ANALYSIS OF DEPTH AND VELOCITY AROUND BANDAL STRUCTURES CONSTRUCTED IN THE ALAIKHAL RIVER, JAMALPUR

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ABSTRACT

Riverbank erosion is a persistent challenge in Bangladesh, driven by highly dynamic hydrological and sediment transport processes that threaten agricultural land, infrastructure, and settlements. Conventional erosion control measures, while effective, are often expensive and environmentally intrusive. Bandal-Like Structures (BLS), constructed from locally available bamboo, offer a sustainable alternative by modifying near-bank hydraulics and promoting controlled sediment deposition. The Alaikhal River, a distributary and tributary of the Jamuna River in Jamalpur district, exemplifies a hydraulically active system undergoing widening and deepening due to unstable morphology and seasonal discharge fluctuations. Its narrow geometry and sandy bed materials amplify erosion risks and flash flooding. To mitigate these issues, fourteen bamboo bandals, 40-60 m in length and angled 25°-45° to the main flow, were installed along a 300 m stretch of the right bank at Shirighat, Jamalpur District, before the 2023-24 monsoon season. This study evaluates the hydraulic performance of these structures using Acoustic Doppler Current Profiler (ADCP) surveys at fourteen cross-sections around the seven bandal structures, with velocity and depth measured both 3 m upstream and 3 m downstream of the bandals. Results consistently show downstream reductions in velocity and depth, indicating effective energy dissipation and sediment trapping. Velocity attenuation ranged from 7% to 38%, with the largest reduction recorded at the 4th bandal (0.26 m/s upstream to 0.16 m/s downstream) and the smallest at the 5th (~7%). The 7th bandal displayed the highest absolute velocities (0.61 m/s upstream, 0.49 m/s downstream), reflecting local channel constriction. Depth reductions were similarly significant, with the 4th bandal exhibiting a ~41% decrease (2.11 m upstream to 1.24 m downstream). Exceptions occurred at the 6th bandal (slight scour-induced depth increase) and 7th bandal (depth nearly unchanged). These findings confirm that BLS effectively weakens near-bank currents, dissipates energy, reduces erosion, and induces localized deposition in small alluvial rivers. Variability in hydraulic response underscores the importance of site-specific design, considering channel geometry, slope, and structure orientation. Overall, bandal structures demonstrate strong potential as cost-effective, eco-friendly river training solutions in Bangladesh and comparable river systems worldwide.

Keywords: *Bandal structures; water depth; velocity; energy dissipation; sediment deposition*

1. INTRODUCTION

Riverbank erosion is a widespread fluvial hazard that is influenced by various factors including hydraulic forces, sediment properties, bank vegetation, and human activities such as deforestation and unplanned infrastructure development (Thorne, 1997). Bangladesh, situated at the confluence of the Ganges-Brahmaputra-Meghna river system, is especially vulnerable to this issue. The Alaikhal River, a meandering distributary and tributary of the Jamuna in Jamalpur District, faces seasonal flooding, high sediment loads, and weak alluvial soils. This combination leads to a gradual loss of agricultural land, homes, and livelihoods in the area.

Conventional erosion control measures, such as embankments, revetments, and groynes, are often expensive, require significant maintenance, and can be environmentally intrusive. To address these issues, researchers have explored more cost-effective and eco-friendly alternatives. Bandal-like structures (BLS), made from bamboo and other biodegradable materials, offer a promising solution. When installed transversely to the flow of water, BLS reduce the velocity near the banks, encourage sediment deposition, and help stabilize the banks. Field studies have shown that BLS can lower bank shear stress, trap fine sediments, and improve channel navigability while causing fewer negative impacts compared to rigid groynes.

From 2019 to 2021, the River Research Institute (RRI) implemented simplified bank protection designs along various rivers in Bangladesh. They removed impermeable upper panels to enhance constructability. The results showed reduced near-bank velocities, increased sedimentation, and improved bank stability, although minor local scour was observed at the base of the structures (RRI, 2021). Despite these promising outcomes, comprehensive evaluations of hydraulic and sediment responses remain limited. The Alaikhal River was selected for this study due to its dynamic morphological features, high sediment load, and significant vulnerability to severe bank erosion, making it an appropriate site for assessing the effectiveness of bandal structure.

This study evaluates the performance of bandal-like structures (BLS) in the Alaikhal River by analyzing flow depth and velocity distribution around the constructed bandal structures in Jamalpur. The findings contribute to understanding the overall performance of BLS and promote sustainable, low-cost riverbank stabilization strategies for similar rivers in Bangladesh.

2. METHODOLOGY

2.1 Design and Layout of Bandal Structures

The bamboo bandal structures implemented in this study were designed by the River Research Institute (RRI) and vetted by the Bangladesh Water Development Board (BWDB). The layout, construction details, and geometric features of these structures at the Alaikhal River site are provided in Table 2.1. Additionally, isometric illustrations in Figure 2.1 depict their spatial arrangement within the channel. During field installations, key design parameters were taken into account, including spacing, length, embedment depth, and orientation relative to the flow.

