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Flow and Scouring Processes around the RCC Spurs

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Abstract. Different types bank protection works have been constructed along the both banks of the braided Jamuna River. Some of the structures are constructed in the main channel and some of them are in the secondary channel of the Jamuna River. The structures constructed either in the main channel or in the secondary channel are affected by failure problems. Among them two Reinforced Cement Concrete (RCC) spurs (Betil and Enayetpur) constructed in the secondary channel are selected for the present study. Acoustic Doppler Current Profiler (ADCP) is used to measure the hydraulic data around the Betil and Enayetpur spurs. It is found from the hydraulic data analysis that the oblique flow, strong parallel flow and flow circulation normal to the earthen shank and the belmouth are generated around the spurs. The generated shear velocity near the earthen shank is five times higher than the critical shear velocity. Due to above types of flow and higher shear velocity near the earthen shank and belmouth deep channel is developed adjacent to the earthen shank. As a result the Betil and Enayetpur spurs frequently damaged when the flood flow comes.

Keywords: Flow, RCC spur, Jamuna River, ADCP

1 Introduction

River bank erosion is a big problem in Bangladesh, especially along the braided Jamuna River. Thousands of hectares of land are eroded each year by the mighty Jamuna River. Social and economical problems are created in consequence of erosion. To protect banks from erosion different types of protection measures have been implemented along the both banks of the braided Jamuna River. These are revetment-like structures, groin-like structures and bandal-like structures. The physical configuration and alignment of these structures are completely different. A revetment-like structure is constructed along the bankline without imposing significant disturbance on the flow. The groin-like structure (permeable and impermeable) is constructed normal to the bankline towards the main channel to divert the flow away from the bank. The bandal structures are aligned at an angle with a bankline in the downstream direction. The bandal-like structures have been recently being used as bank protection along the secondary channel of the Jamuna River on a pilot basis. The bandal-like structures, which are made of bamboo, are a very weak structure. It was usually used to increase the flow depth in the navigational channel along different rivers in Bangladesh for a long time.

The construction costs of a hardpoint, the RCC spur and bandal structures along the Jamuna River are 21,000 US$, 950 US$ and 9 US$ respectively to protect one linear meter of the bank. The construction year of the Betil and Enayetpur RCC spurs is 2001. The RCC spur has two parts: the first part is an earthen shank starting from the bank line or flood embankment and the last part is made of RCC (150m). The Betil and Enayetpur spurs are facing the problem of failure during the flood period since their construction due to an unusual flow pattern and development of the local scour hole around the structures. So it is essential to identify the causes of such problems. The complex flow around the structure is one of the important factors for such failure. The extensive studies on a flow field around groin-like structures and abutments have been investigated by Rajaratnam and Nwachukwu [16], Kandasamy [10], Ahmed and Rajaratnam [1], Barbhuiya and Dey [3], Dey and Raikar [7], Dey and Barbhuiya [6], Kwan and Melville [11], Kuhnle et al. [12], Zhang et al. [19] and many others at a laboratory level.

Rajaratnam and Nwachukwu [16], and Ahmed and Rajaratnam [1], [2] investigated the flow fields at piers and abutment, respectively. They found that the shear stresses at the abutment corner were amplified up to five times as compared to the approach shear stress. The increase in the shear stress above the critical value that is required for sediment entrainment is commonly accepted as the cause of the local scour. Dey and Raikar [7] investigated how the flow and turbulent characteristics of the horseshoe vortex change with the development of the scour hole at a circular pier.

A number of researchers developed numerical models to simulate flow and erosion processes around different types of hydraulic structures. Zhnag et al. [20], classify these numerical models into three groups: (1) the numerical modeling of flow field with planar or unscoured bed [14]); (2) numerical modeling of flow field with scoured beds [17], [20] and (3) the numerical modeling of flow fields and bed deformation with movable beds [13]. Some of these models are reported to well resolve the typical horseshoe vortex in the scour hole area [13], and some are concentrated on the reasonable reproduction of the reattachment length behind the spur dyke [14]).

A study was jointly conducted by IFCDR and JICA on flow and morphological processes about 11 km of the Meghna River reach including Meghna bridge site. The numerical model was applied to simulate the flow field and local scouring near the abutment of the Meghna Bridge. The calculated results were compared with the observed ones. It was verified that the numerical model is a useful tool for simulating flow and scouring processes near the Meghna bridge site.

The results of these studies are usually extrapolated in the field. There are a very few field-based investigations on flow processes, especially in a large scale sand bed braided river like the Jamuna. The 3-D flow and erosion processes have been investigated through the present study around the Betil and Enayetpur spurs so that the failure-related events could be handled effectively.

2 Characteristics of the Jamuna River

The Jamuna River originating from the Himalayas is 2900 km long and has a drainage area of 573,500 km^2. The length the river inside Bangladesh is 240 km. It is a wandering braided river with an average bankfull width of about 11 km. Discharge varies from a minimum of 3,000m^3/sec to a maximum of 100,000 m^3/sec, with a bankfull discharge of approximately 48,000 m^3/sec. The minimum flow is about 3% of the maximum discharge and about 6% of the bankfull discharge. The average water surface slope is 7 cm/km. The range of variation of Brice braiding index of the Jamuna River is 4 to 6 [8]. Due to dynamic nature it always changes its planform within braid belt. Erosion is a major problem along both bank of the river.

From 1973 to 2009, erosion and accretion along the Jamuna river was 90,830 ha and 10,140 ha respectively [4]. The variation of the rate of erosion depends on the hydrological parameters and time. From 1970 to1990 the Jamuna River widened at a very high rate; both the banks migrated outward at an average rate of about 70 m/year. Since the early 1990s, the rate of outward migration of both banks has reduced to 30-50 m/year [5]. To protect bank erosion, more than thirty numbers of bank protection structures (hardpoint, groin and RCC spur) have been constructed along both banks of the Jamuna River. Almost every year a number of structures face different types of failure problems. Out of fifteen number of RCC spurs about seven number of the RCC spurs have been totally damaged. The Sirajgang hardpoint was damaged in 1998 (which was just after construction), 2008, 2009 and 2010.

