 5 (a) Velocity fields and (b) bed topographies from various model-structures (here, all units are in cm, except velocity vectors in cm/sec)

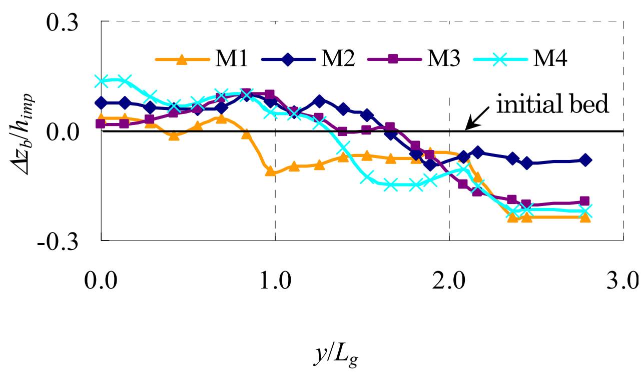
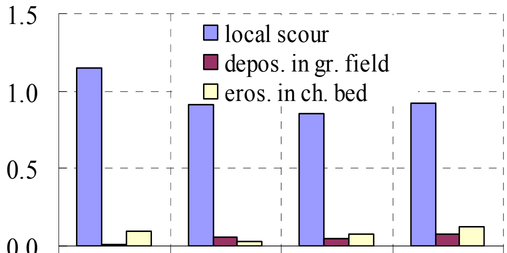


Fig. 6 Transverse distributions of erosion and deposition from different model-structures.

the groyne field, and erosion in the main channel; where the first one signifies the stability of the structure, the second one the anti-erosion of bank, and the third one the maintenance of navigation depth in the main channel. The measured maximum scour depth near the first groyne, average deposition in the groyne field, and average erosion in the channel bed from 25 cm to 45 cm from the side wall where the groynes are placed, are summarized and depicted with a figure, **Fig. 7** for clear understanding of the variation of the features among various groynes. The area considered for finding average feature values of erosion and deposition is similar to their transverse distributions as described in



	M1	M2	M3	M4
local scour	1.15	0.91	0.85	0.92
depos. in gr. field	0.01	0.06	0.05	0.08
eros. in ch. bed	0.09	0.03	0.08	0.12

Fig. 7 Comparison of dimensionless features between groyne-models: local scour ($\Delta Z_g/h_{imp}$), deposition in groyne field ($\Delta Z_{gf}/h_{imp}$), erosion in channel bed ($\Delta Z_{ch}/h_{imp}$).

Section 4.2, to avoid the effect of back flow from opposite wall in case of impermeable structure.

Here better responses in the channel in respect of local scour can be recognized due to both alignments and permeability: local scour reduces from M1 to M2 and also from M2 to M3. The results are also consistent with other studies [15]. Sediment deposition in the groyne field can be seen higher for models M4, and then M2 and M3, and it is found minimum in the case of model M1; whereas, average erosion in the channel bed is found higher in case of models M4, M1 and then M3, and it is observed relatively regular for M3 and M4 [**Fig. 5(b)**]. Moreover, as seen in **Fig. 5(b)** in impermeable case, flow was reflected from the other side of flume and attacked the groynes in downstream area, where pronounced scour is observed. It could be possible by strong return currents from fully blocked impermeable structures depending on groyne intervals, or reflecting the flow from large sandbars or any hard strata on channel boundaries on opposite side, or following the deeper channel near structures as recognized the failure of Betil and Enayetpur spurs several times in Bangladesh due to obliquely striking flow [8), 16)].

It can be seen from **Fig. 5(a)** that flow beneath the upper impermeable portion of model M4 counterbalances the recirculation of flow and causes bed formation in the downstream area; this is also evident from the field data [16)]. Diversion of flow is made by the straight impermeable and inclined upper-blocked portion of the structure which favors deepening the channel bed; whereas, only sediment-laden water near the bed passes beneath the blocked portion and deposited in the groyne field. However, compared to the model M3 scour depth and scour area both are found higher in case of model M4, this may due to the formation of vortices induced by downward flow to pass through lower open part [17)]**;** in contrast, height of deposition in the groyne field and erosion in the channel bed both are found higher in the case of model M4 compared with other structures. Therefore, from the experimental results, though M4 is advantageous in respect of anti-erosion of bank and maintenance of navigation channel, structural safety may have to be sacrificed or much attention should be paid for that at high flow condition. In addition, it is difficult to maintain certain area-ratio between upper impermeable and lower permeable portions for better functioning, as water level varies highly in the river, especially in Jamuna over the annual hydrological cycle. Even if bankfull stage, say, is considered in consideration of bank protection from erosion [8)], this may not function properly to address low flow problem due to less diversion of flow by lower highly permeable portion. As the erosion in channel bed in the case of model M3 is significantly improved than M2 and relatively uniform due to its modified configurations, so introducing the modification in the groyne design, which minimizes both local scour and big diversion of flow, does not have to compromise the quality of waterway or stability of river bank.

6. Conclusions

The present study was mainly aimed at exploring fluvial responses from various configurations of groynes to identify a suitable design for lowland river problems. From the discussion in the aforementioned section, the following conclusions can be drawn:

(1) Intense separation of flow occurred in the case of fully blocked impermeable model M1, consequently caused higher scour near groyne-tip. Also the flow was highly diverted to hit the other wall and turned back to attack the downstream embayments.

(2) Due to permeable nature, model M2 allowed flow through them, so that flow separation was minimized; moreover, velocity was reduced gradually and local scour was minimized. However, erosion in the main channel was not regular; rather deposition occurred after third groyne area.

(3) Model M3, modified in configuration with both alignment and permeability favored much lower local scour to occur than all other models; also deposition in the groyne field as well as erosion in the main channel were relatively uniform, but moderate in magnitude.

(4) Scour near model M4 was found higher in area and magnitude both in comparison to model M2 and M3; however, two other important features: erosion and deposition are better responded by the straight impermeable and inclined upper blocked portions for water diversion and lower open portion for allowing sediment laden water.

Therefore, the modified combined structures (M2, M3 and M4) offer more gradual transition from main channel to bankline compared with the conventional impermeable ones, thus these bear a high importance for the quality of landscape. Besides, as these structures minimize scour near groynes and strong return currents, aspect ratio could be increased, thus a cost-effective design approach can be expected. The features explored from the laboratory investigations imply that further modification in the lower permeable portion in M4 can be made with the arrangements for permeability in M3, so that the modified structure can serve optimal function both at high flow and low flow condition for lowland river problems; however, it needs detailed investigations for better understanding of the fluvial processes.

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