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Bank erosion and protection on the Brahmaputra (Jamuna) River

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Abstract

Bank erosion is a major problem for river and floodplain management along the Brahmaputra-Jamuna river system of Bangladesh. Considerable resources are spent protecting the river banks from erosion. Consequently an understanding of the erosion processes as well as the suitability of protection methods are important issues to be explored. In this paper bank erosion processes are examined considering the hydrogeological conditions with particular reference to the Jamuna river. The critical condition for bank erosion by mass failure can be defined by the critical bank height for cohesive soils and the critical slope angle for noncohesive soils. Basic analyses show that the critical condition for failure, and hence the critical bank height or critical slope angle, change considerably depending on the hydrogeological condition as affected by river and groundwater levels. A river bank that appears to be stable in the dry season may fail subsequently in the wet season without any significant change of bed levels in the river. This phenomena, combined with fluvial action, would explain the temporal variation of bank erosion rate on the Jamuna from pre-monsoon to post-monsoon period. To protect banks of the Jamuna river from widespread erosion, several types of structural measures have been used. These include groyne and revetment type constructions. As evident from the variable degree of performance of such structures in this river, a critical evaluation should be undertaken before implementing such measures. The performance of the structures is drastically impaired by the generally unpredictable development of the multiple channels in the braid belt and resulting damage to the structures by the combined effects of fluvial action and geotechnical instability. Based on the field evidence, important issues related to the design of bank protection structures are discussed.

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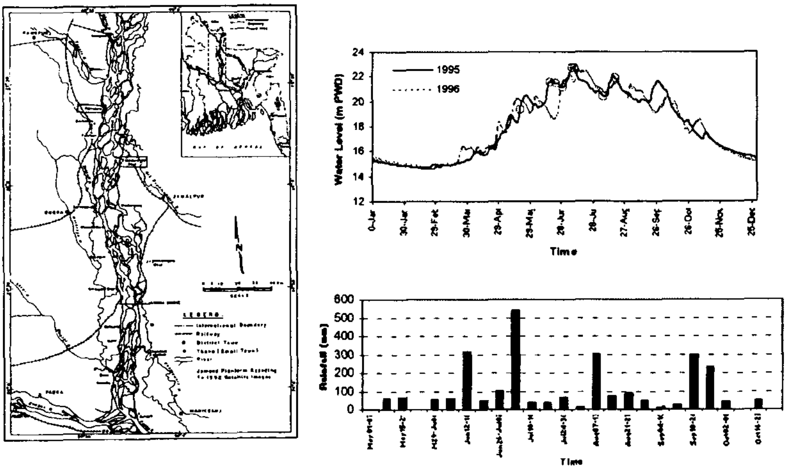

Figure 1: Brahmaputra river, typical flood hydrograph (1995-96) and weekly rainfall (1995).

1 Introduction

Bangladesh, the lowest riparian country of the GBM (Ganges-Brahmaputra-Meghna river) basin, experiences serious economic and social problems as a result of widespread bank erosion along its mighty rivers. Erosion-accretion processes continue every year and the associated river planform changes result in a net loss of about 8700 hactres of land which displaces nearly 64 thousand people [10]. Following independence in 1971, expenditure on bank protection projects has increased rapidly. By June 1998, 246 major bank protection projects had been undertaken at a cost of 834 million US dollars. Expenditure is likely to increase in the coming years to implement projects in new erosion zones, to mitigate the effect of newly constructed structures and to cover the annual maintenance costs of implemented projects. Compared to other rivers, erosion processes in the Brahmaputra-Jamuna river system (Fig.1) are more erratic and occur on a bigger scale. In this paper bank erosion processes on the Jamuna have been interpreted with simple type analysis. The present trend in bank protection methods are reviewed and the issues related to proper design of such works in the context of the Jamuna river are explained.

2 Bank erosion rate

The Brahmaputra-Jamuna river system is one of the largest braided rivers in the world with an overall braid belt width of some 5 to 17 km (Fig. 1) and with individual channels up to 2 km wide. The average flood discharge is about

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65,000 m^3/s with discharge variation of about 15 times (comparing the minimum and maximum values) throughout the years. Coleman [3], first studied the bank erosion rate of the Jamuna river by analysing old maps. Erosion- accretion rates were shown to average between 5 and 8 km for two different periods: 1944-1952 and 1952-1963. He concluded that the bank erosion rate was particularly erratic, ranging from 0 m/year to 800 m/year.

