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Hydraulic and Morphological Consequences of Bank Protection Measures along the Jamuna River, Bangladesh

Hao ZHANG, Hajime NAKAGAWA, Yasuyuki BABA, Kenji KAWAIKE,
Md. Munsur RAHMAN* and Mohammad Nazim UDDIN**

* Institute of Water and Flood Management, Bangladesh University of Engineering and Technology
** Department of Civil Engineering, Dhaka University of Engineering and Technology

Synopsis

Bank erosion is a severe problem in the rivers of Bangladesh. Besides the important scientific and engineering relevance, bank erosion also exerts significant social and economic impacts in this southern Asian country. This paper describes typical bank protection measures as well as their hydraulic and morphological consequences in the lower part of the Brahmaputra River (named the Jamuna River in Bangladesh). Based on a series of field investigation results, attempts have been made to clarify the mechanisms of bank erosion along this large alluvial river. Moreover, the performances of existing bank protection measures are evaluated and possible solutions for further enhancement are proposed. Special attention is paid to a historied and indigenous river training structure: Bandal. The recurrent use of Bandal-like structures is suggested for bank protection and channel stabilization of the braided Jamuna River.

Keywords: Brahmaputra/Jamuna River, bank protection, channel stabilization, field investigation, Bandal, spur dyke

1. Introduction

The southern Asian country: Bangladesh is one of the most populated nations in the world. The land of Bangladesh is covered by a complex river network system consisting of three major rivers: the Ganges, the Brahmaputra and the Meghna, together with their numerous tributaries and distributaries. A brief overview of the rivers in Bangladesh is referred to Oka (2004). One important hydrological aspect of rivers in Bangladesh is that 92% of the drainage basin of these rivers lies outside of the country (FAP21, 2001). Moreover, the sediment within Bangladeshi rivers consists primarily of fine sands and silts with little clay matrix (Coleman, 1969). Therefore, river banks are highly susceptible to erosion when the flow conditions change. In the past several decades, frequent flood and continuous erosion have consumed large areas of floodplains, made thousands of people homeless and destroyed a huge amount of infrastructures. The problems related to the Brahmaputra River are particularly gigantic, and this river is selected as the target for the current study.

The Brahmaputra River is named the Jamuna River within the border of Bangladesh. It originates from the Kailas Range of the Himalayas and flows across China, India and Bangladesh. The river meets with some major rivers in its lower part: the Teesta, the Ganges and the Meghna and supplies sediment into one of the world’s largest deltas before finally entering the Bay of Bengal. The location and the catchment area of the Brahmaputra/Jamuna River are shown in Fig.1.

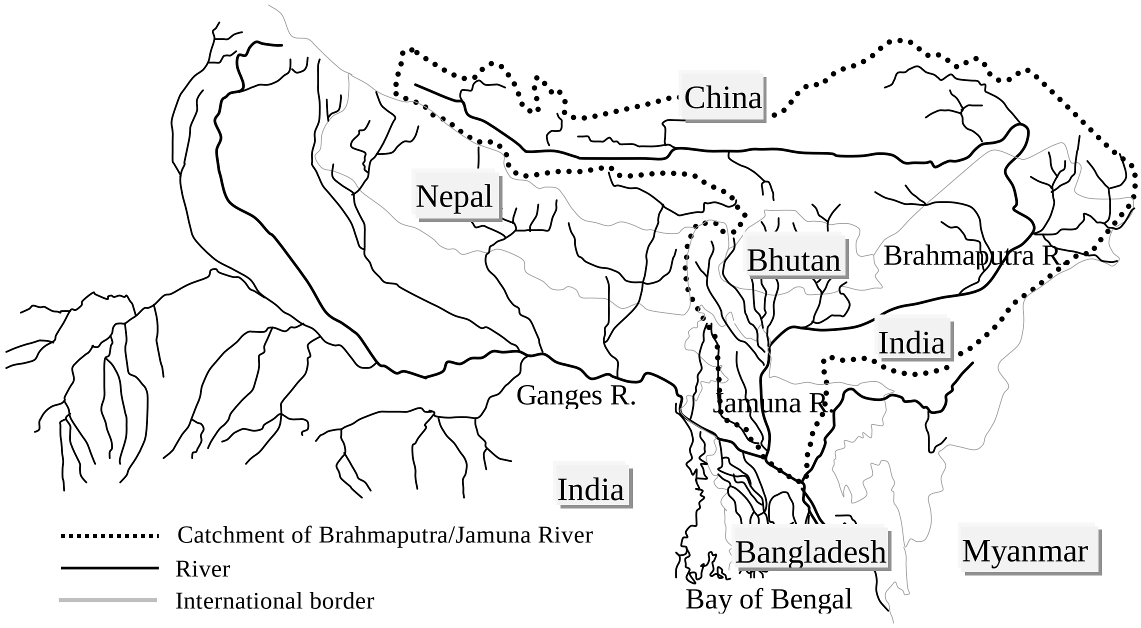


Fig. 1 Location and catchment of the Brahmaputra/Jamuna River

As is known, the Brahmaputra/Jamuna River ranks in the top group of the earth's large rivers in terms of both water and sediment discharges. In the reach within Bangladesh, the river wanders with a distance of approximately 240km and has a mean bankfull width of some 11km. The average annual flow discharge of the Jamuna River is around 20,200m^3/s and sediment transported through the river is about 590 million tons per year at the Bahadurabad gauging station (Sarker et al., 2003). The annual hydrograph of the Jamuna River is characterized by low flows during the winter dry season and high flows during the summer time due to snowmelt in the Himalayas and heavy local rainfall in the monsoon. The river is braided with meta-stable islands and nodal reaches, mobile sandbars, shifting anabranches and severe bank erosion (Thorne et al, 1993). Systematic analysis of time-series of dry season satellite images and with the supplement of available historical maps and aerial photographs, CEGIS reported that the Jamuna River shows a persistent trend of westward migration (CEGIS, 2004, 2005, 2006 and 2007). Analysis indicates that the centerline of the river has moved an average of 4.3km towards west since year 1830 with a maximum westward movement of 13km at its northern end. In recent years, the Jamuna River is migrating westward at an average of 75m per year. Moreover, the river is widening at an average rate of 145m/year, accompanied by the annual creation of 1960 hectares of char land from sediment trapped within the channel. As one of the most crowded countries in the world and the majority of the population being still wholly dependent upon land holdings, the bank erosion and migration of the river have significant impacts on the development of the society and economy. According to combined analyses of population data with satellite images, it is found that during the period of last 10 years, an average of almost 46,000 people were relocated every year due to bank erosion along the Jamuna River (IWFM, 2008).

In order to protect lives and properties from frequent flooding, an earth embankment was built during the later 1950s and mid 1960s along the west bank of the Jamuna River, extending for some 220km. The embankment is generally known as the Brahmaputra Right Embankment (BRE). The on-going bank erosion by the river, however, has led to breaches of the BRE with attendant crop loss and damage to buildings and infrastructures as well as successive costly retirements of the BRE over the past several decades (Halcrow et al, 1994). Improvement of the performance of the BRE is therefore an important part of flood protection and measures against bank erosion. In order to seek long-term strategy for the protection of the BRE, the Government of Bangladesh has commissioned a series of studies since 1990. A master plan was formulated and construction of bank protection structures at different probable locations was suggested to save priority areas. From the mid 1990s, construction of major structures was started and there are now around 28 major bank protection structures along the BRE. In general, these structures may be categorized into two kinds: one kind is intended to mainly strengthen the resistance of the bank to be protected with insignificant interference on the river flow, e.g. revetments. The other kind is aimed to decrease the hydraulic impacts directly in front of the protected area, e.g. spur dykes.

It has to be mentioned that most of the existing bank protection structures along the BRE were designed using extrapolation methods based on research results and experiences of small rivers in other places such as some European countries. The resulted structures were generally very huge in both size and cost corresponding to the scale of the Jamuna River. Although positive roles of some of the bank protection structures have been reported after an overall performance assessment based on available literatures, field investigations and discussions with engineers and the stakeholders (BWDB, 1999), the applicability and sustainability of these structures were still questionable for large Bangladeshi rivers. The fact is that most of them experienced frequent damages or failures after their completion. On the other hand, a locally developed structure: Bandal, deserves special attention. A Bandal structure may be simply described as a vertical screen mounted on a frame. The main construction materials are bamboo mats with a bundle of bamboo sticks. Bandal structures are quite cheap since bamboos are locally available and inexpensive labors are easily employable on site without any special training. When the sediment-laden flow approaches the Bandal, flow separation occurs: low sediment-concentrated flow at the upper layer is diverted to the main channel and is accelerated, resulting in bed degradation in the main channel, while high sediment-concentrated flow at the lower layer passes through the Bandal and deposits behind it due to velocity reduction there. Bandal structures may be physically considered as combined structures of spur dykes and pile dykes (Zhang et al., 2010). They have been successfully used in the India subcontinent historically. Unfortunately, their working principles are not well clarified and design guidelines are not available yet due to shortage of scientific evidences.

In this paper, the hydraulic and morphological consequences of typical bank protection measures in selected river reach are investigated. Based on the investigation results, the performances of these measures are evaluated. The mechanism of bank erosion in large alluvial rivers is discussed, improvement methods for existing bank protection structures are suggested and probable cost-effective solutions for the training of the Jamuna River are proposed.

2. Study sites and research methods

Referring the master plan report of the Brahmaputra River training studies of the Bangladesh government and based on the first-hand knowledge and experiences from field visits, the Sirajganj Hardpoint (revetment) and the Betil/Enayetpur spur dykes were selected as the target structures to investigate the existing bank protection measures. These two sites ranked in the top group of the priority areas to be protected designated by the government. Bandal structures near the Jamuna Bridge at the Randhunibari market are also included in the study as a reference site. Field investigations to the three sites were made in 2008, 2009 and 2010. The locations of them are sketched in Fig.2.

