Journal of Engineering Science 02(1&2), 2011, 63-72

JES
an International Journal

RIVERBANK EROSION AND SUSTAINABLE PROTECTION STRATEGIES

Md. Shofiul Islam

Senior Scientific Officer, River Research Institute (RRI), Faridpur, Bangladesh

Received: 22 July 2009 Accepted: 25 September 2011

ABSTRACT

Bank erosion is the most common problem faced in river engineering practices in many countries, especially in Bangladesh and this has been recognized as an awful threat to the society. So control of erosion is very much important to save agricultural land, property and infrastructures like bridges, culverts, buildings etc. located alongside the rivers. In this paper the probable causes, mechanisms and methods of predictions of bank erosion and sustainable strategies of different bank protection measures with special attention to economic analysis are briefly discussed. Prediction as well as appraisal of bank erosion rate along the Jamuna River is described a glimpse. However, the physical model study is well employed method to predict bank line shifting along with calculated from spot images.

Keywords: *Bank erosion, Bank protection, River morphology, Sustainable protection measures, Sediment transport*

1. INTRODUCTION

Engineers play important roles for poverty alleviation in many ways, e.g. by designing, planning and implementing infrastructures. As the government fund is limited and there is always a shortage of money, there should have limitations in spending money for public investments because there may be more hospitals, schools, roads, bridges and so on.

Due to the geometric location flood is the recurring problem in Bangladesh, which causes serious devastation to the property and life alongside the river. Bank erosion not only causes damage to the immediate 'blow-out' site, but also responsible for the loss or damage to valuable farmland, wildlife habitat, buildings, roads, bridges, and other public and private structures and property. In economic point of view, mitigation of bank erosion in Bangladesh has become an integral part of poverty reduction. The severity of bank erosion may be realized from Fig.1. Having considered the extreme severity, bank erosion assessment is the prime objective prior to take sustainable protective measures against erosion. Bank erosion is the major source of sediment deposited at the downstream backwater areas. The area dominated by significant sedimentation also simultaneously expands the cross-sectional area by widening due to side bank erosion. So, the riverbank erosion control or riverbank protection in a sustainable manner is necessary to save the expected losses. Sustainability may be ensured by proper diagnosis and predictions of bank erosion and treatment applied to select technically and economically justified protective measures.

Figure 1: Typical Bank erosion along the Jamuna Right Bank

Keeping these facts in mind several studied i.e. FAP 19 and 24 study**,** scale physical model studies conducted at River Research Institute (RRI) to determine geometric and bank shifting characteristics of Jamuna River is extremely important in connection with the appraisal of river bank erosion.

2. CAUSES OF BANK FAILURE

The riverbank undergoes to erosion by hydraulic and geo-technical instability. Hydraulic instability is caused by scour at the toe of a marginally stable bank, flood propagation and flood recession, debris and vegetation, removal of bank vegetation, detachment of coarse sediment by wave action, secondary current etc. Besides, constricted bridge crossings or other encroachments that involve acceleration and concentration of flood flows

* Corresponding author: shofiul72@yahoo.com

tends to cause 'back eddies' or reverse circulation downstream, which can sometimes erode huge embankments into river bends. Local bank protection and river training works designed to protect against bank erosion at one point or reach of a river often provoke accelerated bank erosion elsewhere. The shearing of bank material by hydraulic action at high discharges is a most effective process, especially on non-cohesive banks and against bank projections. Large scale eddying induced by bank irregularities can enlarge existing embayment and increase the amplitude of projections, which become more susceptible to subsequent attack. Geo-technical instability is caused by detachment of more coarse grained layers in any given alluvial bank, by water flowing out of the bank face, termed as 'piping' or 'sapping' (Hagerty and Hamel, 1989). Cohesive banks particularly susceptible to seepage force and piping mechanisms that may so lower the internal resistance of the material as to induce failure. Whereas the lower bank is eroded by hydraulic action, the upper bank is less affected by flow forces but fails because of undercutting which produces different types of cantilever action in the cohesive material. River stage drawdown following floodplain inundation contributes to riverward creep and/or sliding of alluvium as does riverward seepage and consequent piping.