Table 2. 1: The design features of bamboo bandal structure

Type of bamboo	: Barrack
Length of the Vertical main Bamboo pole	: =>7.5 m
Length of Inclined bamboo	: =>7.5 m
Length of Vertical bamboo with Inclined (Tie)	: =>6 m
Length of the Horizontal Bamboo (Runner)	: =>6 m
Inserted bamboo pole below the ground level	: 4.0 m
Bamboo pole above the ground level	: 3.5 m
Diameter of the bamboo	: 6 to 8 cm
Distance between vertical main bamboo	: 30 cm C/C
Distance between horizontal bamboo (runner)	: 50cm C/C
1st Horizontal bamboo above the ground	: 75 cm
Angle towards downstream (depending on situation especially flow condition, depth and width of the river)	: 30^0 to 45^0
Distance between main bamboo pole and tie bamboo	: 0.75 m
Distance between main bamboo pole and inclined bamboo	: 3 m at G.L.
Length of the Bullah	: 7.5 m
Spacing of the Bullah	: 10 m C/C
Diameter of the Bullah	: 10 to 13 cm

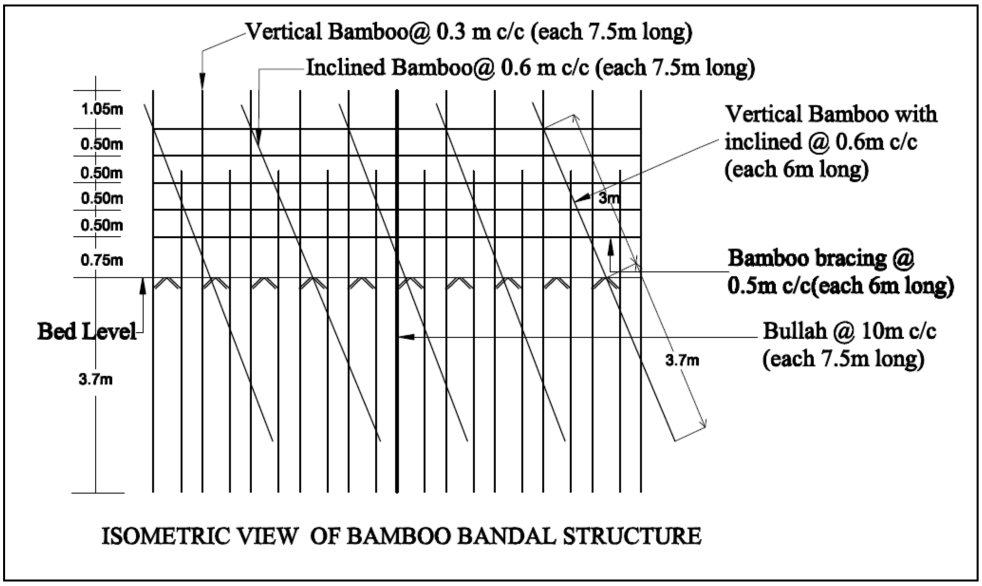

Figure 2.1: Isometric view of the bamboo bandal structure

2.2 Study Area and Construction Details

In the Melandah Upazila of Jamalpur District, 14 bamboo bandals were constructed along a 300m reach of the Alaikhal River at Shirighat to mitigate severe bank erosion. Each structure measures between 40 and 60 meters in length and is oriented at angles of 25° to 45° to the river flow, with adjustments made for local bends and constrictions. Made from locally sourced bamboo, these permeable barriers were installed before the 2023-24 monsoon season to dissipate the velocity of water near the banks, promote sediment deposition, and stabilize eroding banks. The project also adopted community participation by involving local labor and material suppliers. Figures 2.2, 2.3, and 2.4 provide the location of the study area, the placement of the bandal structures, and details on the construction of the bamboo bandal structures.