3 Betil and Enayetpur Spurs

Betil located at about 25 km downstream of the Sirajgang town. Enayetpur is situated at 2.5 km downstream from Betil. The study site is shown in Fig. 1. Betil and Enayetpur are handloom enriched area. The bankline has shifted towards west by 5 km since 1914 [9]. In this reach the bank moves towards west at an average rate of 100 m/y. To protect government and private land and property, two spurs have been constructed at Betil and Enayetpur area. The total length of the Betil and Enayetpur spurs are 801m and 1050m, respectively. The design of both spurs is basically the same, and represents a typical low-cost spur design of Bangladesh Water Development Board (BWDB). The RCC-head replaces the normally used belmouth structure to save material. No model study was performed before construction of the Betil and Enayetpur spurs. Two physical model studies were performed for RCC spur at Simla and Meghai along right bank of the Jamuna River and the estimated net maximum scour depth were 18.5m and 17m, respectively. The head of the RCC is built of in-situ casted, 500 mm diameter concrete piles and a vertical RCC-wall, with a walking path on the top. The pile is driven up to a depth of 24m (i.e. -16.5 mPWD) below the river bed. Public Works Datum (PWD) is the reference level. The design parameters of the Betil and Enayetpur spurs are given in Table 1. The design Highest Flood Level (HFL) is considered (+) 14mPWD. The crest level of the earthen shank is (+) 15.5mPWD. The slope of the earthen shank 1V:2H at the upstream side and 1V:3H at the downstream side. The top width of the earthen shank is 6m. The top of the launching apron is (+) 9.5 mPWD with thickness ranges from 1 to 3 m depending on the position of dumping. At the river end of the RCC-wall, a perpendicular wall is present; it serves as a kind of energy diffuser to dissipate the strong turbulence at the end of the vertical wall. The RCC-part of the spur is protected from scour by dumping 90 m^3/m Cement Concrete (CC) blocks at the bell mouth and 3 m^3/m CC-blocks at both upstream and downstream side of the RCC. It was suggested in the design the earthen shank should be protected by 40cmx40cmx20cm CC-blocks and the toe should be protected by dumping 3 to 9 m^3/m CC-blocks. The RCC wall and the earthen shank are connected through overlapping by earthen shank in the form of a bell-mouth. The earthen shank and the RCC part of the spur are shown in Fig. 2. During construction of the spurs the RCC-wall was constructed on the sandbar (local name char). So the bottom level of the RCC wall was at the low water level.

During 2003 flood a slip circle failure occurred at the earthen shank over a length of 200 m of the Enayetpur. A slip circle failure also occurred of the earthen bell-mouth of the Betil spur during the same flood period. Subsequently the damage part of the spur was repaired. The earthen bellmouths and RCC-parts of both spurs were strengthened by dumping of CC-blocks and geo-bags. Failure of the earthen shank or belmouth (connection of earthen shank and RCC) occurred of the both spurs several times during the monsoon since their construction. The earthen shank of both spurs washed away during the flood of 2004. The disconnected RCC part of the Betil spur is shown in Fig. 3. The RCC part of the Betil spur opened and water started to flow beneath the RCC part. Since then it is working as a permeable spur or to some extent as bandal-like structure. Bandal is a low cost bank protection structures. The upper half of the portion is blocked by bamboo thatched and the half of the portion is opened. A major rehabilitation works performed in 2006. During rehabilitation works RCC blocks are dumped as launching apron at a rate $25m^3/m$ close to the RCC portion and 20 to $50m^3/m$ at the earthen shank and belmouth. Almost every year a portion of the earthen shank damages and a huge amount of maintenance budget is required to repair the failure part. The failure of the earthen shank of the Enayetpur spur in 2007 is shown in Fig. 4.

4 Data Collection Method

The 3D velocity data together with the bed level were measured using the Acoustic Doppler Current Profiler (ADCP: 1200 kHz: WH-ADCP Rio Grande by RD Instruments) to analyze the flow pattern. The ADCP uses the Doppler effect (the change in observed sound pitch that result from relative motion) to measure velocity by transmitting sound at fixed frequency and listening to echoes returning from sound scatters, such as suspended sediment in the water. Global Positioning System (GPS) was used to locate the measuring point. The ADCP was connected with a specially designed plastic boat mounting downward. The plastic boat with ADCP was fixed by a rope with the country boat as shown in Fig. 5. Finally, the entire system was connected with a laptop to collect the hydraulic data. The 3-D velocity component could be measured by this instrument at desired interval along the depth of flow. At a particular point the lower velocity data is recorded by ADCP at a distance about 0.08h above the channel bed. One set of the 3-D flow velocity data was collected during July 2008. The flow velocity and discharge usually vary with time.

Table 1. Design parameters of the Betil and Enayetpur spurs

Design Parameter	Betil and Enayetpur spurs
High Flood Level (HFL)	(+) 14mPWD
Crest level	(+) 15.5mPWD
Top width of the earthen shank	6m
Top of the lunching apron	(+) 9.5mPWD
Thickness of lunching apron	1m to 3m
The depth of pile	(-) 16.5mPWD
Diameter of pile	0.5m
Size of the CC block	40cmx40cmx20cm
Side slope at the upstream side	1V:2H
Side slope at the downstream side	1V:3H

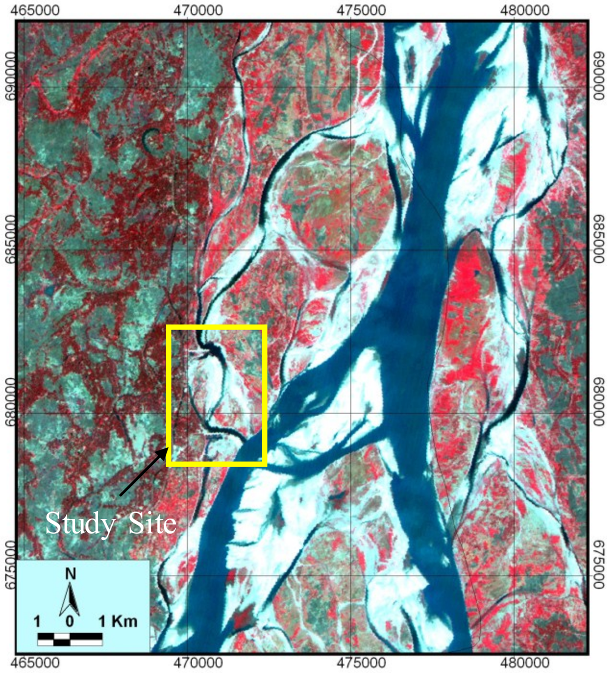


Fig. 1. Study site

Fig. 2. RCC part and earthen shank of the Betil spur

Fig. 3. Washed out of the earthen shank of the Betil spur (2004)