3. BANK EROSION MECHANISMS

The traditional perception is that banks fail by basal scour. The shear stress associated with the water flow along the bank corrodes the toe of the bank, which steepens the bank, makes the slope unstable, and, eventually, gives rise to structural failure of subaqueous and upper banks. This perception is the basis of several mathematical models of bank erosion in which rate of bank retreat is assumed to be directly related to near-bank flow velocity and shear stress (Darby and Thorne, 1996; Throne and Osman, 1988). Several studies suggest that there are other hydraulic factors than shear stress exerted on banks, which may also significantly affect rate of bank retreat. Among them, piping due to seepage is an important one.

Bank erosion phenomenon in large-scale rivers is a cyclic process of the following four sub-processes:

(i) Steepening of bank slopes caused by erosion of lower part of the slope and riverbed near the slope toe.
(ii) Slip failure of the steepened bank slope by losing its stability.
(iii) Movement of failed bank material toward riverbed along the slip surface.
(iv) Removal of failed bank material on lower part of the slope and riverbed near the slope toe.

Erosion that steepens bank slope occurs locally because of sediment continuity, in other words, because channel widening by longitudinally uniform erosion must raise riverbed at the equivalent amount of sediment produced by bank erosion. The local steepening of bank slope is considered to take place due to flow concentration following channel plan forms and bed topographies.

Bank shifting through erosion-deposition processes in an alluvial river is a characteristic feature and one of the most conspicuous changes affecting fluvial landscapes. At a meander bend high velocity occurs in the outer bank causing recession of bank and also the spiral flow tends to deepen the outer bank. In a bend flow, the secondary current is produced by the non uniform vertical distribution of centrifugal force (per unit mass of fluid) which in turn is a result of the primary flow that is nonuniformly distributed over the depth. The secondary current exists because the faster moving fluid near the free surface experiences a larger centrifugal force than the slower moving near-bed fluid.

In a river rates of such bank erosion can be rather high but such rates apply to certain bends only; others on the same river at the same time shift more slowly. Generally, the rate of bank shifting is determined by the strength of the bank on one hand and the fluid forces on the other hand. Under natural conditions regular pattern of bank shifting can not survive. This is due to the fact that apart from the effects of river flow fluctuations, river and valley floor sediments are rarely uniform and the lateral redistribution associated with bank cutting and point bar construction introduces size sorting. Continued shifting with spatially variable boundary conditions must inevitably lead to distortion of the waveform with some bends, or parts of bends, eroding faster than others as the pattern as a whole becoming irregular. A deterministic analysis of meander development is extremely complicated because an irregular meander pattern is even less likely to be in a steady state. However, a statistical equilibrium can be envisaged in which the pattern retains its aggregate characteristics despite changes in detail. If some bends grow, but others decline or are eliminated, the scale and degree of meandering, and the overall level of irregularity, may remain more or less constant over the years.

4. FACTORS TO CONSIDER IN BANK EROSION ASSESSMENT

The following factors should consider when bank erosion is assessed for planning protection works:

(i) Hydraulics (stage-discharge, flow structures, flow resistance, maximum near-bank velocity, distribution of shear stress, secondary currents and turbulence, water level variations).

(ii) Morphology (Riverbed deformation by computing bed shear stress, bed topography, channel plan form, migration of bar and bed shear stress).
(iii) Sediment transport (suspended sediment, bed load, wash load).
(iv) Stability of banks and riparian structures (vegetation, bank angle, critical bank height is a function of bank angle, tension crack depth).
(v) Soil properties (size, gradation, stratification of bank sediment, bulk density, friction angle, cohesion etc.).

5. BANK EROSION PREDICTIONS

The prediction of future rates and direction of bank erosion along a river is difficult problem that arises in many engineering applications. In natural rivers, the best guide to future patterns of bank erosion is a local study of past patterns. Topographic maps and satellite images of several years, supplemented by local witnesses, are usually the best sources of information. However, the satellite images, due to their scale and resolution limitations, give qualitative results to some extent. Although bank erosion is quite a complicated process, over the years a number of methods were developed to predict the bank erosion rates. One of the methods is related to 2D mathematical model to compare bank erosion on the basis of local geometry, flow and sediment processes (Mosselman, 1992 and DHI, 1996 as described in DELFT/DHI, 1996). Other method estimates the yearly bank erosion rate on the basis of (1) overall channel parameters (discharge, bank material characteristics) and (2) local geometry (Hickin and Nanson, 1984). In general, bank erosion (E) is the function of bed and bank material properties, geometry of the river, flow characteristics. Hickin and Nanson (1983) stated that the bank erosion rate, E is likely to depend on many variables as

$$E = f(\Omega, \gamma_b, h, R_c, w) \tag{1}$$

in which Ω = stream power per unit bed area ; γ_b = opposing force per unit boundary area resisting erosion (co-efficient of resistance to lateral migration, N/m^2 analogous to Manning's n) dependent largely on bank strength; h = bank height; R_c = bend radius or radius of curvature; and w = channel width.