Klassen and Masselink [7] used satellite images from 1976-1987 to study bank erosion rates and tried to relate the radius of curvature and width of curved anabranches with bank erosion rates following the method of Hickin and Nanson [5]. Estimated bank erosion by Hickin and Nanson's method showed much smaller values than the observed erosion rate on the Jamuna river. Similar analyses was carried out by Thorne et al. [8] using satellite images taken between 1973-1992. They estimated bank erosion rates on the right bank of Jamuna river measured at 500 m intervals averaged over 10 km . In agreement with the previous studies, they also identified higher bank erosion rate over shorter time scales. Average annual bank erosion rate ranged between 0 to 160 m/year over the adopted period. Catastrophic bank erosion (>350 m/year) generally occurs over a 2-4 year period on the outer bank of the curved anabranches.

In Fig. 2. erosion-accretion rates along left bankline are shown in different reaches [4]. The bankline has shifted about 1.6 km to the east and the temporal distribution of movement is more unsteady than that of the right bank. The left bankline moved substantially in the early 1990s and changed little after that. In the same period, the right bankline eroded along most of its length but the retreat rate declined recently. The left bankline shows net erosion and accretion zones. The general accretion and advance of this bank is indicative of the western migration of the centreline of the river.

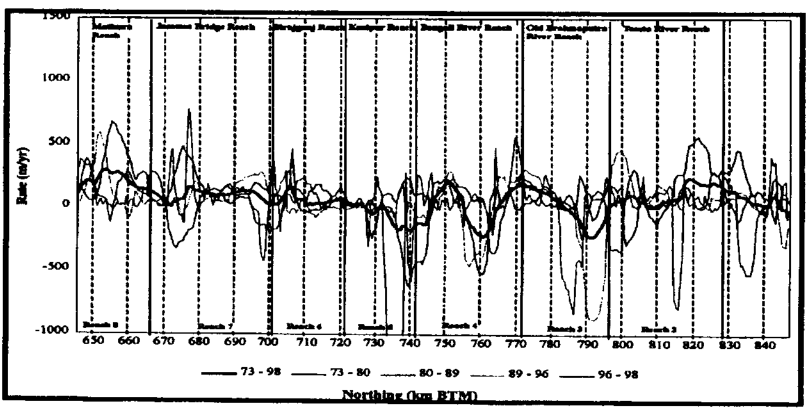

Figure 2: Bank erosion rate along the left bank of the Jamuna River [4].

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3 Mechanism of erosion

The two main processes controlling river bank erosion are fluvial erosion and geotechnical failure following different weakening processes. The first one is the primary reason for sustained erosion of otherwise stable banks in natural rivers. This results from the flow exerting form and drag forces on the bed and bank materials. If these forces exceed a certain critical level (which can be withstood by the boundary particles) than the sediment is entrained. Erosion resulting from the direct entrainment of surface material by the flow predominantly occurs at the base of the bank where boundary shear stresses are the highest. Surface erosion of the upper bank is mainly due to drag forces from wave action, or due to seepage forces. In the Brahmaputra river, the critical mean flow velocity for the initiation of sediment transport is very low (0.2 and 0.4 m/s) in comparison to the mean flow velocity during floods (2~3 m/s). For this reason, scour and erosion rates are very high and maximum scour depths can be reached in one flood season. Coleman [3] identified two types of bank failure namely flowage of material related to liquefaction and shearing away of bank materials. Flowage and liquefaction occur mainly during the receding stage of the flood hydrograph following high water level. Shear failure is very common when flow directly attacks the bank due to oblique flow in one of the anabranches by a thalweg approaching the bank. The critical condition of a bank in incipient mass failure can be expressed by the critical bank height in case of cohesive soils and critical bank slope when the bank soil is non cohesive.

3.1 Critical bank height

Critical bank height may be defined as the height of a bank in a specific hydrogeological environment that is in an incipient failure condition. A specific Factor of Safety (generally unity) is assigned to define the incipient condition or limiting allowable condition. In the case of a riverbank, the hydrodynamic condition of the river system influences this height. By attributing the hydrodynamic effects to the changes in the shape of the bank as a result of bed degradation, lateral erosion and resultant steepening of the river bank, the critical bank height can be determined from consideration of static water levels and the bank material properties. For incipient condition, considering a plain failure surface, the following expression for critical bank height (H_c) is obtained:

$$H_c = \frac{4c(1-k_t)}{\gamma_w\left[M_1\sin 2\beta - M_2\cos 2\beta + (M_2 - 2M_3) - 2M_4\tan\beta - 2K\right]} \tag{1}$$

where, $K = C_5 \sin\beta(\sin\alpha + \cos\alpha\tan\phi)$; β, ϕ and α are the failure plane angle, friction angle and angle related to confining pressure; c = soil cohesion; The coefficients M_1, M_2, M_3, M_4, k_t and C_5 are functions of bank geometry, tension crack, soil unit weight, groundwater level, river water level and pore water