Fig. 4. Failure of the earthen shank of the Enayetpur spur

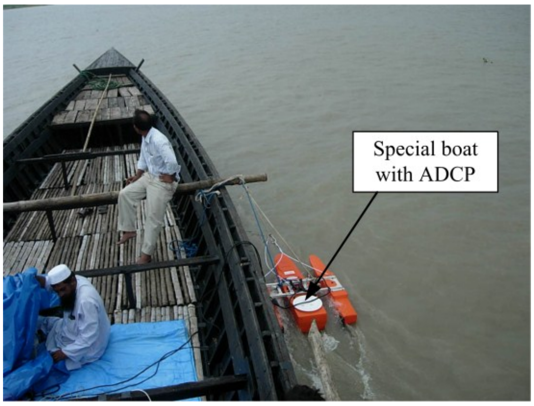


Fig. 5. Data collection using ADCP

5 Change of Morphology

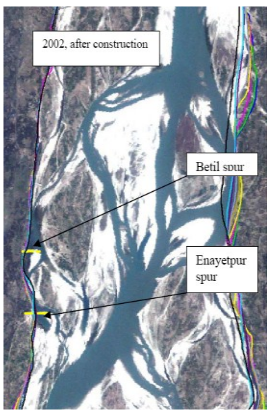
The morphological change around the Betil and the Enayetpur are shown through satellite images. A series of satellite images from 2000 to 2008 are shown in Fig. 6. A branch channel was passing near Betil and Enayetpur area in 2000 before construction of the spurs. The channel became relatively wider in 2001. The Betil and the Enayetpur spurs were constructed in fiscal year 2001-2002. A small sandbar is formed just downstream of the Betil spur after construction of it. The sandbar became larger in 2003. A channel is developed parallel to the Enayetpur spur. The earthen shanks of the both spurs were washed away during 2004 flood season. The channel in between the Betil and the Enayetpur spurs is turned into wider. After a major rehabilitation works in 2006 the morphology around both spur is stable. Though, almost every year the earthen shank of the both spurs are damaged during high flood.

6 Flow Processes

The discharge of the different channels around the Betil and Enayetpur spur are shown in Fig. 7. The western approach channel travels downstream from Randhunibari market towards Betil. The discharge of the western approach channel is 775m^3/s. Another secondary channel originated from main channel travels towards Betil spur. The discharge of the eastern approach channel is 750m^3/s. Finally two secondary channels joined together just upstream of the Betil spur (Fig. 7). The total flow downstream of the confluence was 1525m^3/s. As the Jamuna is a braided river so within its braid belt one or two main channel and more than one secondary channel are exists at the same time. The most important characteristics of the secondary channels of the Jamuna River are that they have no flow during the dry season. But during monsoon the main channel spills out to the secondary channels and water starts to flow through those secondary channels. They become active and play an important role for bank erosion or failure of the bank protection structures. The flow is divided into three parts when it passes the Betil spur. The confluence of the two of the three channels is just upstream of the Enayetpur. The flow passing near the Enayetpur RCC spur was 1460 m^3/s. The measured maximum depth and approach average velocity around Betil spur and Enayetpur spur were 28m and 18.5m and 0.7m/s and 0.5m/s, respectively.

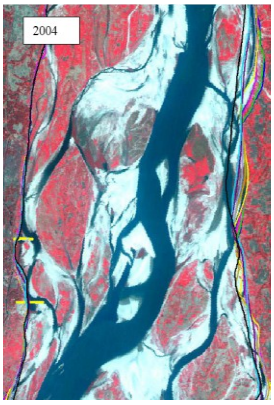
(a) 2000

(b) 2001

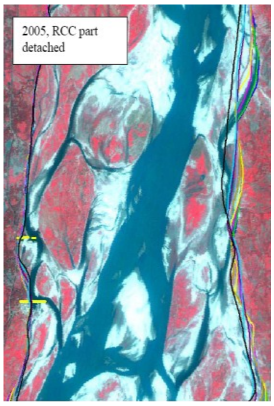


(c) 2002

(d) 2003

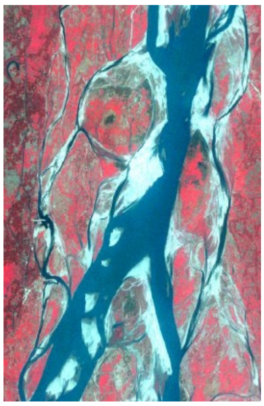


(e) 2004

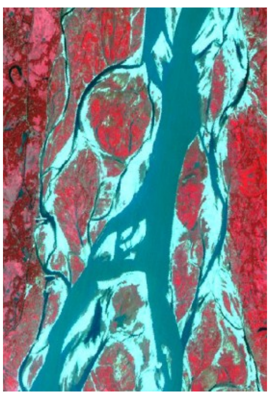


(f) 2005

(g) 2006



(h) 2007



(i) 2008

Fig. 6. Change of the morphology around the Betil and the Enayetpur spurs

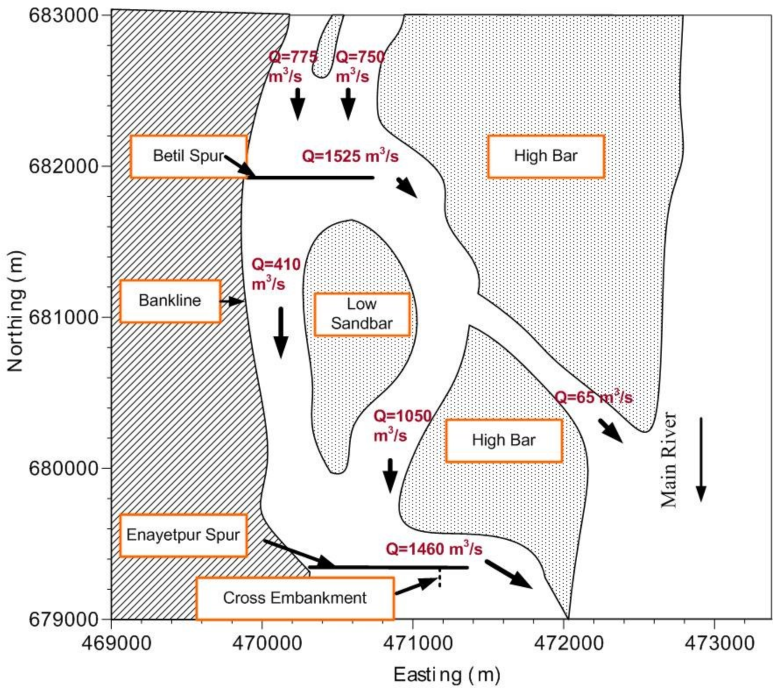
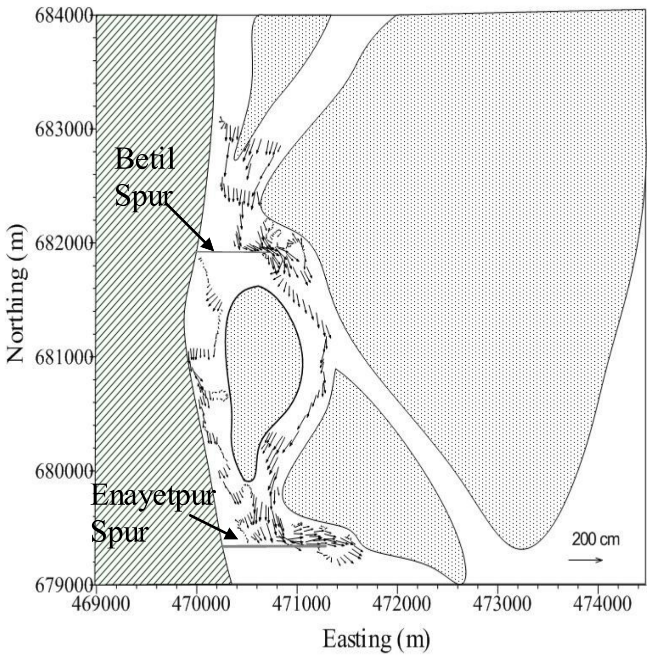