Stream power is the rate of potential energy expenditure per unit length of channel discharge and expressed mathematically by

$$\Omega = \gamma Q i \tag{2}$$

where, γ (= ρg) is the specific weight of water, Q is discharge, i is slope.

Eq.1 may be expressed by a non-dimensional form as

$$E = k\frac{\Omega}{\gamma_b}\left(\frac{h}{w'};\frac{R_c}{w}\right) \tag{3}$$

in which, k is a constant, $\frac{R_c}{w}$ used as a ratio to assess bank erosion rate or the amount of hydraulic stress placed on the outside of the river bend (Bagnold, 1960; Ippen and Drinker, 1962; Hickin and Nanson, 1975).

It is seen in the previous study that correlation exists between the dimensional parameters as

$$\frac{Eh}{w} = k\frac{\Omega}{\gamma_b} \tag{4}$$

Measurements on the Beatton River in the United States clearly show that bank erosion rates are strongly controlled by bend curvature.

The lateral erosion of cohesive riverbank is given by Arulanandan *et al.* (1980) and may be expressed as (Osman and Thorne, 1988)

$$\Delta w = \frac{R(\tau - \tau_c)\Delta t}{\nu \tau_c}; \qquad R = 0.0022\tau_c e^{-0.13\tau_c} \tag{5}$$

in which Δw = bank erosion distance (m) in one bank; τ_c = critical shear stress (dynes/cm^2) for cohesive soils; ν = soil unit weight (KN/m^3) ; τ = average shear stress (dynes/cm^2) and Δt = computational time interval in minutes.

For turbulent flow, shear stress (τ) is expressed by

$$\tau = \mu \frac{du}{dy} + \rho\varepsilon \frac{du}{dy} \tag{6}$$

where, $\dfrac{du}{dy}$ is the velocity gradient at depth y, u is the local mean velocity at distance y from the boundary, μ is dynamic viscosity, ρ is density of water, ε is eddy viscosity.

5.1 Prediction of bank erosion rate along Jamuna River

The bank line migration of the Jamuna left bank downstream of Bahadurabad calculated from SPOT images indicates that the bank erosion rates vary along the bend and the maximum erosion occurred at the downstream end of the bend (DELFT/DHI, 1996). The maximum yearly bank erosion rate at the river bend downstream of Bahadurabad was about 800m, which is classified as an extreme event of bank erosion (Klaassen and Masselink, 1992). Within less than three years the maximum retreat was approximately 2 km. The observed bank erosion rates in the river bend were compared with the different predictive methods. The method of computing bank erosion rate using near bank flow velocity by Mosselman (1992) and DHI (1996) has been compared with the observed bank erosion rate (Fig.2). This figure shows that the bank erosion rates increases linearly with the near bank velocity as per Mosselman (1992), while bank erosion rates and near bank velocity shows power relationship between them as per DHI. It is envisaged that DHI prediction was complied with observed, where the rate was moderate in Kamarjani location. However, the rate is very high at the downstream of Bahadurabad, where, DHI prediction is not accurate. It was concluded that probably the flow structure in the bend and the effect of bank erosion product in changing the planform is very important. Klaassen and Masselink (1992) noticed that applying the method of Hickin and Nanson (1983) for predicting the bank erosion rate in the Jamuna River yields very less bank erosion rate than the observed erosion rate.

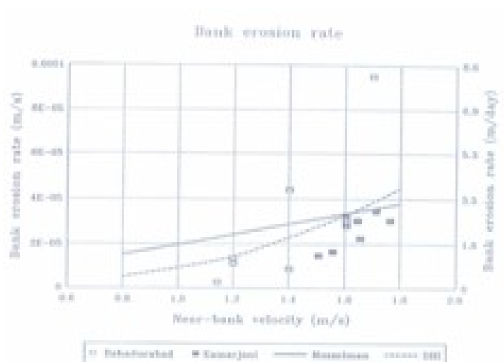


Figure 2: Comparison of Bank erosion rate estimates in relation to near bank velocity.