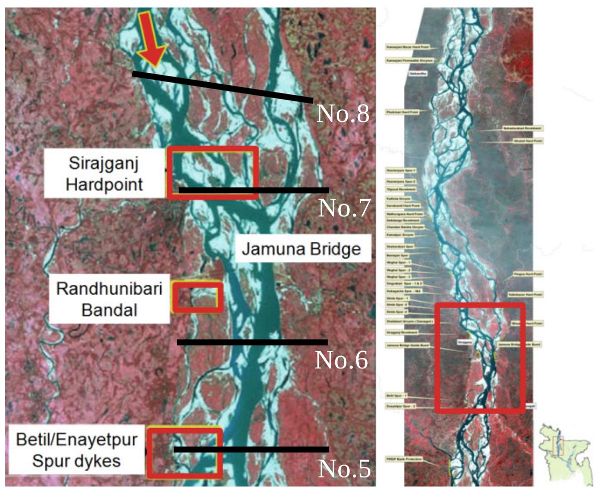


Fig. 2 Location of study sites (Left to Right: Study sites, the Jamuna River and Bangladesh)

This study is conducted primarily on the basis of literature review, field measurements, discussing with local people and collecting information from BWDB (Bangladesh Water Development Board), CEGIS (Center for Environmental and Geographic Information Services) and BUET (Bangladesh University of Engineering and Technology) with the aid of our collaborators in Bangladesh. The authors have conducted a series of researches on spur dykes over the past several years (e.g. Zhang et al., 2006, Zhang et al., 2007, Zhang and Nakagawa, 2008 and Zhang et al., 2009), the knowledge acquired from those studies are partially extended to this research if necessary. Moreover, preliminary experimental and numerical results from the authors' research group on Bandal-like structures are also used as supplement information to understand the fundamentals underlying the physical phenomena.

As a field-based applied research, field trips and field measurement systems are of great importance. In this study, a measuring system consisting of an ADCP (Acoustic Doppler Current Profiler) and a GPS (Global Positioning System) is used to record the 3D velocity vectors in the river. The ADCP (1200kHz, WH-ADCP Rio Grande by Teledyne RD Instruments) was mounted downward beneath the water surface on a particularly designed plastic boat. And the plastic boat was dragged by a local wooden boat during measurements. The ADCP and the GPS are connected with a laptop installed with a real-time data visualization and data analyzing/ post-processing program. A snapshot of the field measurement is shown in Photo1, with the specifications of the measuring system.

Photo1 Field survey on the Jamuna River

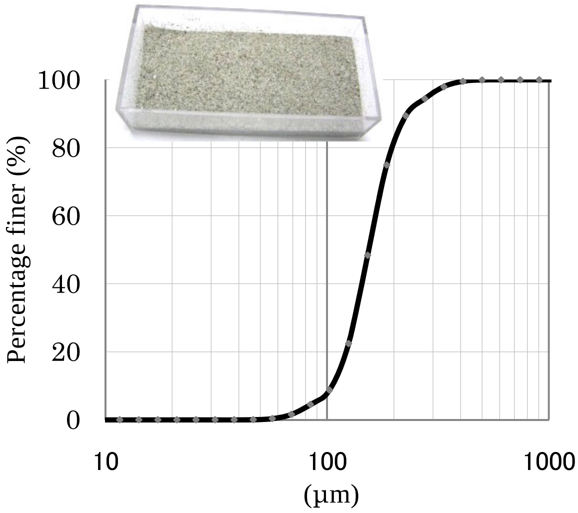


Fig.3 Sieve analysis result of sediment samples

Before filed measurements, basic information on the sediment properties and hydrological and morphological characteristics related to the study area is collected.

The Jamuna River is characterized by fine sedimentary environment with highly mobile beds and banks. The sediment is uniformly graded and has very low strength and transport resistance. Mean sediment sizes of the river vary from 220um to 165um (FAP21, 2001), showing insignificant changes from the upstream to the downstream. Sediment samples taken from the floodplain near the Sirajganj Town were analyzed during the first field trip as shown in Fig.3. It is found obviously that the sediment is much finer than that in typical Japanese or European rivers. The mean diameter is 181um, having a geometric deviation of 1.36.

On the other hand, the daily discharge at the upstream Bahadurabad gauging station and the monumented surveyed cross-sections (Section No.5-No.8 as depicted in Fig.2) near the three study sites were obtained from BWDB are shown in Fig.4 and Fig.5. The hydrograph at the Bahadurabad gauging station shown in Fig.4 ranges from year 1998 to year 2006 temporally. The low flow season and the high flow period are evidently distinguished from year to year. The river generally peaks during the period of July and August. Peak discharge is found to be generally around 60,000cumecs, exhibiting insignificant changes over years. Extreme flood discharge occurred in 1998 and the country suffered one of its worse ever floods between July and September in that year.

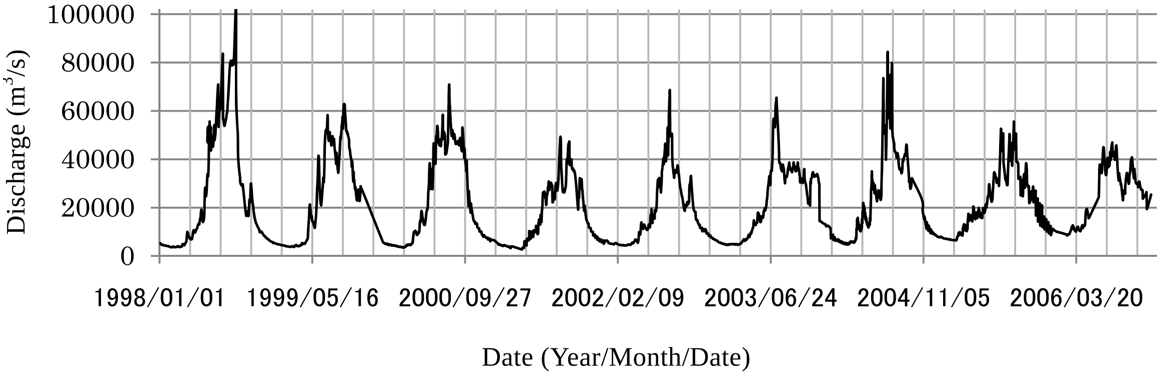


Fig.4 Daily discharge at the upstream Bahadurabad gauging station

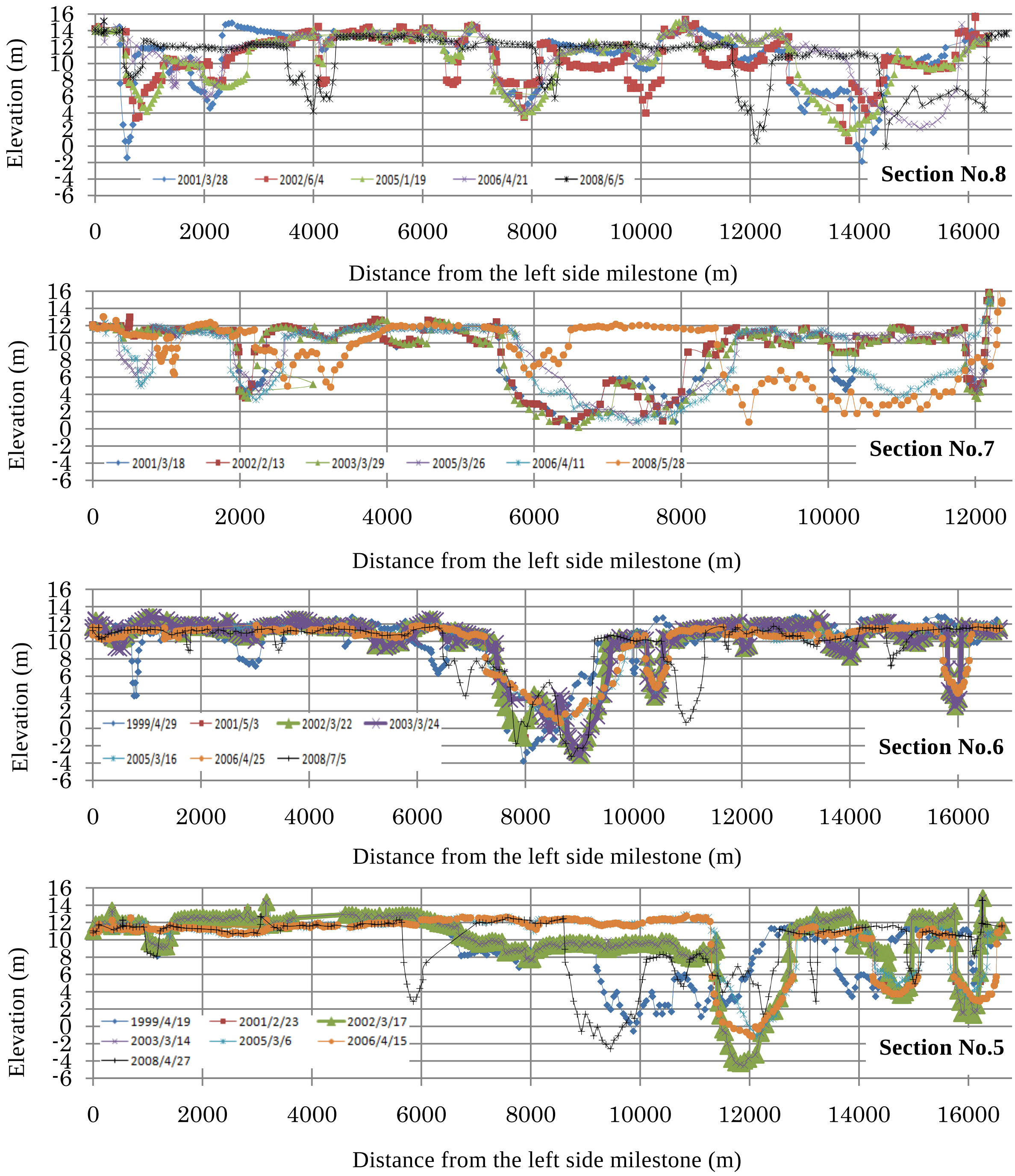


Fig.5 Temporal variation of typical cross-sectional profiles near study sites

The changes of the bed elevation at four typical cross-sections in Fig.5 demonstrate the highly active nature of the mobile bed of the Jamuna River in the past several years. The locations of the sections are depicted in Fig.2. Section No.8 is in the near upstream of the Sirajganj Hardpoint. Section No.7 is very close to the termination of the Sirajganj Hardpoint. Section No.6 is in the near downstream of the Jamuna Bridge and the Randhunibari Bandal sites and Section No.5 is very close to the Betil and Enayetpur spur dykes. The river is obviously composed of numerous channels and these channels frequently shift year to year. In the river, there are all kinds of sandbars and islands and some of which migrate frequently. With the background information on the sediment properties and flow discharges, the morphological changes shown in Fig.5 might not be so much surprising. Nevertheless, the difficulties lying in seeking suitable solutions to manage the morphological processes really come to researchers and engineers as a surprise. Without a detailed understanding on the mechanisms involved and more quantitative field data, decisions cannot be made confidentially and measures cannot be taken appropriately.