Fig. 7. Discharge of different channels around Betil and Enayetpur spurs

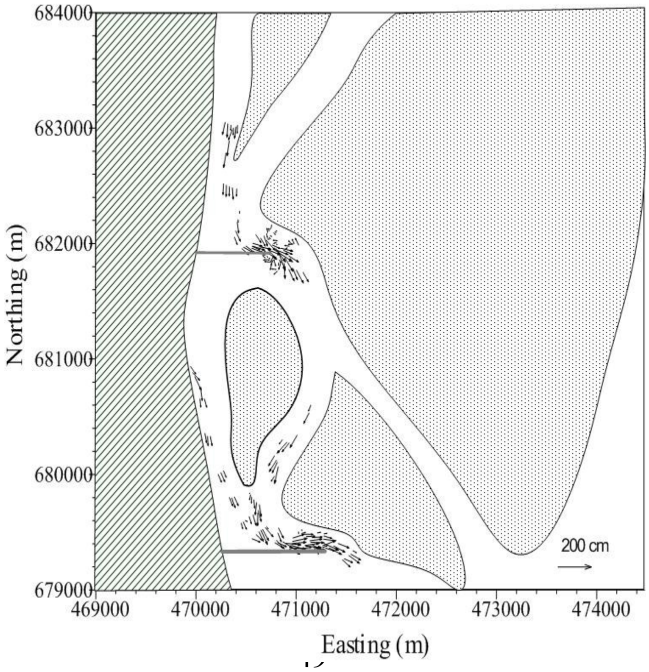
6.1 Flow along horizontal plane

As stated above the flow pattern around bank protection structures depends on different parameters such as flood magnitude, change of upstream morphology etc. The flow patterns along the horizontal plane around Betil and Enayetpur spurs at a depth of 1m, 5m, 10m, 15m, 20m and 24m are shown in Fig. 8 (a-f).

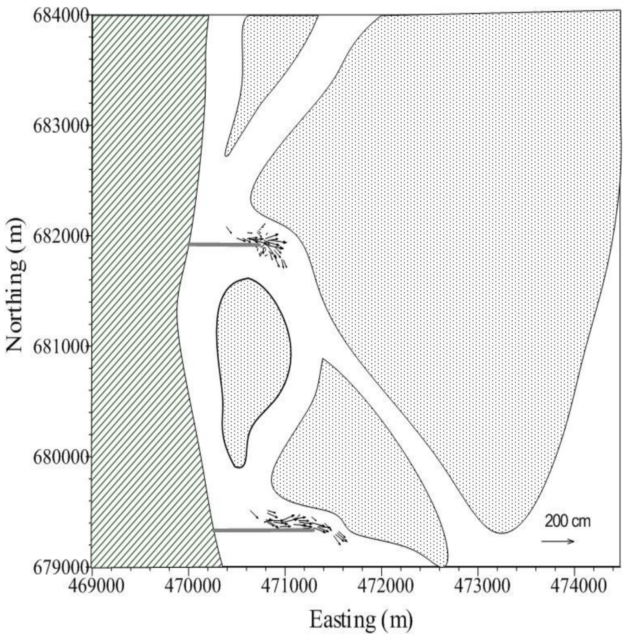
The oblique flow hit to the earthen shank of the Betil spur. It is found that the strong parallel flow is generated upstream of both spurs. The approach average flow velocity upstream of the Betil spur is 0.7 m/s. The parallel flow velocity is amplified up to 1.75 times than approach average flow velocity adjacent to the Betil spur. Usually, a return current is generated downstream of a spur due to flow separation. It is found that some of the RCC spurs along the Jamuna River were damaged due to a strong return current [18]. The length of the RCC spurs is selected depending on the overall width of the braided jamuna river during its design. The secondary channels behave as an individual channel when it is separated from main channel by large sand bar. The length of the secondary channel is relatively higher with respect to the width of the secondary channel. As a result the strong parallel flow is generated along the earthen shank of the RCC spurs.



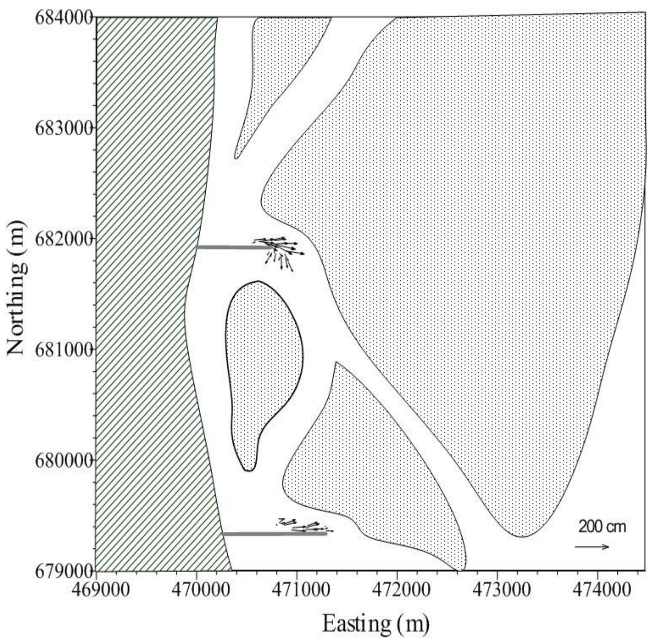
(a) Velocity vectors at a depth of 1m (July, 2008)