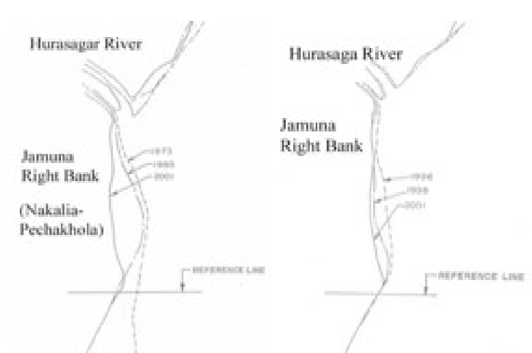


Figure 3: Bank shifting at Nakalia-Pechakhola (1973-2001)

Failure due to piping in non-cohesive riverbank has been investigated experimentally by Odgaard *et al.* (1989) in the laboratory. Relations between pressure gradient and seepage rate, rate of erosion in the non-cohesive soil has been established. Physical models using fine sand gives indication of induced bank erosion as envisaged in the Jamuna Bridge Study (RRI, 1998b). So, the laboratory method may also be employed to predict bank line shifting and in that case use of lightweight materials as bank sediment gives precious result.

6. ESTIMATION OF BANK EROSION ALONG JAMUNA RIVER AT NAKALIA PECHAKHOLA AREA

FAP 24 study: FAP 24 (DELFT/DHI, 1996) studied the Riverbank erosion of the Jamuna River in details and reported the important factors causing erosion are flow, sediment transport, channel geometry and bed topography, vegetation, ground water level and their spatial variation and bank material properties. The flow exerts shear stresses that can remove particles from the bank either via 'peeling off' or via mass movement. The flow in a river bend attacks the toe of the riverbank, removing the sediment from the toe, resulting in an over-steepening of the riverbank and causing the bank failure by slumping. The study revealed that the longest overall bank retreat has occurred near Nakalia. In this reach the bank line has shifted westwards about 1.6 km since 1975. This has caused serious loss of households as well as previous breaching of the South of Kaitala pump house. Bank erosion rates were computed from the digital satellite imagery by superimposing the successive bank lines. Channel migration and bank erosion rates were computed using the method of Hickin and Nanson (1975). Bank erosion rates averaged around 120m/year, (locally up to 250 m/year) during periods of aggressive bend development (1997-2000) and about 50 m/year between 1975 and 2000.

RRI study: A study on the Right Bank erosion of the Jamuna River downstream of the confluence of Hurasagar and Jamuna based on satellite image analysis indicates the prominence of bank erosion in the study area (**Fig.3**). The total maximum bank erosion during 1973-2001 was estimated about 1.4 km towards west, which is comparable to the FAP study (RRI, 2002). The type of bank erosion often encountered in meandering rivers is also present in the Jamuna River, especially at Kamarjani location (DELFT/HDI, 1996). Required data were collected such as cross-sectional date, hydrological data (water level, discharge) and satellite images. Data sources are BWDB, IWM and CEGIS. The entire standard BWDB cross-sections were considered in the study. The location map showing these standard BWDB cross sections was produced as distance along the cross section as abscissa and elevation with respect to PWD datum as ordinate for each of the cross sections considered in the study for 1973-2001. The cross-sectional area for each cross-section was determined by dividing the cross-section into a number of segments by the verticals. For each segment, the cross-sectional area was calculated. Finally sum up all the cross-sectional area of all segments in order to get the total cross-sectional area of that cross-section. The average depth of a cross-section was calculated by taking the average of all depths. The width was determined as the distance between last vertical minus first vertical of a cross-section.

Area-elevation relationships were developed for BWDB cross-sections to determine the variation of cross-sectional area with elevation.

The thalweg level was determined as the deepest point from the cross-sectional map of each of the considered BWDB standard cross-sections for the years 1973 and 2001 to observe the variation of thalweg level along the cross-section.

The mean bed level (MBL) of standard BWDB cross-sections was determined by subtracting average depth from average bank level of each cross-section for the years 1973 and 2001 to observe the variation of MBL at these cross-sections. Change in MBL was also determined at all the cross-sections during 1973 to 2001.

The relationships between area & width and between width & hydraulic radius were also developed for the years 1973 & 2001 in each case. The trend was determined for all standard BWDB cross-sections.