3. Revetments

3.1 Description of the Sirajganj Hardpoint

The old established town: Sirajganj is located in central Bangladesh, about 8km upstream of the Jamuna Bridge and about 110km northwest of the capital city: Dhaka. According to analyses results of satellite images, Sirajganj is observed to have the highest erosion rate in the catchment area (CEGIS, 2007). The erosion of the bankline since the 1950s has resulted in parts of the historic town fronting directly onto the river bank (Halcrow et al., 1994). In order to protect the town, revetment works were launched by the Bangladesh Government in 1998, known as Sirajganj Hardpoint. The hardpoint intends to control the shape of the BRE with the lowest level of intervention to the river flow. The hardpoint was constructed with cement concrete cubic blocks and consisted of a straight portion along the BRE together with a round upstream termination. The basics of the Sirajganj Hardpoint are listed in Table1 and a photo is shown in Photo2.

Table 1 Basics of the Sirajganj Hardpoint

Length of revetment reach	2.55km
Crest level over PWD	16.75m
High flood level over PWD	15.75m
Low water level over PWD	6.80m
Apron setting level over PWD	-4.20m
Design scour level over PWD	-13.25m
Thickness of apron	1.93m
Side slope	1:3.5
Size of cement concrete block	55cm & 85cm
Completion of the hardpoint	1998

*PWD: Public Work Datum, 0.457m below the seal level

Photo 2 Sirajganji Harpoint

The Sirajganj Hardpoint is exposed to the main anabranch channel of the Jamuna River, receiving year-round hydraulic attacks. The hardpoint, especially the area near the upstream termination, has been almost damaged almost every year since 2007. Velocity measurements were conducted during March 22-23, 2008 and March 19, 2009. In addition, the bathymetry survey data around the upstream termination was collected from the branch office of BWDB.

3.2 Bed change around upstream termination

The monthly change of the bed elevation around the upstream termination of the Sirajganj Hardpoint from January 2008 to February 2009 was plotted in Fig.6. The plot series provided valuable information on the bed evolution characteristics in the proximity of the termination. Basically, the bed morphology around the termination was dominated by a scour hole and the hole changed its shape as well as its bottom elevations almost all the time even in the dry season. The similarities in the scour geometry and the fluctuations in the maximum scour depth from January to the beginning of July indicated that the transport of bed forms played an important role in the bed evolution during the low flow season.

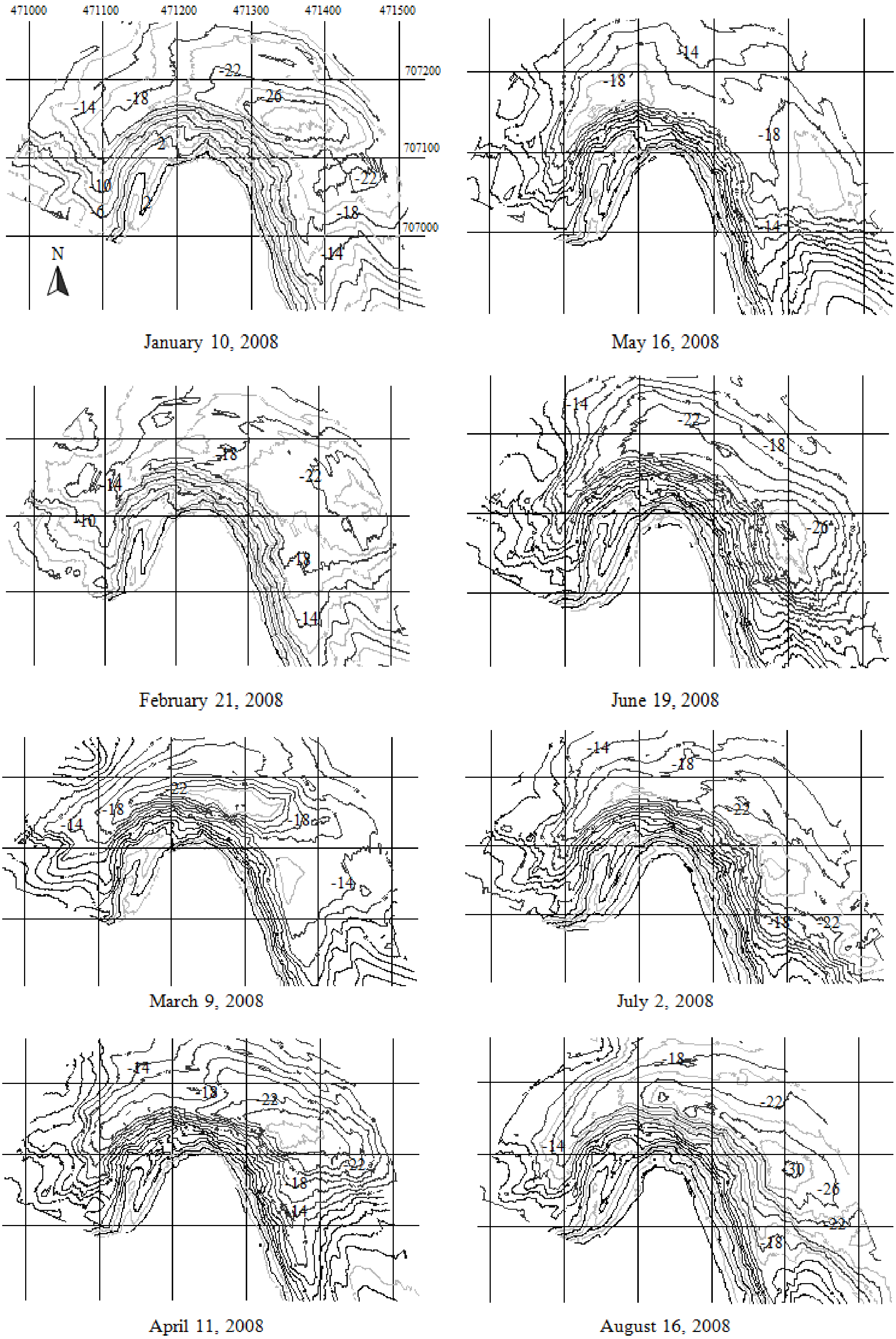
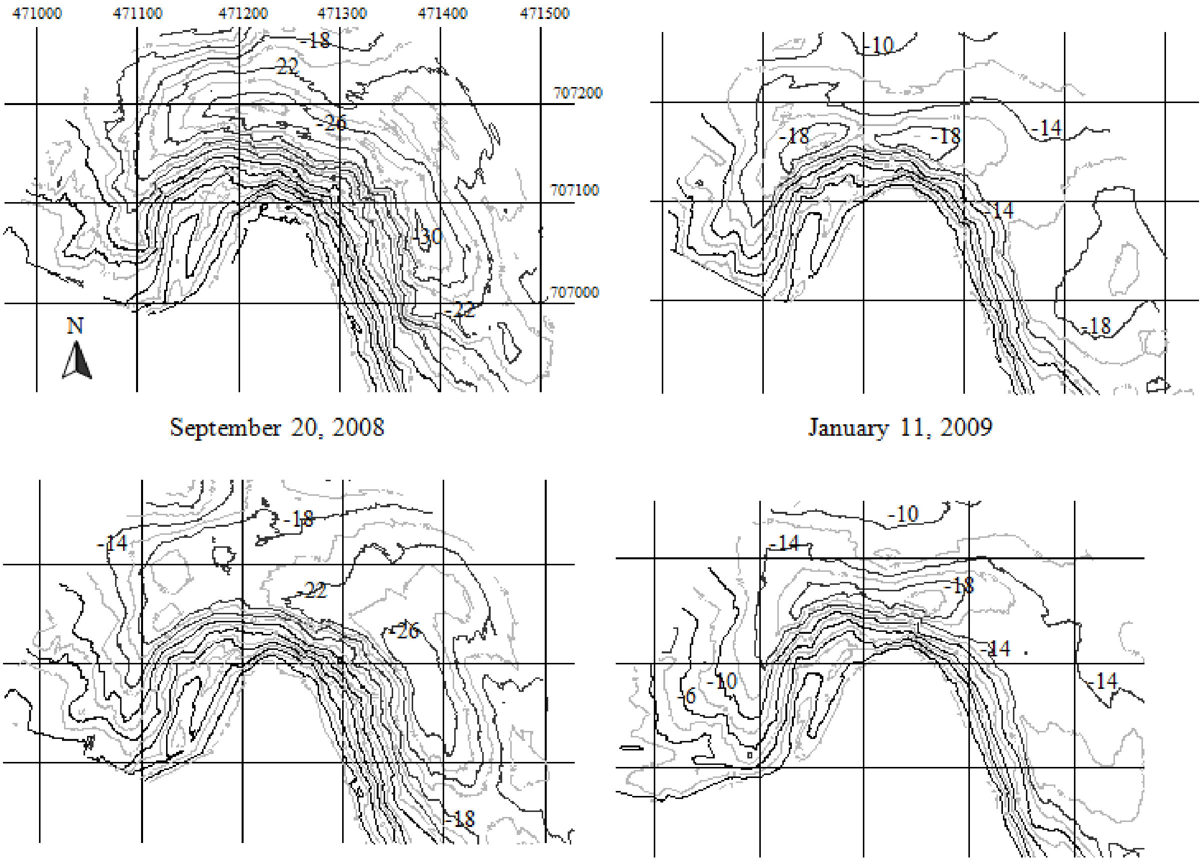