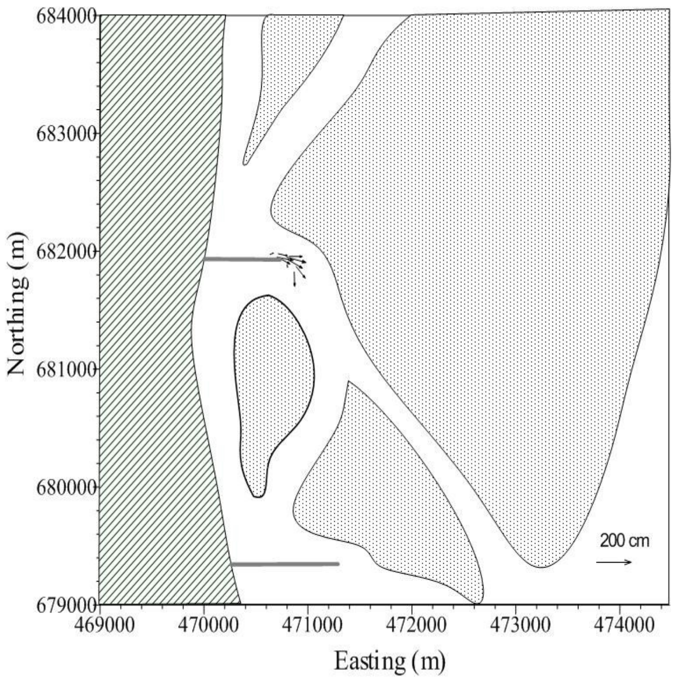
(b) Velocity vectors at a depth of 5m (July, 2008)



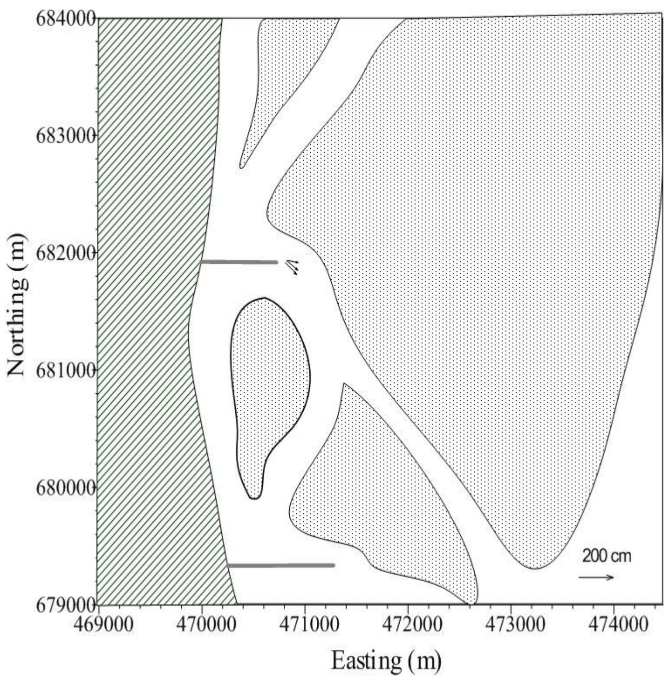
(c) Velocity vectors at a depth of 10m (July, 2008)



(d) Velocity vectors at a depth of 15m (July, 2008)



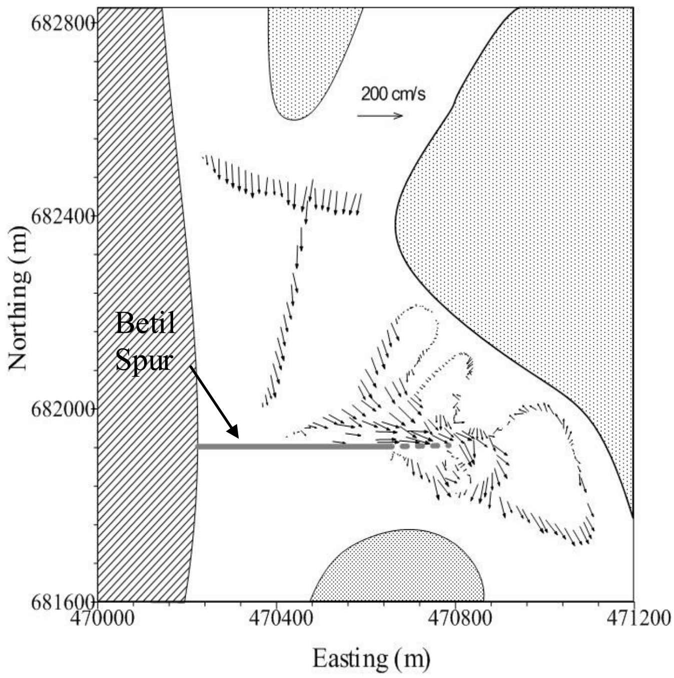
(e) Velocity vectors at a depth of 20m (July, 2008)



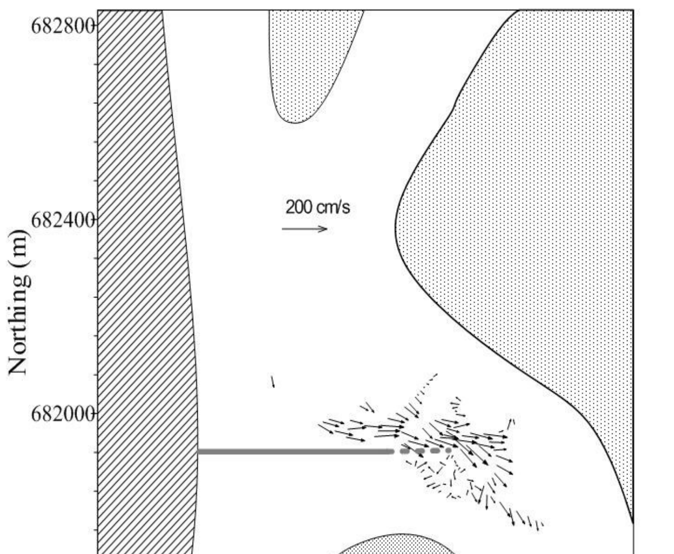
(f) Velocity vectors at a depth of 24m (July, 2008)

Fig. 8. 2-D velocity vectors around Betil and Enayetpur spurs at different depths (July, 2008)