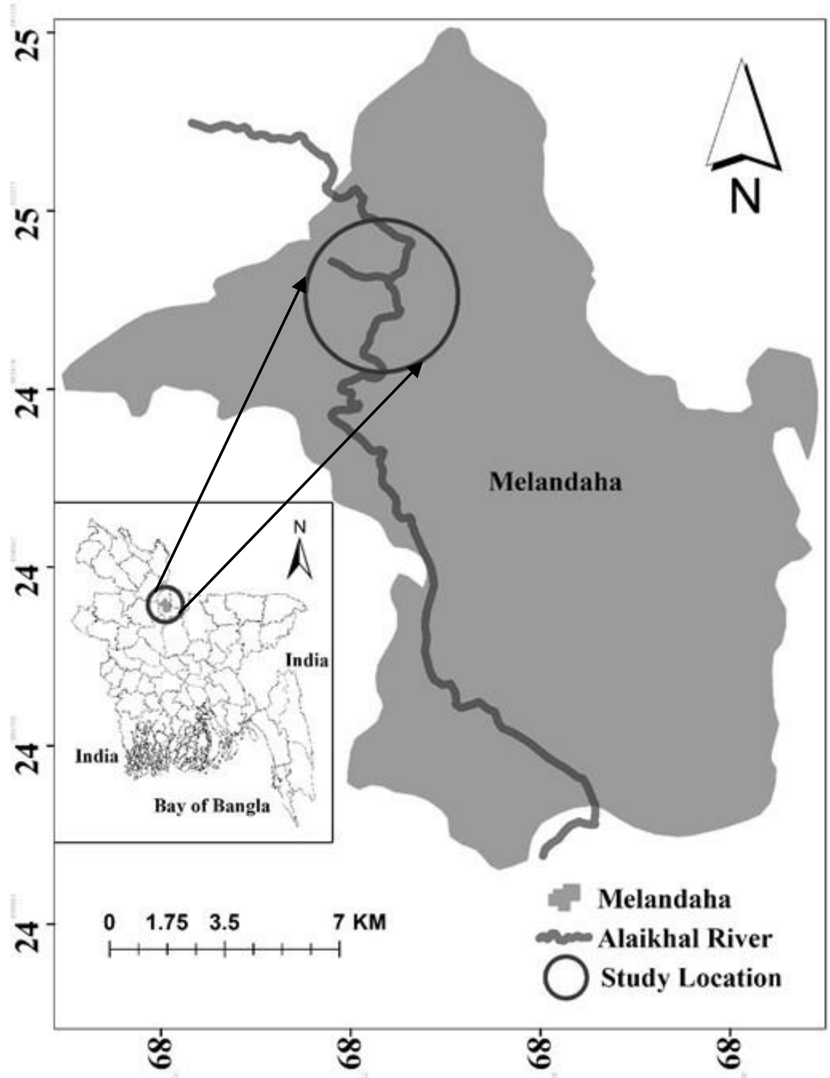

Figure 2.2: Location of Alaikhal river at Shirighat, Melandaha, Jamalpur

Figure 2.3: Location of the bandal structures in the right bank of Alaikhal River (25°0.76' N; 89°47.26' E)

Figure 2.4: Construction of bamboo bandal structures in the right bank of Alaikhal River

2.3 Data Collection

Primary field data were collected through multiple surveys to ensure consistency over time. The main hydraulic variables measured included flow velocity, water depth, and discharge. Measurements were taken at seven selected bandal sites using an ADCP. Velocity surveys were conducted 3m upstream and 3m downstream of each structure to capture any hydraulic modifications. The ADCP units were mounted on survey boats for mobile transects, while fixed platforms were utilized in areas where navigation was challenging. The locations for flow velocity measurements and the procedure for using the ADCP are illustrated in Figures 2.5 and 2.6.

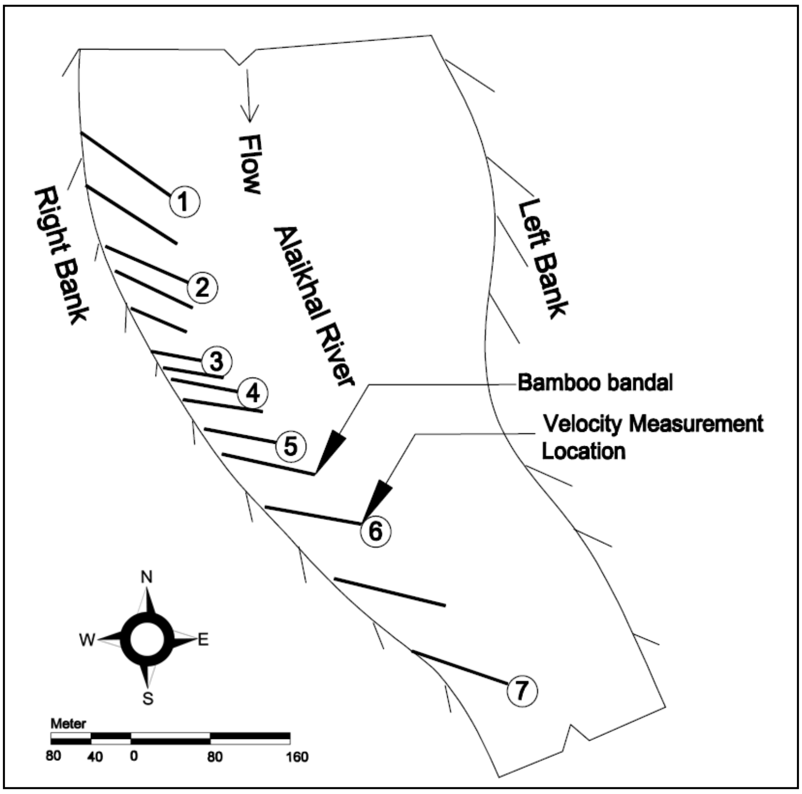

Figure 2.5: Velocity measurement location in the Alaikhal River

Figure 2.6: Flow velocity measurement in the Alikhal River using ADCP (21st June 2024)