Fig.6 Bed level change at termination



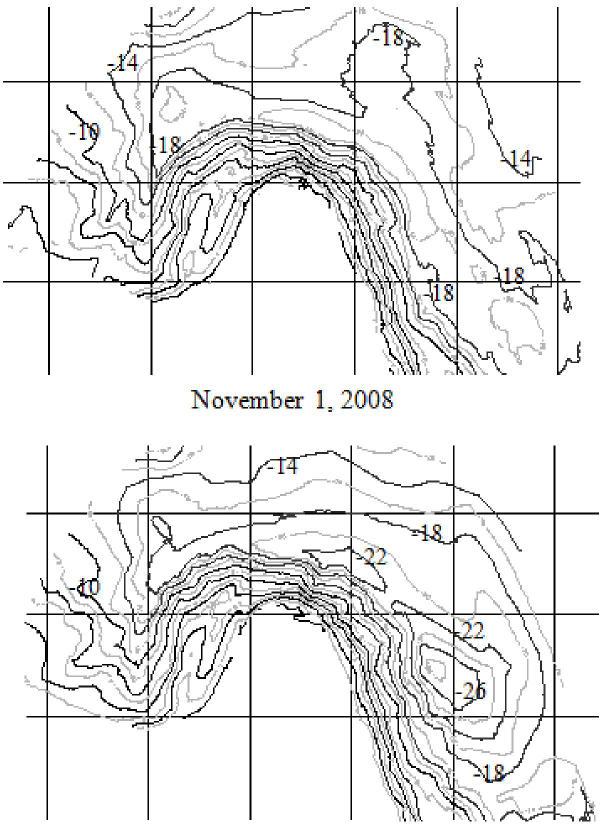
September 20, 2008

January 11, 2009

October 8, 2008

February 4, 2009

Fig.6 Bed level change at termination (Ctd.)



November 1, 2008

November 20, 2008

Fig.6 Bed level change at termination (Ctd.)

The scour hole exhibited significant changes during the flood as shown in the plots in August and in September. In particular, the maximum scour depth was dramatically increased and the location of the deepest point also shifted a bit to the downstream of the termination. After the flood, the scour hole area was refilled with sediment and the maximum scour hole depth returned to the pre-flood level as obviously shown from the plots after October. Although the 2008 flood enlarged the scour hole, the final scour hole in January of 2009 was even much smaller and shallower than that in January of 2008. It has to be mentioned that the termination partially failed in September of 2008 during the flood. The severe scour at the toe of the termination resulted in stability problems of the termination, i.e. the sliding of the apron and the sand materials beneath it took place. The observations suggested that the mitigation of the scour due to flood and the enhancement of the termination against scour were probably the keys to ensure the effectiveness of the Sirajganj Hardpoint.

3.3 Flow field at the Sirajganj Hardpoint

Although the hardpoint did not exert direct influence on the flow field, it altered the flow field through the morphological changes around it. The typical flow velocity patterns in year 2008 and year 2009 were plotted from Fig.7 to Fig.10 and compared with each other.

The horizontal velocity vectors near the water surface were shown in Fig.7 and Fig.8, together with the sketches of major sandbars based on field investigations and satellite images. In 2008, the approach flow channel was diverted into two parts by two sandbars. The flow attacked the termination of the hardpoint and resulted in two circulation flows in front of and behind the termination, respectively. In 2009, the west part of the big sandbar on the east was washed away and the width of the approach flow channel was significantly enlarged. On the other hand, a small sandbar appeared in the approach flow channel just in front of the termination. These changes affect a lot on the flow structure near the termination. The two circulations remained in 2009, but became much weaker than those in 2008. The flow in 2009 was further divided into two parts after passing the hardpoint due to the detachment of the downstream sandbar from the embankment. If one took a look at the velocity field in the vertical direction passing the termination in Section P as shown in both Fig.8 and Fig.9, the differences in the flow structure could be evidently distinguished. A vortex occupied the scour hole in front of the termination in both years, but the one in 2008 was much stronger than that in 2009. As this vortex was the major engine for the local scour around the termination, it was then easily understandable that the scour depth in 2009 was smaller than that in 2008 as have been confirmed by the bathymetry data in Fig.6.

The observations indicated that the movement of sandbars significantly influenced the flow structure and the bed morphology around the hardpoint. Although the problem related to the hardpoint was a very local scale one, understanding the migration characteristics of sandbars in a broader scale was of crucial importance. Moreover, the horizontal and vertical velocity vectors indicated that the local flow structure around the termination was of three-dimensional nature.

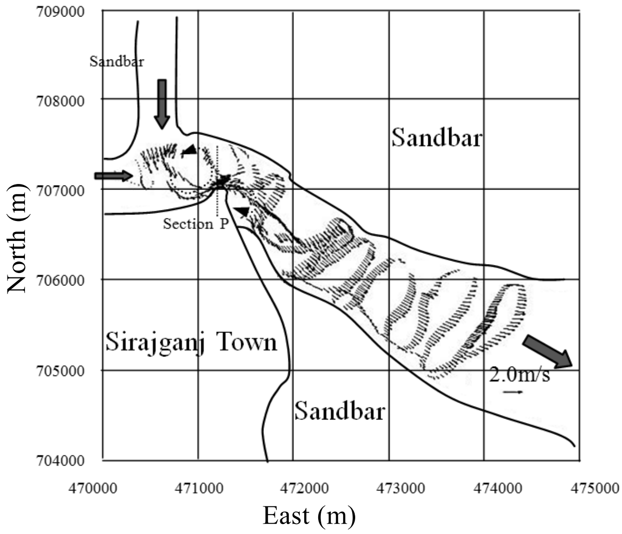


Fig.7 Horizontal velocity 0.86m beneath the water surface in 2008

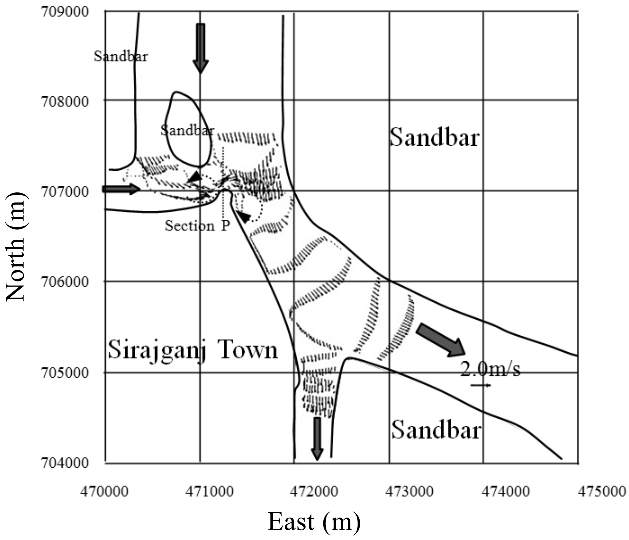


Fig.8 Horizontal velocity 0.86m beneath the water surface in 2009

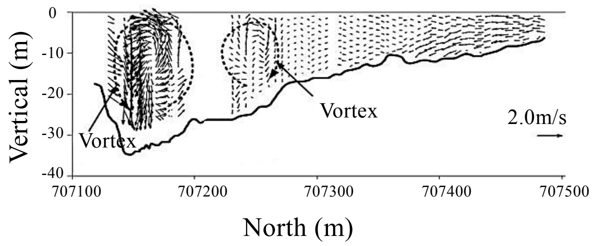


Fig.9 Vertical velocity vectors at section P in 2008

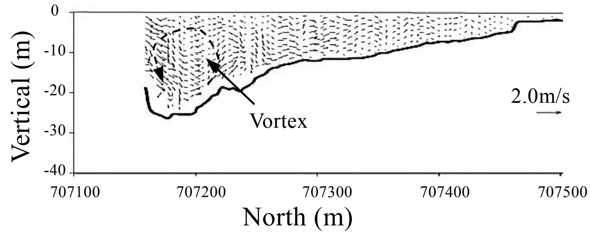


Fig.10 Vertical velocity vectors at section P in 2009

4 Spur dykes

4.1 Description of Betil/Enayetpur spur dykes

The Betil and Enayetpur spur dykes are located in the eastern part of Belkuchi and Chowhali Upazilla, about 25km south of Sirajganj town. The Betil and Enayetpur Bazar areas are historically well known for their handloom textile production. There are lots of important public and private establishments such as schools, madrasahs, colleges, mosques, hospitals and industries. This area is one of the high priority areas to be protected designated by the government.

Since 1914, the bankline of this area has shifted towards west by around 5km (Halcrow, 1994). In order to protect the bank, two spur dykes were constructed in 2002. The distance between the two spur dykes is around 2.5km. The Betil and Enayetpur spur dykes basically follow the same design methods. Either of them consists of an earthen shank and a RCC (Reinforced cement concrete) head. The RCC head is not deep penetrated into the riverbed but is supported by in-situ casted concrete piles with a diameter of 0.5m. Therefore, the lower part will be permeable if the bed level is degraded enough. The connection between the RCC head and the earthen shrank is in the form of a bell-mouth and has been found to be one of the weakest points according to past failure experiences. Although RCC blocks and geo-bags are dumped into the water to provide additional protection to the spur dykes, the earthen parts have suffered from damages frequently in monsoon seasons since their completion. The main parameters related to the Betil/Enayetpur spur dykes are listed in Tab.2.