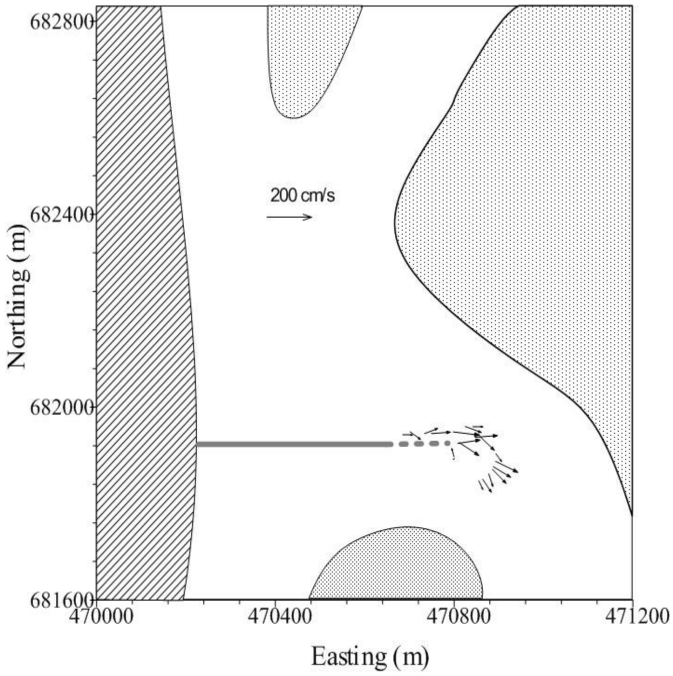
It is clearly found in Fig. 9 (a-c) that the return current is counter-balanced by the flow passing beneath the RCC part of the Betil spur. A reverse circulation of the flow is found adjacent to the bar (located opposite to the nose of the RCC part).



(a) Velocity vectors at a depth of 1m (July, 2008)



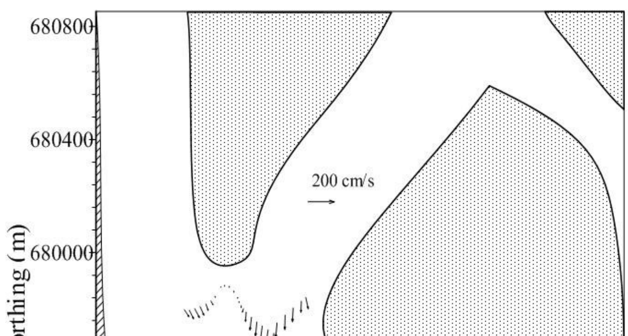
(b) Velocity vectors at a depth of 10m (July, 2008)



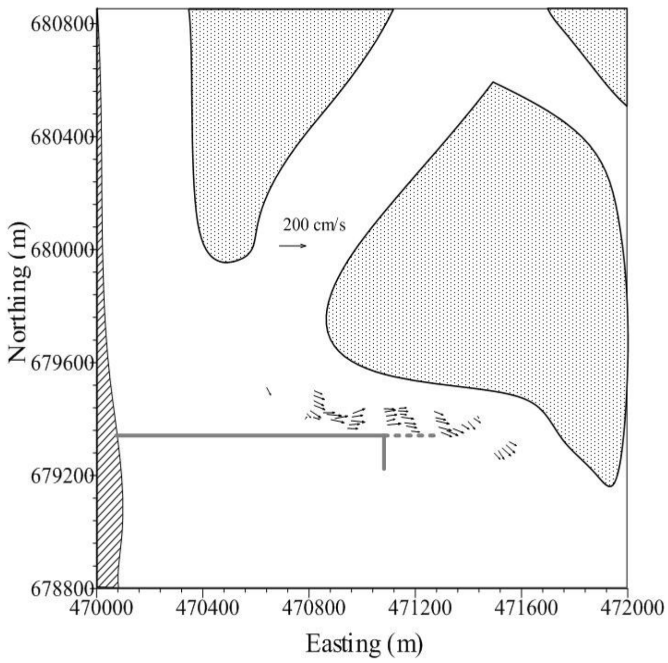
(c) Velocity vectors at a depth of 22m (July, 2008)

Fig. 9. 2-D Velocity vectors around Betil spur at different depths (July, 2008)

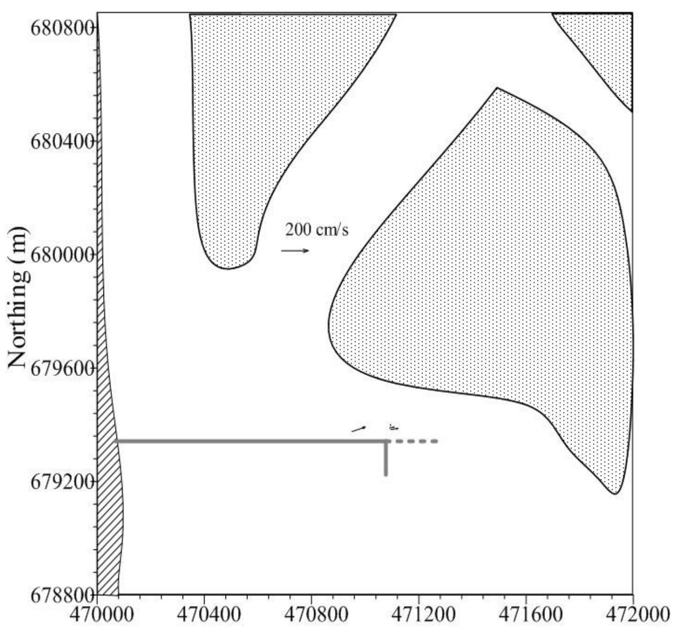
The flow patterns along the horizontal plane around the Enayetpur spur at a depth of 1m, 5m, 10m and 15m are shown in Fig. 10 (a-d). The oblique flow hit to the earthen shank of the Enayetpur spur. A strong parallel flow is generated upstream of the Enayetpur spur which is similar to that of the Betil spur. The approach average flow velocity is 0.5 m/s. But the parallel flow velocity is amplified adjacent to the Enayetpur spur up to 2.3 times than approach average flow velocity. Though, the approach average flow velocity of the Enayetpur spur is less than that of Betil spur. But the amplification is higher in the case of the Enayetpur spur than the Betil spur.