2.4 Hydraulic Measurements

Each cross-section was divided into vertical bins, with velocity measurements recorded at 0.2h and 0.8h (where *h* is the local water depth) to represent upper and lower portions of the water column. Total discharge, Q (m^3s^{-1}) was estimated using the velocity–area integration method:

$$Q=\sum(V \times A) \quad (1)$$

where V (ms^{-1}) is the mean velocity in each bin and A (m^2) is the corresponding area. Measured discharges were validated against historical hydrological records for reliability.

2.5 Data Processing and Analysis

Velocity, depth, and discharge data were analyzed using River Surveyor Live software, which allowed for spatial visualization of flow characteristics. The analysis concentrated on evaluating velocity attenuation, patterns of local scour and deposition, and the overall hydraulic response. These findings were used to assess the effectiveness of bamboo bandals in stabilizing riverbanks and promoting sediment accretion.

Equations used for data analysis

- **Velocity attenuation (%)**

$$\text{Attenuation}(\%)=\frac{V_{up}-V_{down}}{V_{up}}x100 \quad (2)$$

- **Depth reduction (%)**

$$\text{Depth reduction}(\%)=\frac{h_{up}-h_{down}}{h_{up}}x100 \quad (3)$$

- **Head loss (Bernoulli, nearly horizontal channel)**

$$h_L=(h_{up}-h_{down})+\frac{V^2up\text{-}V^2down}{2g} \quad (4)$$

- **Loss coefficient K**

$$K=\frac{2g\,h_L}{V^2_{up}} \quad (5)$$

- **Energy dissipation per unit mass (approx.)**

$$\varepsilon = \frac{g h_L}{\Delta x} \tag{6}$$

- **Manning friction slope (approx., R≈h)**

$$S_f = \left(\frac{nV}{h^{2/3}}\right)^2 \tag{7}$$

- **Bed shear and shear velocity**

$$\tau_b = \rho g h S_f, \tag{8}$$

$$u_* = \sqrt{\frac{\tau_b}{\rho}} \tag{9}$$

- **Shields parameter**

$$\theta = \frac{u_*^2}{(s-1)gd} \tag{10}$$

8. **Meyer–Peter–Müller bedload (classical form)**
   (only computed as an index; use with caution-applicability depends on grain size and regime)

$$q_b = 8\sqrt{(s-1)gd^3} * (\theta - \theta_{cr})^{3/2} \tag{11}$$

3. RESULTS AND DISCUSSION

3.1 Flow Field Analysis in the Alaikhal River

A comparative analysis of upstream and downstream velocity and depth variations around seven bandal structures in the Alaikhal River, Jamalpur, was conducted using ADCP data. The aim of this investigation was to assess the impact of bandal structures on velocity and depth characteristics. Upstream measurements reflect the natural and undisturbed flow conditions, while downstream profiles indicate the hydraulic adjustments that occur due to flow obstruction and the energy dissipated by the structures. The observed variations in velocity magnitude and flow depth clearly show the significant hydraulic impact of the bandal structures. Generally, downstream areas exhibited reduced velocities and shallower depths, indicating localized energy loss and potential zones of sediment deposition. In contrast, upstream regions typically demonstrated higher flow velocities and increased depths, suggesting a concentration of flow approaching the structures. As a representative example, the velocity and depth profiles corresponding to the fourth bandal structure are presented below, illustrating the distinct hydraulic responses between the upstream and downstream reaches of the Alaikhal River. Similar profiles have been generated for all other bandal structures presented in Islam (2025).

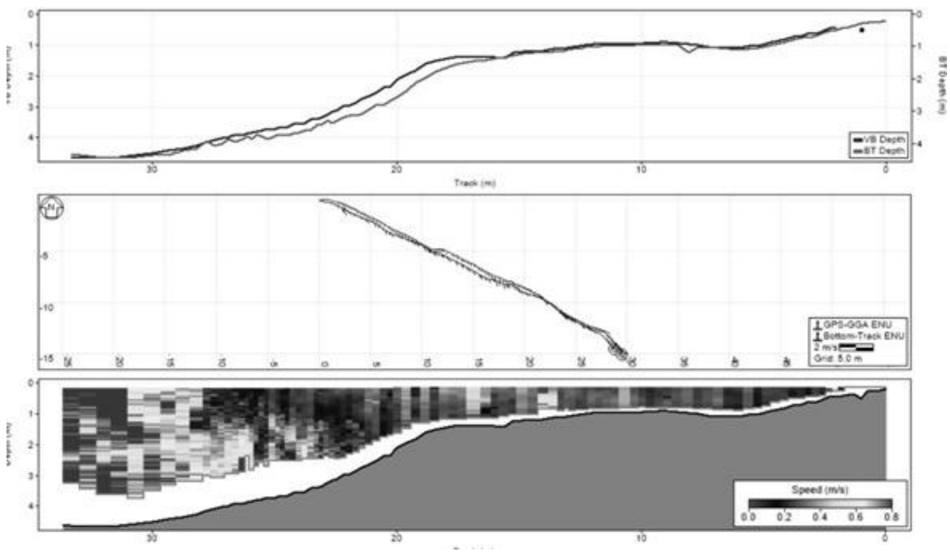

Figure 3.1: Velocity profile for the 4th bandal structure in upstream of the Alaikhal River