Table 2 Basics of Betil/Enayetpur spur dykes

Parameters	Betil	Enayetpur
Length of earth shank	801m	1050m
Length of RCC part	150m	150m
Crest level over PWD	15.50m	15.30m
Width of crest	6m	6m
Side slopes	1:2 (up) 1:3 (down)	1:2 (up) 1:3 (down)
Design scour depth	18.5m	17.0m
Completion of spur	2002	2002

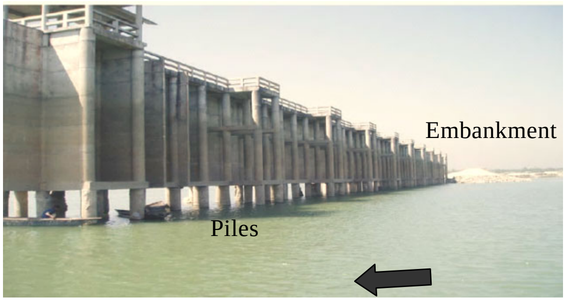


Photo3 The Betil spur dyke

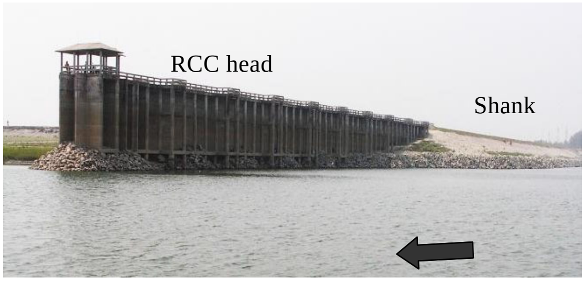


Photo4 The Enayetpur spur dyke

4.2 Bed deformation around Betil/Enayetpur spur dykes during flood

The Betil/Enayetpur spur dykes were constructed along the secondary channel of the river as depicted in Fig.2. In the dry season, almost no flow passed the channel. But during the flood period, the channel might become active and made threats to the embankment. The temporal variations of the bed bathymetries around the two spur dykes during the 2008 flood were plotted in Fig.11 and Fig.13. The information on the flow discharge of the river at the upstream Bahadurabad gauging station was plotted in Fig.12 for reference.

Due to severe local scour at the toe of the Betil spur dyke, the lower portion of the RCC part became permeable. Therefore, the hydraulic and morphological function of the RCC part of the Betil spur dyke would be similar to those of a Bandal. The downstream Enayetpur spur dyke, however, was still impermeable. It was evident from Fig.11 that the local scour area at the toe of the Betil spur dyke exhibited insignificant changes although there was slight increase of the maximum scour depth after the flood peak. Taking into account previous scour records (e.g. Zhang et al., 2008), it might be concluded that the flood discharge would not always enlarge the local scour. The continuous supply of sediment from the upstream channel might prevent the bed from continuous degradation.

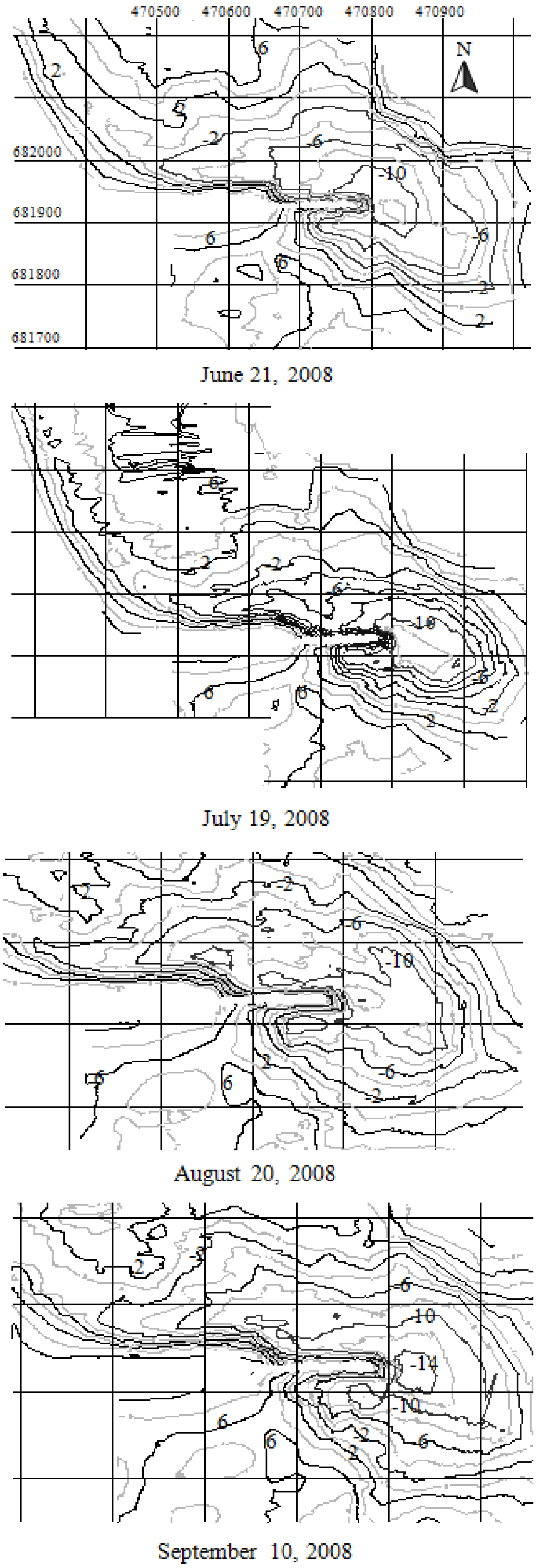


Fig.11 Bathymetry at the Betil spur

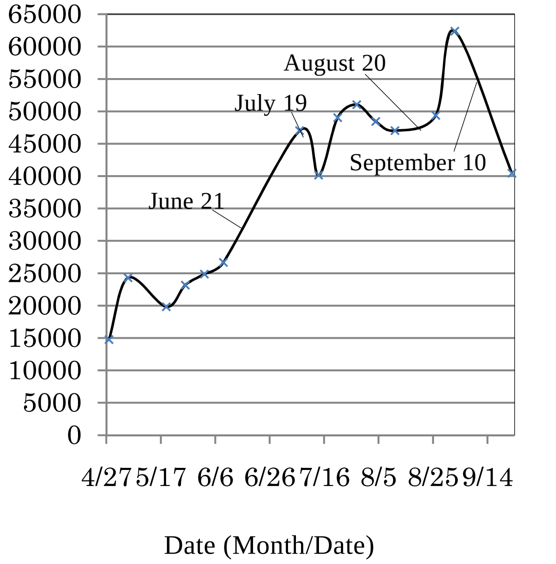


Fig.12 Discharge in 2008 monsoon at Bahadurabad

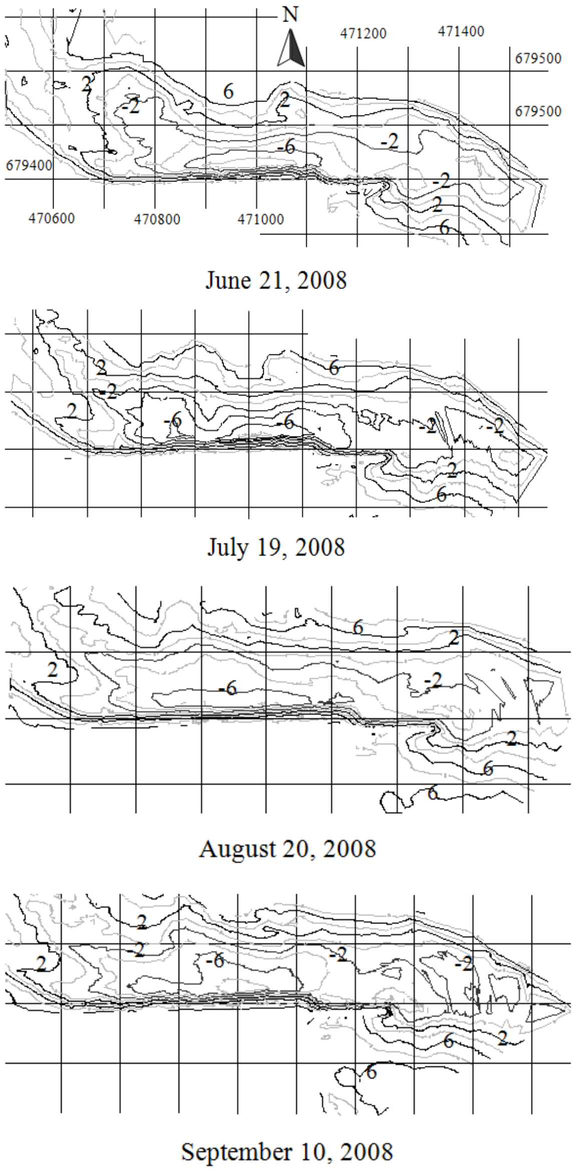


Fig.13 Bathymetry at the Enayetpuril spur

A large area of deposition was found behind the Betil spur dyke, and the Enayetpur spur dyke was situated immediately downstream of the area. The bed level around the Enayetpur spur dyke did not change so much in the flood season (Fig.13), indicating the flow and the bed morphology were well controlled by the upstream Betil spur dyke. Moreover, the lowest bed located along the earthen shank of the Enayetpur spur dyke instead of the toe, which was completely different from that around a typical impermeable spur dyke. Similar to that of the Betil spur dyke, land was created behind the Enayetpur spur dyke due to sediment deposition there.

4.3 Flow structure around Betil/Enayetpur spur dykes during flood

The velocity field was measured on July15, 2008 and the resulted velocity vectors in a horizontal plane near the water surface around the two spur dykes were plotted in Fig.14. Major sandbars were also sketched in the figure according to field investigations and satellite images. Due to the existence of various sandbars, the approach flow did not attack the head of either spur dyke, which made the scour phenomena around the two spur dykes somewhat unique.