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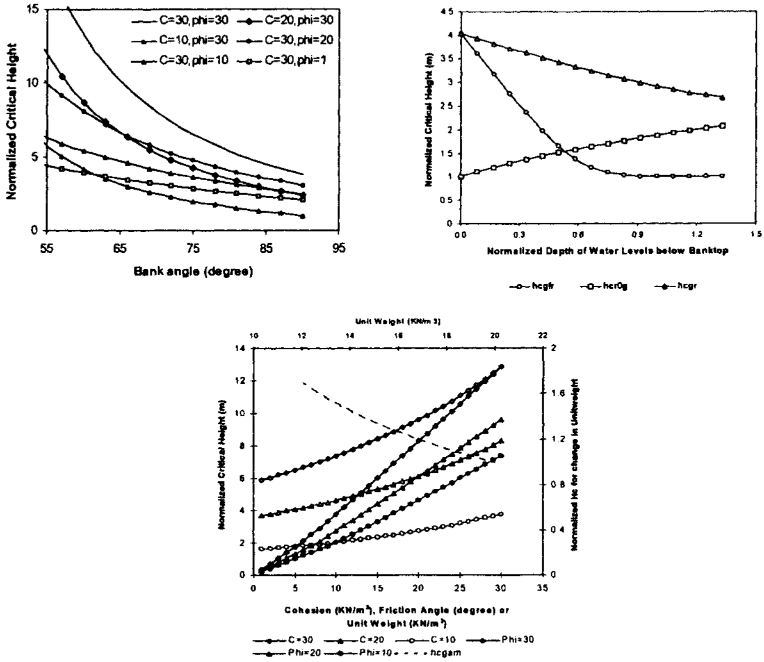

Figure 3: Variation of critical bank height with bank angle (top left), soil properties (below) and water levels (top right).

pressure. The derivation and explanation of these are available from Bhuiyan [1]. In Fig. 3 variation of critical bank height with various related parameters are shown. When friction is dominating bank soil (i.e., ϕ high and C low) the sensitivity of H_c with bank angle is higher than with highly cohesive soil which have lower frictional properties. On the Jamuna, bank soils are friction dominated. This indicates that when the angle of a bank increases by surfacial erosion processes, the bank may rapidly reach its failure condition without significant bed degradation.

The critical bank height is less sensitive to change in friction angle (Fig. 3). The variation of H_c with cohesion indicates that the curves are not only steeper but also relatively linear. On the Jamuna, the bank soils range from silty fine sand to sandy silt. The top 5-10 m of the bank soils are slightly cohesive while below this depth, up to around 20 m, the subsoil consists mainly of micacious silty sand. Subsoil investigations carried out by different FAP studies and laboratory tests and back calculation from failed blocks carried out in the Engineering University (BUET), Dhaka showed that the effective friction angle (ϕ) varied from 18 to >30 degree. The variation of cohesion is quite considerable (0 - 26 KN/m^2). Consequently H_c would not change significantly between reaches due to variation of friction angle if a very low cohesion is considered. On the other hand, H_c may vary up to 10-15 times (<1-15m) within

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the range of cohesion. Nevertheless to say that, in the higher range the mode of failure may change due to lack of cohesion in the deeper soils and the variation in water levels may change the critical condition substantially.

An additional curve, namely hcgam (Fig. 3), shows the variation of H_c with unit weight (from 12 KN/m^3 to 20 KN/m^3) of the soil. This range includes the dry and wet condition of the Jamuna soils. The reported moisture content of the bank soil of the Jamuna is 26% to 39%. The reduction of H_c (from a value above 13 to 8m) indicates the significant effect of unit weight on critical height. This point is important as the unit weight of a given river bank soil can significantly change under different hydrogeological conditions. The pre-monsoon bank erosion along the Jamuna can be explained partly by this phenomena. After prolong dry condition, the stage in the river becomes low. In this condition pre-monsoon rainfall or wetting by rising water levels may increase the moisture level of the soil significantly causing failure of the banks. The process is accelerated by any existing tension cracks that had developed in the dry period and loss of apparent cohesion due to wetting of the poorly cohesive or noncohesive soil.