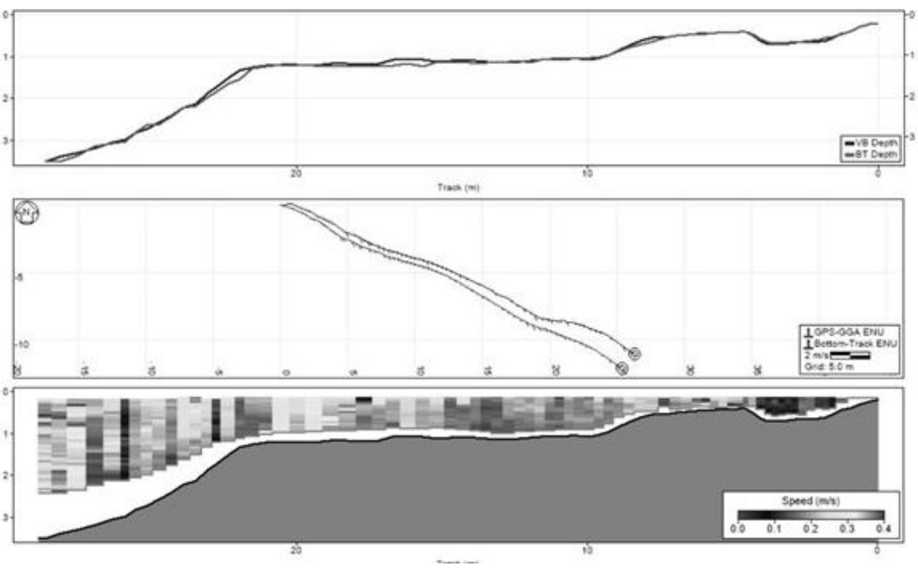

Figure 3.2: Velocity profile for the 4th bandal structure in downstream of the Alaikhal River

3.2 Velocity Profiles around Seven Bandal Structures in the Alaikhal River

The velocity distribution around the seven bandal structures in the Alaikhal River illustrates how these low-cost hydraulic interventions alter local flow patterns and sediment transport processes. Each structure creates a distinct upstream-downstream velocity contrast, which affects turbulence intensity, bed shear stress, and sediment deposition patterns. The results detailed in Tables 3.1, 3.2, and 3.3 summarize the observed hydraulic behavior and computed flow parameters for each structure.

At the 1st bandal, the upstream flow was relatively uniform, with velocities ranging between 0.2-0.6 ms^{-1} (mean 0.23 ms^{-1}). Near-bed velocity reached 0.4 ms^{-1}, supporting moderate sediment mobility. Downstream, turbulence increased and mean velocity declined to 0.16 ms^{-1}, resulting in spatially variable near-bed flow conducive to localized deposition interspersed with shallow scour. The calculated velocity attenuation (30%) and depth reduction (24%) indicate partial energy dissipation and the onset of bed stabilization downstream.

At the 2nd bandal, upstream velocities peaked at 0.6 ms^{-1} (mean = 0.23 ms^{-1}) and reduced downstream to 0.4 ms^{-1} (mean = 0.15 ms^{-1}). The weaker near-bed transport capacity and slightly increased downstream depth (1.45 m) suggest redistribution of sediment and attenuation of turbulence in shallower zones. The bandal thus acted as a deflector, directing the flow toward deeper zones while promoting sediment deposition near the banks.

At the 3rd bandal, upstream flow was relatively energetic with a maximum velocity of 0.8 ms^{-1} (mean =0.31 ms^{-1}). Downstream velocity decreased to 0.21 ms^{-1}, forming a wake region characterized by energy loss and moderated bed shear (τ_b = 0.91 to 0.42 Nm^{-2}). This hydrodynamic adjustment induced depositional conditions, accompanied by a computed head loss of 0.06m and energy dissipation rate of 0.10 m^2s^{-3}.

At the 4th bandal, the most pronounced upstream-downstream contrast was observed. Mean velocity declined from 0.26 ms^{-1} upstream to 0.16 ms^{-1} downstream (attenuation is 38%), with a substantial depth reduction (2.11 to 1.24 m). High upstream bed shear (τ_b = 0.63 Nm^{-2}) induced localized scour, while weakened downstream shear (τ_b = 0.29 Nm⁻²) favored sediment deposition. The associated head loss (h_L = 0.87m) and high energy dissipation (ε=1.43 m^2s^{-3}) confirm intense turbulence damping by the bandal structure.