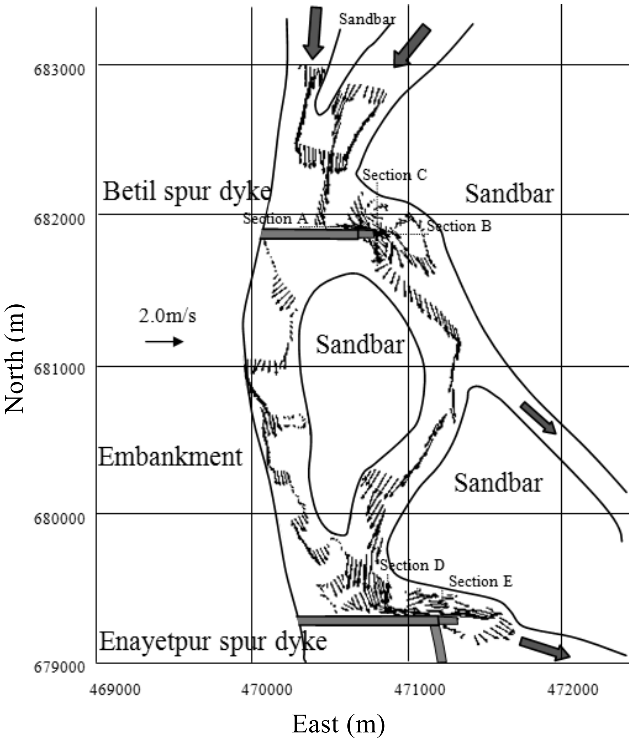


Fig.14 Velocity vectors around the Betil/Enayetpur spur dykes 0.86m beneath the water surface

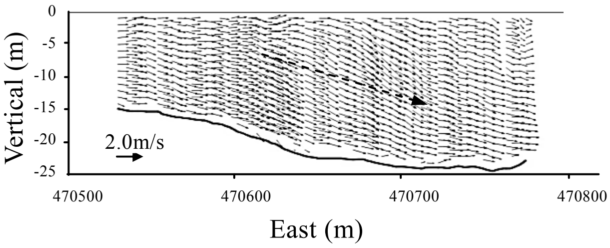


Fig.15 Velocity vectors at Section A

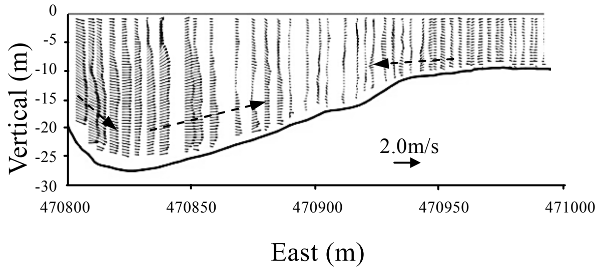


Fig.16 Velocity vectors at Section B

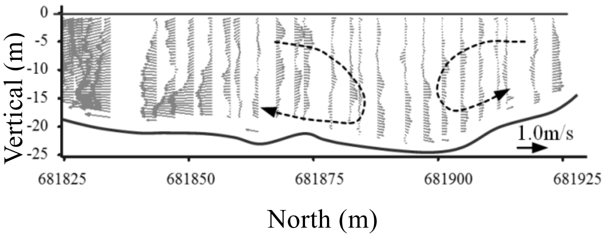


Fig.17 Velocity vectors at Section C

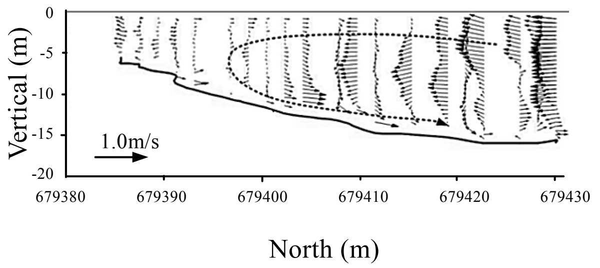


Fig.18 Velocity vectors at Section D

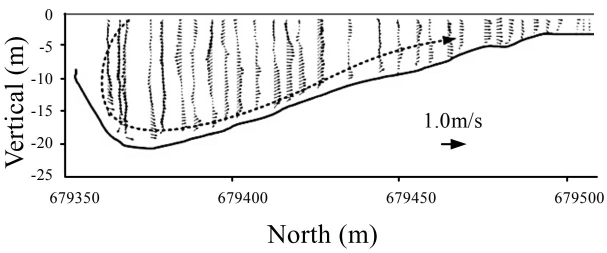


Fig.19 Velocity vectors at Section E

When the flow approached the spur dykes, it was blocked, changed its direction paralleling to the spur dyke and flowed towards the spur dyke heads. The parallel flow had a potential to remove sediment on its way to the head which gave the answer why severe scour took place along the earthen shank of the Enayetpur spur dyke. At the head of either spur dyke, flow circulation was recognizable although the data was not fine enough to resolve the details.

The velocity vectors in several vertical planes were also presented from Fig.15 to Fig.19. The locations of the vertical planes were depicted in Fig.14. The velocity vectors in Section A described the typical parallel flow along the earthen shank of the Betil spur dyke. And similar flow structure was expected around the Enayetpur spur dyke. In Section B, strong downward flow detached from the Betil spur dyke was observed. This downward flow was the main cause for the lateral enlargement of the local scour hole. The downward flow attacked the bed, turned upward and mixed with the downward flow from the sandbar in front of the spur dyke. Section C showed the longitudinal variation of the flow velocity at the head of the Betil spur dyke. Two circulating cells were recognized: one was situated in the upstream and the other one was in the downstream of the spur dyke. They were the major engines for the development of the scour hole in the longitudinal direction. The circulating cells resulted from the blockage of the approach flow at the earthen shank and the RCC head of the Enayetpur spur dyke were shown in Section D and Section E, respectively. Although the bed profiles were quite different, the circulating flows followed the same direction. Both of them are capable of removing sediment from the bed and result in scour at the foot of the spur dykes.

5 Bandal and Bandal-like structures

5.1 Introduction

The handloom enriched Randhunibari locates along the west bank and immediately downstream of the Jamuna Bridge as shown in Fig.2. Oblique flow towards the bankline during the monsoon season put the Randhunibari market nearby in a very dangerous situation. In order to protect the bank from erosion and to test the performance of traditional river training structures, a group of Bandals was constructed by RRI (the River Research Institute) during the period of year 2007-2008. Each Bandal structure protruded into the water course with a length of about 10m and made an angle of 50^{o}-60^{o} to the bankline. The Bandal was made of groups of vertical bamboo piles with a spacing of 46cm. The diameters of the bamboo piles ranged from 6cm to 9cm. The piles were connected with each other by cross bamboos with a vertical spacing of around 75cm. Moreover, inclined bamboos were set at an angle of 45^{o} to the bamboo piles to enhance the stability of the Bandal structure. The upper part of the Bandal was closed with bamboo thatch while the lower part is open. The Bandals were arranged in a group along the secondary channel of the river as show in Fig.2. The distance between two consecutive Bandals is around 32m. The details of one of the Bandals are shown in Photo1 which was taken during the field investigation in July, 2008. On the other hand, Photo2 demonstrates the sediment deposition behind the Bandal structure along the bank and the photo was taken in July 2009, one year after the first field trip. It is found that a large area of land is created behind the Bandal within only one year. The two photos give visible evidence on the deposition-promoting performance of the Bandals.

Photo 5 Randhunibari Bandal (July, 2008)

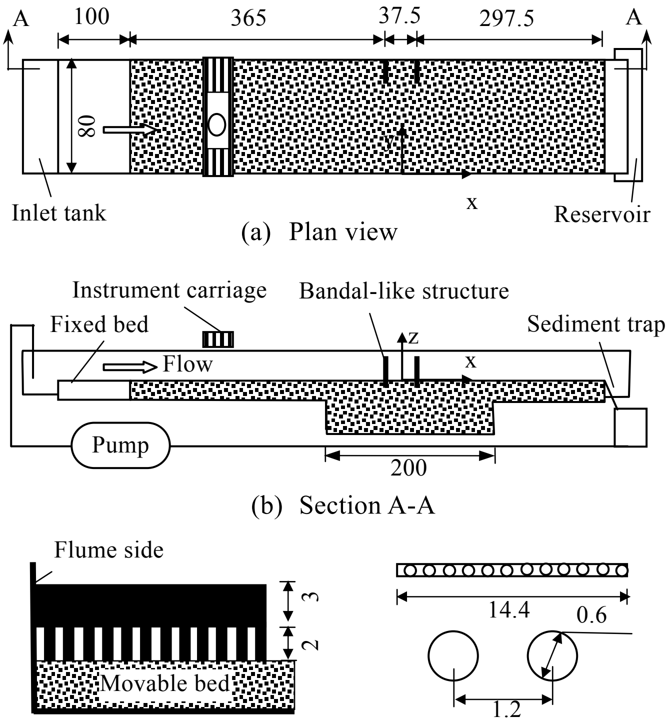
Photo 6 Randhunibari Bandal (July, 2009)

5.2 Experiments

A structure, having the similar functions as a Bandal, is named a Bandal-like structure herein despite its construction materials, shape and layout. Hence, the Betil spur dyke may be considered as a Bandal-like structure and the flow velocity information of which may be of reference for the Randhunibari Bandal site. In order to understand the flow structure more precisely, laboratory experiments are conducted in the Ujigawa Open Laboratory, Kyoto University. In the experiment, powdered anthracite is used as model sediment, which has a mean size of 0.835mm and a specific gravity of 1.41. A pair of Bandal-like structures is set perpendicular to the left side of a flume. The flume is 10m-long and 80cm-wide and has a slope of 1/800. Each Bandal-like structure is made of 12 brass cylindrical piles, having a vertical steel plate mounted at the upper part. The details of the Bandal-like structure and the experiment setup are shown in Fig.20.

The experiment is carried out under live-bed scour condition, i.e. the approach flow velocity is larger than the critical flow velocity for the sediment entrainment. As a result, bed forms develop in the whole movable bed area. It is the case in the Jamuna River. The hydraulic parameters in the experiment are shown in Tab.3.