The critical height changes progressively in response to simultaneous changes in river or groundwater levels (Fig. 3, hcgr). When the groundwater level increases relative to a low river flow (hcr0g) or when the river water level changes against a fully saturated bank (hcgfr), the critical bank height changes rapidly. The flood hydrograph of the Jamuna is characterised by rapid rises and falls (Fig. 1). The rise and fall may be 0.2 to 0.8 m/day compared to coefficient of permeability of the soil of the order of 10^{-5}-10^{-7} m/s. Consequently, widespread erosion of the banks occur in either drained or undrained condition, facilitated by rapid removal of the failed debris and the changing geometry of the banks due to the strong currents in the river. During the rising stage, the river water level may show a stabilising effect by increasing H_c. However this may be over-ridden by higher toe erosion rates, changes in the shape of bank profiles and change in seepage condition by heavy rainfall (Fig.1).

3.2 Critical slope angle

For noncohesive banks the critical bank angle, θ_c rather than critical bank height controls bank stability. Failure of noncohesive bank is complicated when there is seepage in the bank soil and this may even change the failure mode. With poorly or apparently cohesive or noncohesive soils, seepage may destabilize individual soil particles which may ultimately result in instability of the bank. This process causes surface erosion and is referred to as piping and sapping. Such erosion can trigger en masse instability by Coulomb failure or liquifection.

The stability of seepage face materials can be analysed by considering three forces, namely seepage force, tractive force and the gravitational force. For the limiting condition , the critical slope angle (θ_{cr}) from Coulomb type analysis can be written as:

$$\theta_{cr} = \phi - \sin^{-1}(z\sin(\delta + \phi)) \quad (2a)$$

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where, z is the ratio between seepage force to submerged unit weight of the soil; δ is the seepage direction. When a specific relation of seepage magnitude (j) and seepage direction is considered (e.g., $j = \sin\theta / \sin\delta$) then the following relationship can be obtained:

$$\theta_{cr} = \tan^{-1}(G_b \tan\phi / (G_s + \tan\phi \cot\delta)) \tag{2b}$$

where, G_b and G_s are the specific gravity of the soil in submerged and normal conditions respectively. This relation shows clearly the effect of seepage direction on critical slope angle i.e. with increasing seepage angle δ the critical slope angle increases. From eqn (2b), θ_{cr} shows a variation of very small angle to exceeding friction angle. The higher end values relate to the condition where seepage is towards the bank.

The above analysis is based on infinite slopes. It has also implications for noncohesive river banks which are frequently subjected to unfavorable pore water and seepage conditions. Seepage effects can result in the development of an ultimate slope angle significantly lower than the friction angle. For example, considering seepage parallel to the slope it is argued that $\theta_{cr} = 1/2\phi$ is the ultimate stable slope angle. From the above analysis, it is apparent that in a natural fine sand subjected to diversified seepage condition no such ultimate angle can be defined without referring to the seepage condition. This view is also supported by the observations of the fine sand banks on the Brahmaputra and Missssissippi river. From similar analysis it can be shown that in certain conditions the Coulomb failure criteria for noncohesive soil also satisfy the condition of static liquefaction [6]. This occur when groundwater seepage reduces the effective normal stress and the frictional strength in static cohesionless soil to zero everywhere in the mass.

Different studies showed that the subsoil of the Jamuna consists of loose micacious sands in the first 20 m of depth. The relative density of these soils is low (<50%). This material tends to consolidate when subjected to shearing stresses, thereby allowing the load of a saturated material to be partly carried by the water which, thereby, reduces its shearing strength. Consequently bank erosion and damage of earthen structures by flow sliding are common along the Jamuna river. If a flowslide affects the whole profile of a slope, then the post flow slide slope may become very flat (e.g. 1:20) in the lower part of the bank with subsequent steepening of the upper part. Liquefaction may occur in the seepage face of the bank (in between high and low water levels) or subaqueous liquefaction may occur [3,9]. Another implication relates to the characteristics of the failed material. Blocks that fail by Coulomb failure may be deposited intact near the bank toe thereby inhibiting further geotechnical failure or fluvial erosion. Liquefied material will be more prone to fluvial entrainment and removal from the near bank region which encourages other types of failure in the upper bank. This has important implication for the temporal distribution of bank erosion.

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4 Bank protection practice

As bank erosion is a long standing problem, several major coordinated protection works have been initiated and executed over the last fifteen years. These include priority based bank protection works (RBPP) and protection works undertaken in connection with the the Jamuna bridge (BMB). Large groyne-type structures had been constructed at 14 sites by 1999. Eight of these were impermeable groynes (x-bar), with lengths ranging from 125 to 980 m. Another two are impermeable groynes; Bell-head and T-head with lengths of 366 and 952 m respectively. Permeable groynes have been installed at two locations. One of these is the test structure at Kamarjani, on the right bank of the Brahmaputra. This structure has been studied in considerable detail under a project which has extended over several years.