(a) Velocity vectors at a depth of 1m (July, 2008)



(b)Velocity vectors at a depth of 10m (July, 2008)



(c) Velocity vectors at a depth of 18m (July, 2008)

Fig. 10. 2D-Velocity vectors around Enayetpur spur at different depths (July, 2008)

An earthen cross dam, normal to the earthen shank of the Enayetpur spur, has been built by the local people to prevent the return current. A weak return current is found at the backside of the RCC part of the Enayetpur spur due to the cross dam. The elevated land existed downstream side of a RCC spur is very effective for the stability of the spur. It is already stated that the measured maximum scour depths around the Betil and the Enayetpur spurs on 17th July 2008 were 28m and 18m, respectively. The maximum scour depth around the Betil spur is 10m higher than that of the Enayetpur spur. One important point is that the magnitude of the parallel flow velocity is amplified up to 2.3 times upstream of the Enayetpur spur than approach average velocity. The parallel flow velocity is amplified up to 1.75 times than approach average flow velocity adjacent to the Betil spur. The Enayetpur spur is 250m longer than the Betil spur. It can be concluded that the amplification of flow velocity upstream of the Enayetpur is higher due to longer spur.

6.2 Flow along the vertical plane

The Betil spur

Some vertical sections were selected around the Betil and the Enayetpur spurs to identify the flow patterns along vertical planes. The flow patterns along these vertical planes are discussed in this section. A vertical section is taken along line a-a normal to the RCC part of the Betil spur. The primary and secondary vortices are found along this section (Fig. 11). The velocity vectors along line b-b parallel to the Betil spur are shown in Fig. 12. The water is flowing towards the deepest scour hole near the tip of the RCC spur. Another vertical section is taken along line **c-c** from the tip of the RCC part towards the sandbar. The velocity vectors along this line are shown in Fig. 13. The velocity magnitude along line c-c is higher in lower layer than upper layer.

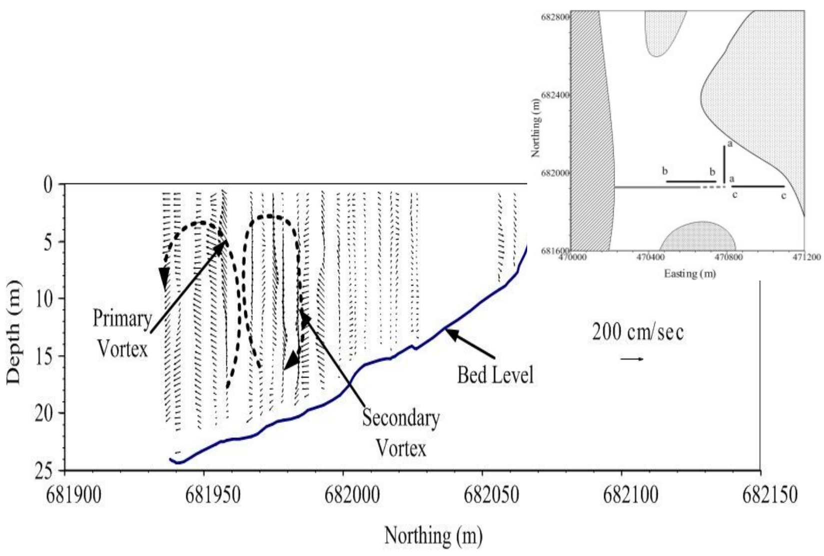


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Fig. 11. The primary and secondary vortex around the Betil spur along line a-a

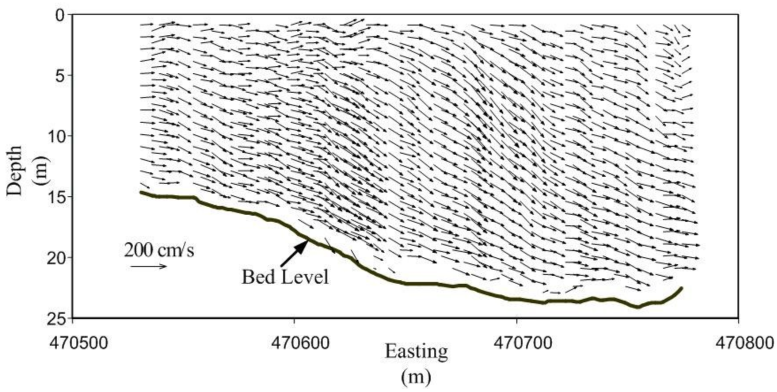


Fig. 12. Velocity vectors in the vertical plane around the Betil spur along line b-b

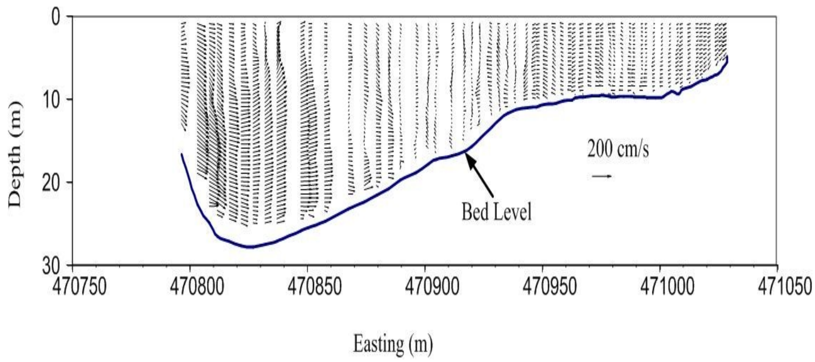


Fig. 13. Velocity vectors in the vertical plane around the Betil spur along line c-c

Enayetpur spur

During the hydraulic data measurement it is found (15th July, 2008) that the earthen shank of the Enayetpur spur damaged. To identify the flow phenomena adjacent to the failure portion of the earthen shank a vertical section is taken along line d-d normal to the earthen shank. The direction of the flow through the upper portion flow is towards the earthen shank. But the direction of flow near the bed level is outward from the earthen shank (Fig. 13). As a result the bed materials are washed away by the outward near-bed-level flow. The lunching materials are dislocated and a create gap between CC blocks. The soil particles from the gap of CC blocks are washed out. If this process is continued deeper channel is developed near the earthen shank. The upper part of the earthen shank slides down if the driving force exceeds the resisting force. Usually, a slip circle failure of the earthen shank is found. The failure of the earthen shank (Fig. 4) is occurred due to the above type of flow phenomena (Fig. 14 and Fig. 15). Another vertical section normal to the Enayetpur spur (adjacent to the belmouth) is taken along line e-e. The flow circulation is observed along line e-e (Fig. 15). This type of flow patterns (similar to secondary current at a bend) is usually observed around the Betil and the Enayetpur spurs. The median bed materials size d_{50} is 0.2mm at the study area. The variation of the ratio of the shear velocity along line e-e is shown in Fig. 16. The critical shear velocity u_{*c} is 1.5 cm/sec. The ratio of u_* / u_{*C} is 5 near the belmouth of the RCC spur which is much more than critical shear velocity ratio (i.e. one). So, the sediment particles are transported by the flow circulation from near the earthen shank of the RCC spur towards the sand bar. Resulting deep channel is developed near the spur which is a big threat to the structural stability of the spur.