The 5th bandal exhibited comparatively balanced flow characteristics, with mean velocity decreasing only slightly from 0.28 ms^{-1} upstream to 0.26 ms^{-1} downstream. Bed shear values were nearly identical (0.77 to 0.69 Nm^{-2}), suggesting stable sediment transport conditions and low flow disturbance. The small head loss (0.23m) and moderate bedload transport (3.62x10^{-5} to 2.98x10^{-5} m^2s^{-1}) indicate gradual downstream sediment accumulation.

At the 6th bandal, with velocity decreasing from 0.21 ms^{-1} to 0.19 ms^{-1} (attenuation is 10%). The slightly increased downstream depth (1.46 m) and reduced shear stress (0.48 to 0.38 Nm^{-2}) signify deposition and bed aggradation. The corresponding Shields parameter (0.34 to 0.27) remained above the critical value (θc = 0.047), confirming continued but reduced sediment transport.

Finally, at the 7th bandal, upstream velocity peaked at 1.2 ms^{-1} (mean = 0.61 ms^{-1}) with a high bed shear of 3.81 Nm^{-2}, driving strong sediment transport. Downstream velocity declined to 0.8 ms^{-1} (mean = 0.49 ms^{-1}), leading to partial energy dissipation and sediment retention. The reduction in bed shear (2.47 Nm^{-2}) and drop in Shields parameter (2.67 to 1.74) denote a transition from an erosive to a depositional zone, signifying localized bed stabilization.

Table 3.1: Upstream and downstream velocity-depth characteristics at bamboo bandal structures

Bandal No.	Section	Max Velocity (ms^{-1})	Mean Velocity (ms^{-1})	Mean Velocity at Bandal End (ms^{-1})	Near-bed Velocity (ms^{-1})	Max Depth (m)	Avg. Depth (m)
1st	Upstream	0.60	0.23	0.40	0.15–0.40	1.71	0.84
	Downstream	0.60	0.16	0.35	0.03–0.30	1.75	0.64
2nd	Upstream	0.60	0.23	0.42	0.02–0.40	4.06	1.58
	Downstream	0.40	0.15	0.27	0.05–0.30	3.97	1.45
3rd	Upstream	0.80	0.31	0.78	0.04–0.40	4.68	2.06
	Downstream	0.60	0.21	0.41	0.08–0.30	4.47	2.00
4th	Upstream	0.80	0.26	0.62	0.20–0.30	4.63	2.11
	Downstream	0.40	0.16	0.26	0.00–0.25	3.98	1.24
5th	Upstream	0.60	0.28	0.44	0.20–0.50	4.44	1.83
	Downstream	0.60	0.26	0.26	0.07–0.30	3.61	1.60
6th	Upstream	0.60	0.21	0.29	0.05–0.35	3.06	1.35
	Downstream	0.40	0.19	0.22	0.06–0.25	3.23	1.46
7th	Upstream	1.20	0.61	1.00	0.08–0.70	2.26	1.62
	Downstream	0.80	0.49	0.49	0.20–0.70	2.27	1.59

Table 3.2: Different parameters at upstream and downstream of bamboo bandal structures

Bandal No.	Velocity, up(ms^{-1})	Velocity, down(ms^{-1})	Depth, up(m)	Depth, down(m)	Velocity Attenuation (%)	Depth Reduction (%)	Head loss, h_L(m)	Energy dissipation, $\varepsilon(m^2s^{-3})$
1st	0.23	0.16	0.84	0.64	30.43	23.81	0.20	0.33
2nd	0.23	0.15	1.58	1.45	34.78	8.23	0.13	0.22
3rd	0.31	0.21	2.06	2.00	32.26	2.91	0.06	0.10
4th	0.26	0.16	2.11	1.24	38.46	41.23	0.87	1.43

5th	0.28	0.26	1.83	1.60	7.14	12.57	0.23	0.38
6th	0.21	0.19	1.35	1.46	9.52	-8.15	-0.11	-0.18
7th	0.61	0.49	1.62	1.59	19.67	1.85	0.04	0.06

Table 3.3: Different parameters at upstream and downstream of bamboo bandal structures