The relationships of hydraulic geometric parameters such as water width, water depth, and flow velocity & water area against discharge were developed for each year.

Use of non-dimensional parameters in the study of alluvial river phenomena. It may be emphasized to state that flow through an alluvial river incorporates a good number of variables and that is why dominant variables were chosen to form non-dimensional parameters to describe the alluvial river behavior.

Non-dimensional analysis was done for the whole years using hydraulic geometric parameter. The average slope of the river was taken to be 1:11,400 and the value of acceleration due to gravity was taken to be 9.81 m/sec^2. The non-dimensional parameters were calculated for whole years. In this study the selected non-dimensional parameters were W/D, $V/(gD)^{1/2}$, $Q/(kD)$, $D/[k^{2/3}/(Sg)^{1/3}]$ and $(Q/k)/[k^{2/3}/(Sg)^{1/3}]$. Non-dimensional relationships were developed between $V/(gD)^{1/2}$ versus W/D, $Q/(kD)$ versus W/D, $(Q/k)/[k^{2/3}/(Sg)^{1/3}]$ versus W/D, $Q/(kD)$ versus $V/(gD)^{1/2}$, $D/[k^{2/3}/(Sg)^{1/3}]$ versus $V/(gD)^{1/2}$ and $(Q/k)/[k^{2/3}/(Sg)^{1/3}]$ versus $V/(gD)^{1/2}$ and the trend of each of the relationship was determined.

The trend of water level and discharge data against time was also determined separately using annual average data. The stage-discharge relationship or rating curve was also developed using water level and discharge data.

From the satellite images, the bankline of 1973 & 1984, 1973 & 1993 and 1973 & 2001 was superimposed in order to determine the bankline movement of 1984, 1993 & 2001 with respect to 1973. For this purpose five representative sections were selected to represent the study area. The amount of bankline movement relative to 1973 and also the rate of erosion/deposition were determined along the representative sections.

7. BANK PROTECTION MEASURES

Numerous methods are available to control bank erosion. The bank protection measures have been categorized as structural, non-structural and biological protection measures. However, structural measures are taken for long-term protection. Different measures are described in short as follows:

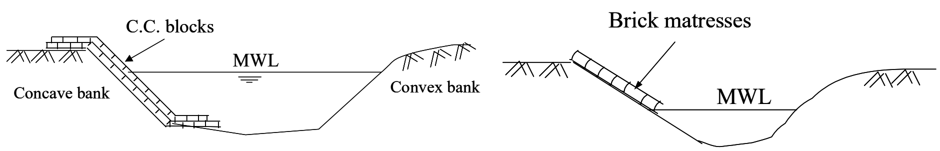
(a) Structural measures

Generally, two major types of structural measures are practiced, namely, hard material protection and barrier across the river.

Hard material protection

This method is known as 'resistive bank stabilization method'. It works by resisting the force of the stream. This is a discontinuous bank protection method; bank scalloping is expected between hard points. The main aim of this method is to protect bank toe by boulder, stone, cc blocks etc. It resists erosive flow of the stream and stabilizes the toe of the bank. Success depends on the ability of stone to launch into the scour hole. The weight of the stone resists the geo-technical failure. This technique is fairly suitable for continuous bank protection, for small radius and/or high degree of curvature bends. For toe protection by placing stones, boulders, C. C. blocks, riprap etc. bank shaping is important. Grading banks to more gradual slope does bank shaping. Toe of the concave bank posed to higher rate of erosion and as a result convex bank needs less protection than concave banks. Some examples of hard material protections are:

(i) ***Revetment*** C. C. blocks are placed on the slope to protect the bank continuously from erosion and geo-textile filters are placed underneath the blocks to protect from seepage failure.
(ii) ***Guide bunds*** constructed at bridge crossings to protect bridge abutments, its upstream and downstream areas from erosion.
(iii) ***Boulders*** Graded boulders are placed at the toe of bank to reduce shear stress and near-bank flow velocity.
(iv) ***Brick matressing*** Brick mattresses are placed on the graded bank slope. **Fig.4** shows different types of hard material protection.