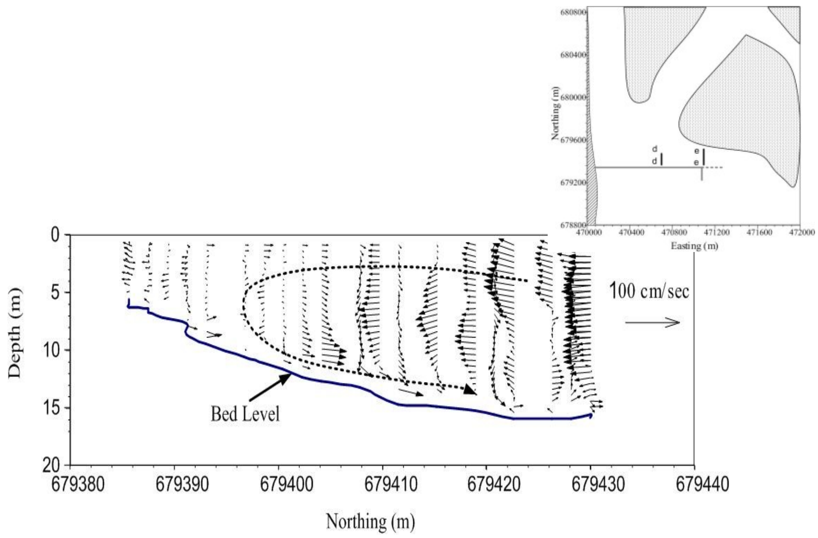


Fig. 14. Flow circulation around the Enayetpur spur along line d-d

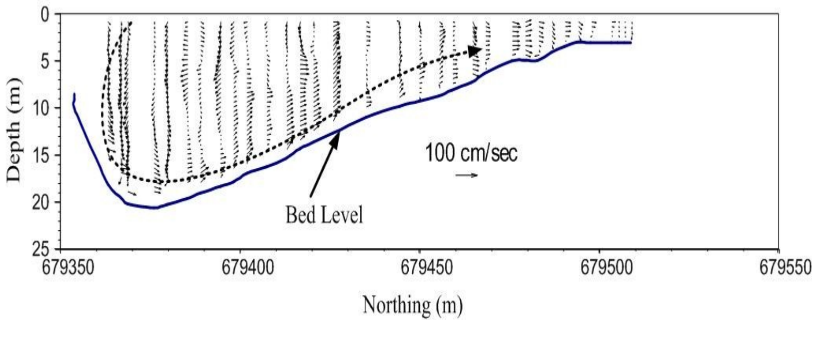


Fig. 15. Flow circulation around the Enayetpur spur along line e-e

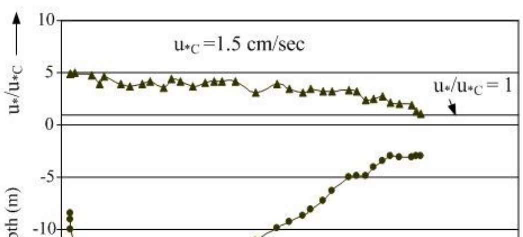
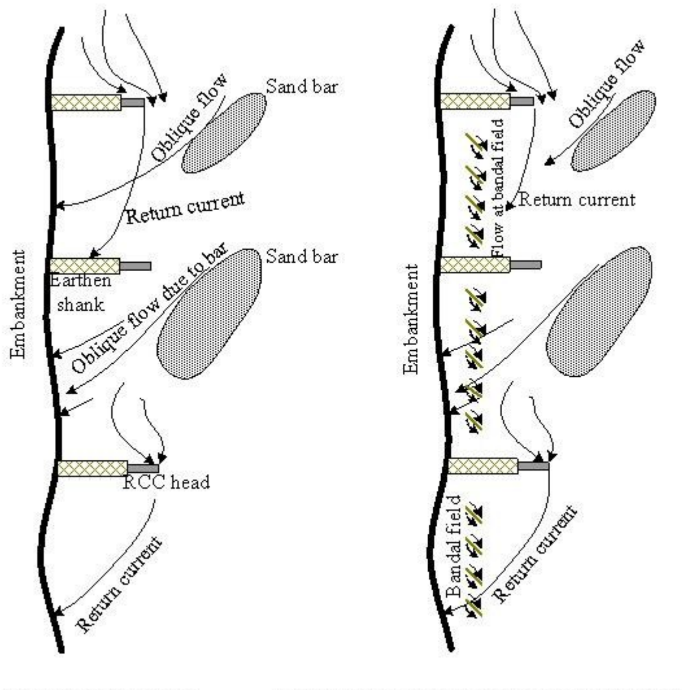


Fig. 16. The variation of the ratio of the shear velocity along line e-e

6.3 Causes of failure of spurs

The main causes of the failure of the earthen shank of the Enayetpur spur are (Fig. 4): (i) the striking of flow obliquely to the earthen shank, (ii) the generating of a strong parallel flow upstream of the earthen shank and RCC part of the spur, (iii) flow circulation normal to the earthen shank and the belmouth, and (iv) development of a deeper channel upstream of both spurs by the higher sediment carrying capacity parallel flow. The deeper channel near the earthen shank affects the structural stability of the earthen shank. Due to above reasons the earthen shank of the spurs frequently failed. Rahman et al. [15] proposed a conceptual model as shown in Fig. 17 to protect the bank as well as the earthen shank of the RCC spur from the oblique flow using bandal-like structures in between spurs or earthen shank of the spur. One of the big challenges for the bandal-like structures is that the selections of durable materials during its construction in reality in a large scale sand bed river like the Jamuna.



(a) RCC Spurs in series (b) RCC spurs in series supplemented by bandals

Fig. 17. Conceptual model of bandal-like structures in between RCC spurs

7 Conclusion

Flow obliquely hits to the earthen shank of the Betil and Enayetpur. The parallel flow velocity is magnified up to 1.75 times and 2.3 times of approach velocity upstream of the Betil and Enayetpur spurs, respectively. Flow circulation is generated normal to the earthen shank of the spurs. The shear velocity is about five times higher than the critical shear velocity. The bed materials from near the earthen shank are transported towards the sand bar. Deep channel is developed near the earthen shank. As a result the earthen shank or the belmouth of the spur is collapsed. To overcome such problem flow diversion measures should be adopted in between the RCC spurs.

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