Bandal No.	Bed Shear (upstream) τ_b(Nm^{-2})	Bed Shear (down), τ_b(Nm^{-2})	Shear Velocity (up), u_*(ms^{-1})	Shear Velocity (down), u_*(ms^{-1})	Shields Parameter (up)	Shields Parameter (down)	Bedload (up), q_b(m^{2}s^{-1})	Bedload (down), q_b(m^{2}s^{-1})
1st	0.67	0.36	0.03	0.02	0.47	0.25	2.8E-05	6.9E-06
2nd	0.55	0.24	0.02	0.02	0.38	0.17	1.8E-05	1.9E-06
3rd	0.91	0.42	0.03	0.02	0.64	0.30	4.9E-05	1.0E-05
4th	0.63	0.29	0.03	0.02	0.44	0.20	2.5E-05	3.6E-06
5th	0.77	0.69	0.03	0.03	0.54	0.49	3.6E-05	3.0E-05
6th	0.48	0.38	0.02	0.02	0.34	0.27	1.4E-05	8.2E-06
7th	3.81	2.47	0.06	0.05	2.67	1.74	5.2E-04	2.6E-04

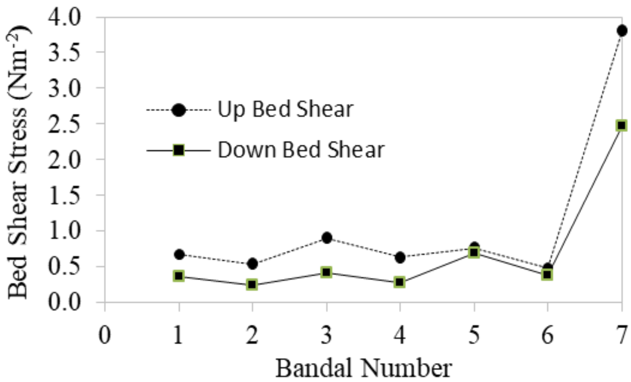

Figure 3.3: Upstream and downstream bed shear stress of seven bandal structures

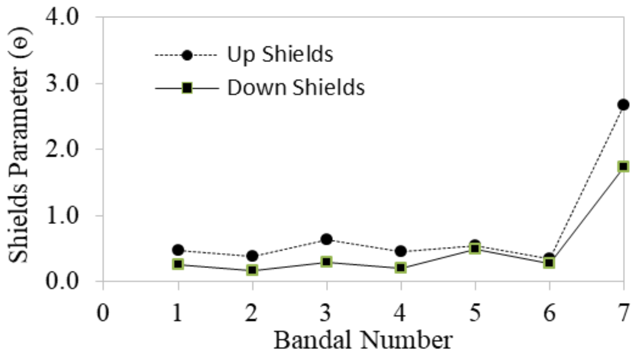

Figure 3.4: Upstream and downstream Shields parameter of seven bandal structures

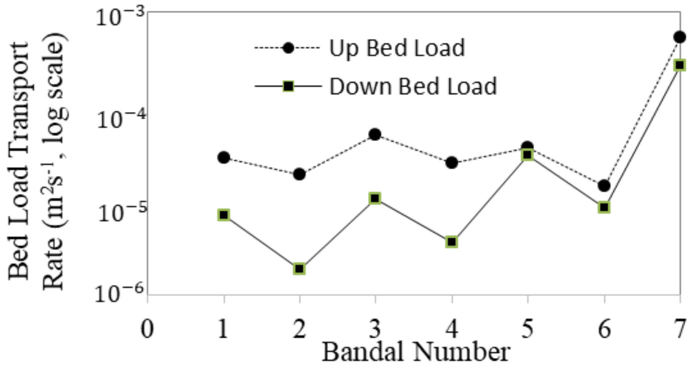

Figure 3.5: Upstream and downstream Bed load Transport rate of seven bandal structures

3.3 Discussion of Flow Attenuation and Bed Response

The hydraulic data, as presented in Tables 3.1-3.3 and Figures 3.3-3.5, consistently demonstrate that bamboo bandal structures in the Alikhal River effectively induce measurable flow attenuation, reduce near-bed shear stress, and suppress sediment transport in the immediate downstream area. Velocity profiles measured at seven consecutive bandals show that mean downstream velocities are lower than those measured upstream, indicating that these permeable, pile-type interventions are successful in dissipating flow energy (Ali, 2024).

3.3.1 Velocity Attenuation and Energy Dissipation

The percentage of velocity attenuation ranged from 7.14% to 38.46%, with the highest reduction observed at the 4th bandal, where mean velocity decreased from 0.26 ms^{-1} (upstream) to 0.16 ms^{-1} (downstream). This notable decrease coincides with the bandal's favorable alignment and partial obstruction of flow, which likely enhanced turbulence decay and energy diffusion. The corresponding head loss (h_L) and energy dissipation rate (ε) were 0.87m and 1.43 m^2s^{-3} respectively-the highest among all bandal structures. Similar experimental and field studies on permeable spurs and bamboo fences report comparable reductions in flow velocity and energy dissipation that promote near-bank sedimentation (Rahman & Osman, 2018). In contrast, the 5th and 6th bandals exhibited relatively low attenuation (7-10%) due to less obstructive alignment and possibly increased local conveyance capacity. Interestingly, the 6th bandal recorded a slightly higher downstream depth, implying minor flow expansion or secondary circulation downstream of the structure.