5 Issues and problems related to major protection works

Unlike smaller rivers, the cost of bank protection structures in a big river like the Brahmaputra are not always profitable in the short term. The structures are constructed with low factor of safety except in special cases like river training structures for the Jamuna Bridge. Consequently these are subjected to frequent damage at different scales and rehabilitation are required which are also expensive. Normally a single structure such as a groyne or revetment does not work satisfactorily. So a combination of these are considered for protecting a certain reach of the river.

The main parameter when designing such a structure is the maximum scour depth. This is determined from historic data analysis, laboratory studies and using empirical equations. None of these can actually represent the real field condition. Due to the highly active nature of the individual channels in the braid belt, the scour pattern around the structure may be changed considerably. The local scour due to the structure can be exacerbated by other phenomena like constriction scour, anabranch bend scour, confluence scour, protrusion scour, bedform scour etc. As channel development is not totally predictable and understandable, the estimation and occurrences of these scours are also uncertain. However, failure to estimate appropriate scour depth can result in severe damage and huge loss of resources. This was the case with the Sirajganj protection works. The observed scour depth was 47 m against the design scour depth of 33 m (below high flood level). The rehabilitation work for the damage of the structure was estimated at 10 m US dollar [2].

Fig. 4 shows the variation of scour depth around the Jamuna test structure at Kamarjani. The sudden rise and fall of the maximum scour levels indicate the effect of the various external factors on scour development. Maximum scour depths around the groynes were affected by the angle of attack of the flow, bedform movement, rapid siltation following channel changes, slides on the flanks of the scour hole and on the nearby banks and floating debris accumulating at the upstream face of the permeable part. The variation of scour

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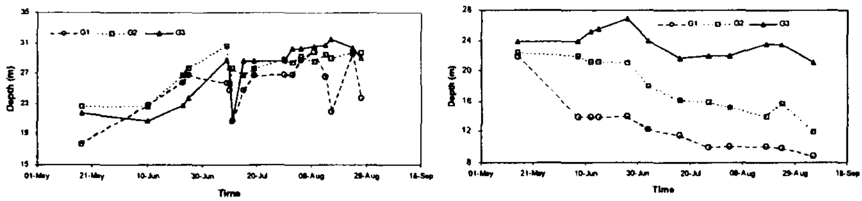

Figure 4: Scour depths (below high flood level) downstream of three groyne structures at Kamarjani in 1995 (left) and 1996 (right).

depth due to flow slides and siltation has also been observed with other structures e.g., Kalitola groyne and Sirajganj hardpoint in 1998-1999. Scouring as high as 4-5 m/day occurred in loose sediments. Such high rate of scour encourages the development of flow slides.

The structures constructed in the Jamuna show significant downstream effects by forming embayments in the bankline. These can occur both upstream and downstream of revetment structures and downstream of groynes, as for example, downstream of Kamarjani composite groynes and Sailabari groyne. At Kamarjani, the thalweg and apex of the anabranch bend gradually moved downstream from the site of the structure causing severe erosion there. This change may affect channel development and the efficacy of the bank protection structure in the next reach by changing the flow pattern. It is thought that the Sailabari groyne contributed to major damage at the Sirajganj revetment in 1998 which was located at 3 km downstream.

As described above, the proper identification of local soil materials and seepage conditions is another important issue when undertaking construction works on the Jamuna. Previously, major damage has occurred at several projects during and after construction which related to the geotechnical instability. Examples are in the BMB west guide bund (1995-96), Kamarjani test structure (1995-96), Sirajganj revetment work (1998-99), Kalitola groyne (1999) etc. Damage to the structures was induced and accelerated by the combined effects of geotechnical instability and hydraulic forces (except BMB). It seems that local soil is not suitable for earthen core of bank protection structures unless carefully designed for proper drainage, containment and armour protection.

6 Conclusions

The seasonal variation of bank erosion along the Brahmaputra-Jamuna river system depends on the instream channel processes as well as hydrogeological conditions and geotechnical properties of the bank soils. The simple analysis to determine the critical condition considering the variable shape of the banks and river and groundwater levels explains the different levels of erosion potential during the pre-monsoon to post monsoon period. For the design of bank

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protection structures, the most important issues are the estimation of design scour depth, the proper identification of the local soil properties and consideration of the effect of upstream structures. This requires a proper understanding of the local erosion processes and channel development in the braid belt.

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