The experiment starts from a flat bed and continuous sediment supply is ensured from the upstream of the flume. The total amount of sediment supplied is the same as that collected from the downstream, which is determined by some trial experiments. After 6 hours, a dynamic equilibrium condition is reached. The pump is then stopped. When the bed is drained out, a laser displacement meter is then used to measure the bed deformation. The measured bed configuration is shown in Fig.21. In the deformed bed, bed forms and large areas of sandbars occur due to sediment movement in the whole movable bed domain. Local scour takes place at the toes and along the bodies of the Bandal-like structures, particularly the upstream one. Moreover, sediment deposition is observed in the wake zones behind both structures. The local bed morphology around the Bandal-like structure exhibits typical features of both an impermeable spur dyke and a permeable spur dyke (Zhang and Nakagawa, 2009).



(c) Structure details: side view, top view & piles details

Fig.20 Experiment setup (Unit: cm)

Table 3 Hydraulic conditions of the experiment

u_* : friction velocity, u_{*c} : critical friction velocity

Flow discharge	7.76 l/s
Mean velocity	24.25 cm/s
Approach flow depth	4.0 cm
u_*/u_{*c}	1.91 (live-bed scour)
Reynolds number	7,460
Froude number	0.387

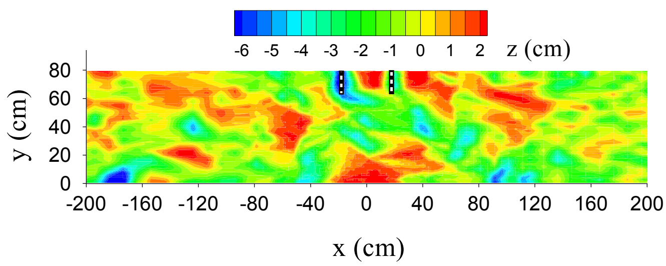


Fig.21 Final bed configuration in the experiment

Instant cement is sprayed to the bed surface and the deformed bed becomes fixed. Water is then pumped to the flume again. The velocity on the water surface is obtained with PIV (Particle Image Velocimetry) techniques and two electromagnetic velocimetries are used to measure the 3D velocity in the water column. Water level is recorded with a point gauge.

5.3 Numerical model

Since the flow around a Bandal-like structure is highly 3D, the details of the flow cannot be resolved without a 3D model. Moreover, a Bandal-like structure is generally sophisticated in shape and the boundary of an actual river is commonly irregular. Hence, the numerical model should be capable of resolving complex geometries as well. The authors have developed a numerical model satisfying the above requirements (Zhang et al., 2006). In the numerical model, the complex flow field is obtained based on the RANS (Reynolds-averaged Navier-Stokes) equations with the k-ε model for the turbulence closure. In the near-wall domain, the wall-function approach is applied and the resistance of the wall can be easily accounted for. The widely used FVM (Finite Volume Method) is adopted in the formulation of the numerical model and the governing equations are discretized based on an unstructured mesh.

The flow field on the deformed bed in the laboratory experiment is investigated with the proposed numerical model. The measured water stage and bed level are used in the mesh generation. In order to reproduce the details of the Bandal-like structures, a hybrid mesh consisting of different types of polyhedra is employed. The mesh system includes 58842 cells and 57870 nodes. The computational mesh in the proximity of the Bandal-like structures is depicted in Fig.22. At the inlet boundary, all flow variables are known and are prescribed according to the mean velocity. At the outlet boundary, zero diffusion flux is assumed for all flow variables. The free surface is considered as a rigid lid and is unchangeable during the computation. Near the wall boundaries such as the channel bed, the Bandal-like structure and the side of the flume, the flow velocity is assumed to be parallel to the walls.

5.4 Results

Flow velocities resulted from both experiments and simulations are plotted in Fig.23-27. The flow velocity on the water surface, near the bed and typical lateral and longitudinal sections is shown.

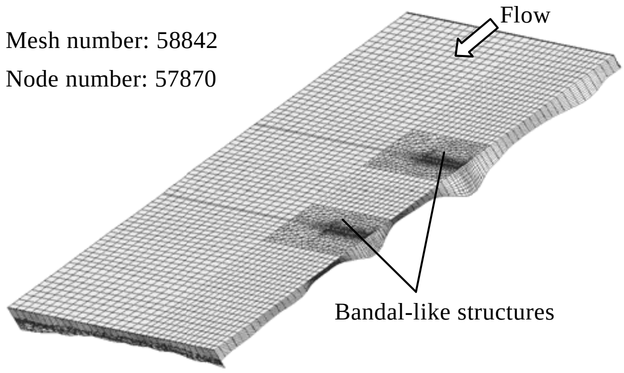


Fig.22 Computational mesh around Bandal-like structures.

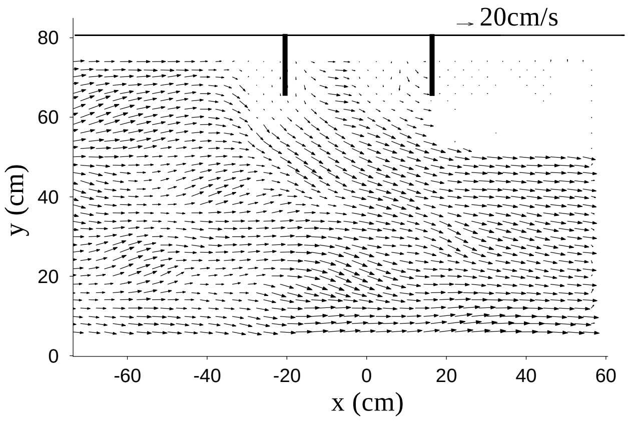


Fig.23a Flow velocity (u, v) on water surface (PIV)

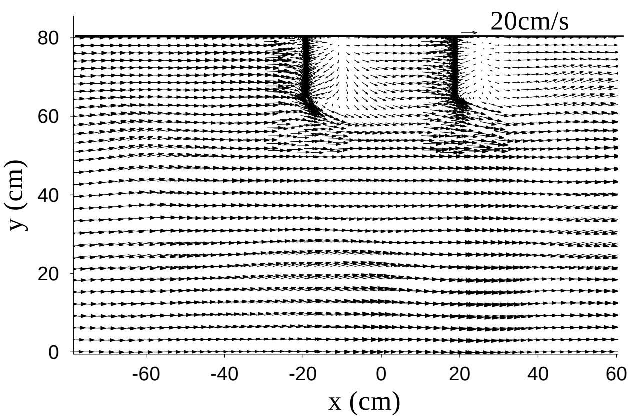


Fig.23b Flow velocity (u, v) on water surface (Sim.)

According to Fig.23 and Fig.24, it is found that the flow velocity on the water surface is affected significantly by the blockage of the upper part of the Bandal-like structures and 3D vortices in the scour. On the other hand, the flow velocity at the lower layer is closely related to the bed geometries and the existing of the piles of the Bandal-like structures. In general, the numerical model reasonably reproduces the experimental results.

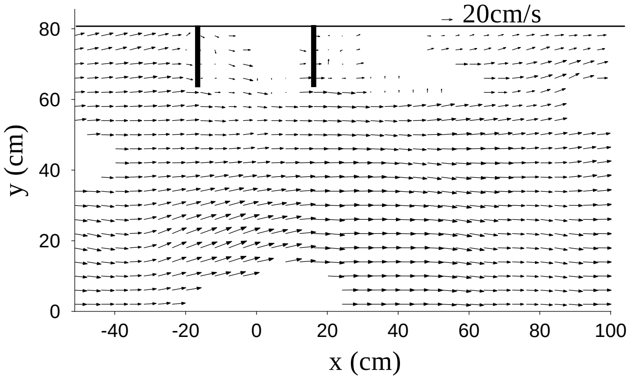


Fig.24a Flow velocity (u, v) at 2cm from the initial bed (Exp.)

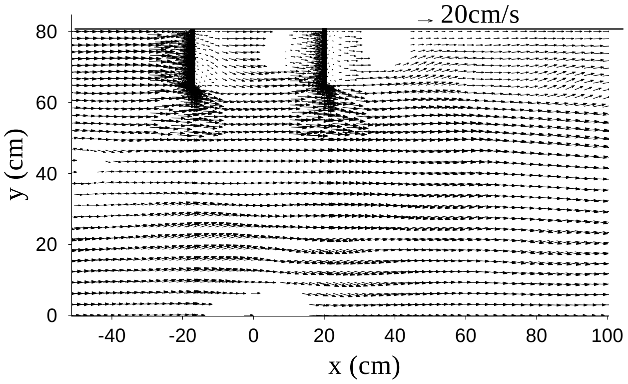


Fig.24b Flow velocity (u, v) at 2cm from the initial bed (Sim.)

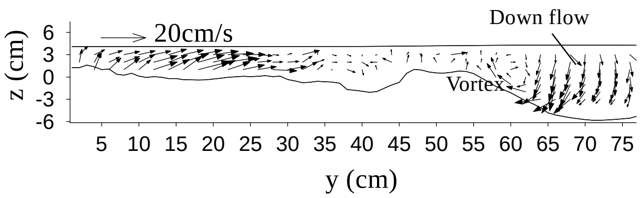


Fig.25a Flow velocity (v, w) at x=-22cm (Exp.)

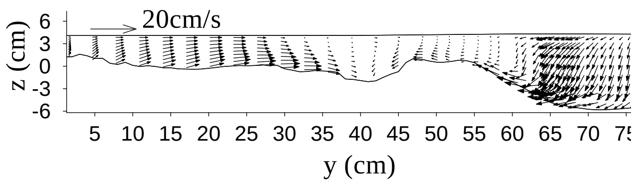


Fig.25b Flow velocity (v, w) at x=-22cm (Sim.)

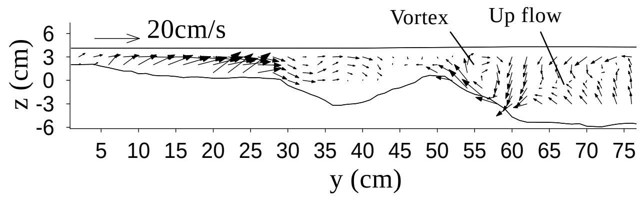


Fig.26a Flow velocity (v, w) at x=-16cm (Exp.)