Overall, the average velocity attenuation across all structures was approximately 25%, accompanied by a proportional decline in flow energy. These results highlight the hydraulic efficiency of bamboo bandals in reducing velocity and dissipating energy, thereby stabilizing the riverbank.

3.3.2 Bed Shear Stress and Sediment Transport Response

The bed shear stress (τ_b) and bedload transport rate (q_b) show a strong correlation with velocity reduction. The mean downstream τ_b decreased by about 40% relative to the upstream values, with corresponding bedload flux reductions ranging from 18% to 90%. For instance, at the 3rd bandal, τ_b dropped from 0.91 Nm^{-2} upstream to 0.42 Nm^{-2} downstream, leading to a decrease in bedload flux from $4.9x10^{-5}$ to $1.0x10^{-5}$ m^2s^{-1}. Similarly, the 4th bandal exhibited τ_b reduction from 0.63 to 0.29 Nm^{-2} and a corresponding drop in q_b from $2.5x10^{-5}$ to $3.6x10^{-6}$ m^2s^{-1}. Such substantial reductions indicate that flow resistance induced by the bamboo piles and cross-bracing elements effectively attenuated near-bed shear and constrained sediment entrainment capacity. The downstream decline in the Shields parameter (θ) further confirms that entrainment thresholds were not exceeded within the depositional zones created by the bandals (Ali, 2024).

3.3.3 Flow Structure and Morphological Adjustment

The upstream zones experienced moderate flow acceleration and localized scour, especially around the clusters of piles and the gaps between the bandal elements. This scour functions as a self-adjusting mechanism, helping to balance flow momentum and ensure hydraulic continuity. In contrast, the downstream zones transformed into low-energy depositional environments, which are characterized by reduced turbulence intensity and lower shear velocity (u_*). The ongoing reduction of flow energy encouraged the deposition of fine sediments, resulting in local aggradation and stabilization of the riverbed. This pattern of upstream scour and downstream deposition is a common morphodynamic response to a series of permeable elements and bamboo bandalling in alluvial rivers (Rahman & Osman, 2018). Among all bandal structures, the 4th bandal showed the most pronounced hydraulic response-strong velocity reduction, high head loss, and significant bedload reduction-indicating optimal hydraulic performance under the given flow regime. The 7th bandal, however, experienced

elevated shear (τ_b = 3.81 Nm^{-2} upstream), reflecting localized acceleration likely caused by channel constriction or structural alignment across a narrower reach.

3.3.4 Implications for River Training

The findings indicate that bamboo bandal structures can effectively redistribute flow energy and alter near-bed hydraulics to produce desirable morphodynamic responses. By reducing shear stress and the capacity for sediment transport downstream, these low-cost, eco-friendly structures promote localized aggradation and provide bank protection without causing large-scale hydraulic disturbances. The observed flow attenuation of 7-38%, an average reduction in bed shear of about 40%, and a decrease in average bedload flux of approximately 63% collectively demonstrate the effectiveness of bandal-like systems as sustainable and adaptive river training measures for small to medium alluvial rivers in Bangladesh. Permeable, sequentially placed bandals help redistribute flow energy, lower near-bed stress downstream, and encourage local aggradation and bank protection-all without creating the large-scale hydraulic disturbances typically associated with rigid structures. Their performance highlights the potential of permeable flow interventions as sustainable and adaptive solutions for river management.

3.4 Summary of Observed Trends

- Mean velocity consistently reduced across most structures, signifying effective energy dissipation.
- Bed shear and Shields parameters dropped downstream, aligning with the onset of sediment deposition.
- Bedload transport decreased sharply downstream, especially at bandals 1st, 2nd, 3rd, and 4th, illustrating the trapping efficiency of these structures.
- Sites with minimal velocity reduction (bandals 5th-6th) showed stable flow and balanced sediment conditions.
- The 7th bandal, being located in a higher-energy reach, played a crucial role in stabilizing the downstream channel through controlled energy reduction.

4. CONCLUSIONS

The study shows that bamboo bandal structures significantly change the local hydraulics in the Alaikhal River by reducing near-bank velocities and flow depths. Velocity reductions ranged from 7% to 38%, with the most substantial impact observed near the 4th bandal. Additionally, depth reductions of up to 41% suggest effective sediment retention and flow energy dissipation. However, exceptions were noted at the 6th and 7th bandals, indicating that channel geometry and flow constriction affect the performance of these structures. These findings support the use of bamboo bandals as sustainable and low-cost river training tools for mitigating erosion in small to medium alluvial rivers. Future research should include measurements of sediment concentration and long-term monitoring of morphological changes to optimize the design and spacing of these structures.

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DECLARATION OF USE OF AI:

ChatGPT and Grammarly were used only for language-related support, including grammar correction, sentence restructuring, and improving academic tone. All scientific decisions, data collection, analyses, and conclusions were made solely by the authors.

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