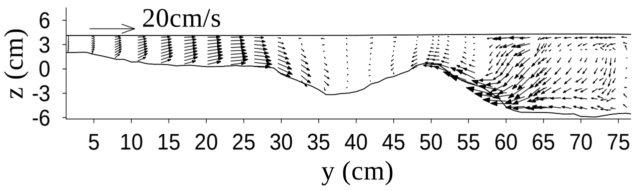


Fig.26b Flow velocity (v, w) at x=-16cm (Sim.)

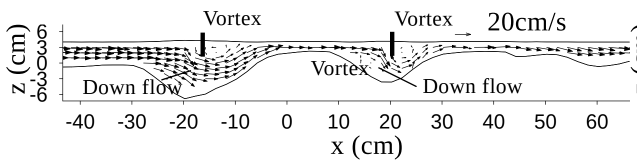


Fig.27a Flow velocity (u, w) at y=72cm (Exp.)

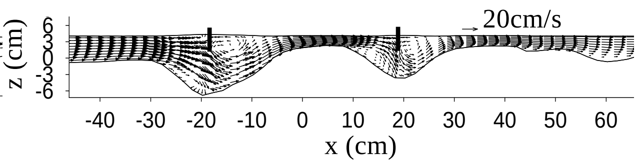


Fig.27b Flow velocity (u, w) at y=72cm (Sim.)

If one takes a closer look at the free surface velocity field, one may note that bed morphology influences a lot on the flow structure. The flow separation angle at the head of the structure is much smaller compared with that of the PIV measurement. As has been argued in previous research (Zhang et al., 2009), the over-estimation of the current PIV method due to an over-accumulation of tracers is considered to be a probable reason. The inherent deficiency of the eddy viscosity based turbulence model is also another probable cause, but further evidences are needed.

3D vortices are obviously confirmed in Fig.25-27, concentrated in the extent of local scours and being similar to those observed around spur dykes (Zhang et al., 2009). These vortices are engines for the scour development. However, there are many properties unique to the Bandal-like structures. Fig.26 and Fig.27 indicate that the wake vortex behind the upstream structure is not well developed. The vortex is very weak and is confined in the shade of the impermeable part of the structure other than inside the scour hole. It is attributed to strong flows which pass the piles of the structure and make great disturbances to the wake zone. It is also found in Fig.27 that there are vortices located in front of and behind the downstream structure. Due to the vortex in front of the structure, flows passing the piles lose their energy and the vortex behind the structure develops more freely and even extends to the inside of the scour hole. The vortex in front of the downstream structure is resulted from the down flow and the relatively small scour depth (hence, a small opening ratio). Similar vortex pair appeared in the field measurements of the Betil spur dyke as shown in Fig.17.

6 Discussions

The information on the flow field and bed deformation of the study sites provides a key to understand the fundamental working principles and performances of typical structural measures against bank erosion along the Jamuna River. Compared with conventional revetments and spur dykes, the flow structure and the bed morphology around the Sirajganj Hardpoint (revetment type) and the Betil/Enayetpur spur dykes (spur dyke type) are much more complex due to the complex flow and bed conditions.

Owing to its unique location, the upstream termination of the Sirajganj Hardpoint works like an impermeable spur dyke to some extent. Several vortex systems of obviously 3D nature form in the proximity of the termination and they are strongly dependent on the local bed morphology as well as the migration of the sandbars nearby. The termination is a weak point of the structure due to local scour at the toe and possible sliding down of the sand materials on which the apron is set. The area a little downstream of the termination is also very weak due to the direct attack of the return currents. Both parts experienced failures in the past several years. The comparison of the flow structures in 2008 and 2009 suggests that the performance of the Sirajganj Hardpoint strongly depends on the sandbars in its neighborhood and that the evolution of the sandbars necessitates special attention.

By introducing long earthen shanks, the area protected by the Betil/Enayetpur spur dykes is enlarged and the construction cost is reduced. On the other hand, the earthen shanks become the most frequently failed parts of the two spur dykes due to the direct hit by the approach flow and the parallel flow along the shanks. Countermeasures against the parallel flow are hence important for the stability of the two spur dykes. The RCC part of the Betil spur dyke works like a Bandal structure which blocks the flow in the upper layer and allows the water to flow at the lower elevation. This kind of structure takes the advantages of both the impermeable spur dyke and the pile dyke. As a result, excessive local scour is avoided but either the mainstream degradation or the wake deposition is promoted. Moreover, the return currents behind the spur dyke are also weakened due to the joining of the flow passing through the piles of the RCC part. The downstream Enayetpur spur dyke furthermore prevents the possible return currents caused by the upstream Betil spur dyke from direct attacking the embankment. Due to the influence of the Betil spur dyke, the impermeable Enayetpur spur dyke does not suffer too much from local scour at the RCC toe. The maximum scour depth around the Enayetpur spur dyke is about 9.5m smaller than that of the Betil spur dyke during the field measurement. However, the parallel flow is more dangerous along the Enayetpur spur dyke compared with that along the Betil spur dyke since the former owns a longer earthen shank and an almost impermeable RCC part. Making the lower part of the RCC part permeable to reduce the effective length of the spur dyke might be a solution to reduce the erosion along the foot of the shank.

Although detailed measurements are not conducted for the Bandal structures in site, the effectiveness of the structures are confirmed from both the Randhunibari test Bandal site and the Bandal-like part of the Betil spur dyke. In addition, the laboratory experiment and numerical simulation preliminarily provides the working mechanisms for this kind of structure. Recently, Teraguchi et al. (2011) have made more systematic comparisons on the hydraulic and morphological characteristics among the conventional impermeable spur dykes, pile dykes and the newly highlighted Bandals. It has to be mentioned that the original Bandals are generally made from locally available bamboos and are constructed without reliable scientific design or effective quality management. Therefore they are quite cheap (Table4) and easily implemented but generally suffer from stability problems especially during the flood.

Table 4 Cost of bank protection measures

Measures	Site	Agency	Cost (US$/m)
Guide Bank	Jamuna Bridge	Foreign	33,000
Hardpoint	Sirajganj	Foreign	21,000
Solid spur	Kalitola	Foreign	12,500
Revetment (Geobags)	Jamuna River	Foreign	2000-3000
Revetment	Jamuna River	BWDB	3800-4000
RCC spur	Jamuna River	BWDB	950
Bandal structures	Sirajganj	RRI	9

*compiled based on Rahman et al., 2007

Comparing the Bandals with the conventional impermeable spur dykes, it is noted that the Bandals will generally exert less impact on the flow and channel dynamism. Hence, it has a potential to provide a more nature friendly alternative for the management of large alluvial rivers like the Jamuna River. The Bandals are physically smaller and weaker than conventional impermeable spur dykes. Furthermore, the Bandals may be quickly buried due to huge deposition around it and their working life will be much shorter compared with the conventional impermeable spur dykes. Therefore, the Bandal structures should be better basically used as temporary structures in a recurrent way to cope with changing conditions adaptively. The total cost will include initial investments and timely maintenances.

7 Conclusions

This paper presented a study on hydraulic and morphological consequences of typical bank protection measures along the Jamuna River of Bangladesh. The results indicate that conventional bank protection measures such as revetments and spur dykes play important roles in protecting the BRE and that historied river training measures such as Bandals based on indigenous knowledge exhibit high potential for wider applications.

The flow field and bed morphology around the bank protection structures, either intrusive or nonintrusive, vary spatially and temporally but maintain certain common features depending on the type of the structures. The strong vortex system in front of and the return currents behind the upstream termination of the Sirajganj Hardpoint are the major engines for the morphological variations and are also the main causes of the structure failure. Moreover, the intensity of the flow around the termination is closely related to the evolution of the sandbars nearby. The vortex system and the parallel flow resulted from the flow blockage at the long shanks of the Betil/Enayetpur spur dykes are great threats to the stability of the two spur dykes. The RCC part of the Betil spur dyke works as a Bandal-like structure, providing a well control of the incoming flow and sediment transport for the downstream Enayetpur spur dyke. Compared with the local scour at the toe of the RCC part of the Enayetpur spur dyke, the erosion along the foot of the long earthen shank is a more serious concern. It might be a challenging problem unique to relatively huge structures constructed in large rivers.

Field investigation suggests that the Bandals developed from indigenous knowledge are capable of promoting sediment deposition efficiently. Considering the migration nature of the Jamuna River, the cost-effectiveness and the environmental harmony, the wider application of Bandals or Bandal-like structures is recommended. However, more research is suggested to clarify the associated mechanisms and to formulate guidelines on their designs, constructions and maintenances.

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バングラデシュ国ジャムナ川における河岸侵食防止対策が流れ及び地形に及ぼす影響

張浩・中川一・馬場康之・川池健司・ラマン　ムンスン*・ウヂン　ナジム**

*バングラデシュ工科大学水資源・洪水管理研究所
**ダッカ工科大学土木工学研究科

要　旨

バングラデシュ国の河川では，河岸侵食が大きな問題となっている。河岸侵食は科学と工学的な問題だけでなく，この南アジアの国にとっては，大きな社会や経済問題でもある。本稿は，ブラマプトラ川の下流（バングラデシュ国内ではジャムナ川と呼ばれる）における河岸侵食防止対策及びそれらが流れ及び地形に及ぼす影響について報告する。数回の現地調査及び計測により，ジャムナ川における河岸侵食のメカニズムの解明を図った。また，既存の河岸侵食防止対策の機能を評価し，可能な改善策を提案した。特に，現地の歴史的な方法で土着工法の代表であるバンダル型水制について着目し，ジャムナ川の河道安定及び河岸侵食防止方策としては，バンダル型水制の設置の繰り返しが現地に適応した工法となり得る可能性を示唆した。

キーワード：ブラマプトラ川/ジャムナ川，河岸侵食防止，河道安定化，現地計測，バンダル，水制