(a) Revetment (b) Brick Matressing

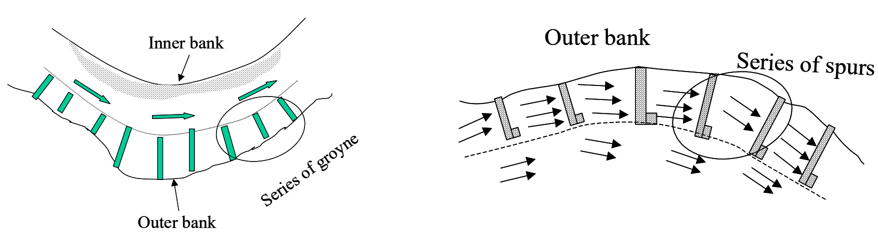
Figure 4: Hard material protections

Barrier across the river

This method is known as 'redirectional bank stabilization method'. The objective is to redirects flow and energy of stream flow away from eroding bank. In this method, erosion is controlled through flow velocity reduction by proper arrangements of the barrier. Some of the examples of barriers are:

(i) ***Groynes*** deflect flow away from the bank and reduce near-bank flow velocity by dissipating flow energy. Groynes are commonly of RCC and earth-boulder mix types
(ii) ***Spurs*** are commonly of earthen, RCC or wooden logs types. Spurs are solid or permeable and submerged or non-submerged types.
(iii) ***Vanes*** are constructed at the river bends to redistribute flow velocity.
(iv) ***Submerged bend way weirs*** placed at the upstream of bend redirects the water flowing along the eroding bank at an angle perpendicular to the weir.

When the weirs are angled upstream water is directed away from the outer bank and toward the inner bend. The stream's strongest secondary current (helical flow) in the bend is broken up. **Fig.5** shows different types of barrier across the river.



(a) Groynes (b) Permeable spurs

Figure 5: Barriers across the river

Fukuoka (1989) discussed that vanes are used to change the velocity distribution of current entering into the bend in meandering channel as uniform as possible by reducing lateral bed gradient. The principle of bank erosion protection by using vanes is that the secondary current due to the centrifugal force is offset by secondary current due to the vanes. It is more rational to consider that vanes deform the flow field locally with resultant reduction of scour of the riverbed near the outer bank.

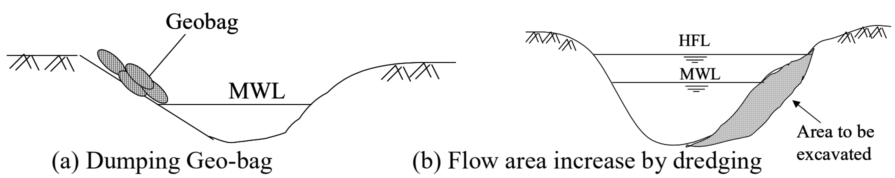
(b) Non-structural measures

Non-structural measures are taken against short-term protection. Some examples of non-structural measures are described below:

(i) ***Flow area increase by dredging*** Shallow area of the channel is dredged and the area of flow is increased, which reduces flow velocity.

(ii) ***Flow diversion at the upstream of the problem area by channelization***: The upstream approach of the problem area is re-channelized by dredging by pass channels and flow is regulated in the mid stream channel.

(iii) ***Geo-bag dumping***: Geo-bags are dumped on the slope of the bank to arrest the bank on temporary basis. **Fig.6** shows different types of non-structural measures.



(a) Dumping Geo-bag (b) Flow area increase by dredging

Figure 6: Non-structural bank protection measures

(c) Biological protections

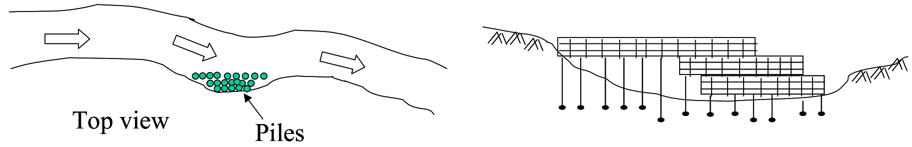
There are techniques other than traditional approaches those are practiced all over the world, known as, bioengineering practices. The widely used biological protection measures are:

(i) ***Bank vegetation*** Vegetation directly protects banks from erosion by reducing the near bank shear stresses. Larger vegetation deflects flow. Vegetation offers the additional benefit of modifying soil properties, increasing soil strength due to the reinforcing properties of roots and lowering pore water pressures.

(ii) ***Wooden piling***: Wooden logs are piled along the bank toe to arrest erosion.

(iii) ***Willow posts***: This technique is the means of controlling stream bank erosion through the systematic installation of posts to stabilize eroding banks. It lowers floodwater velocity on and near the eroding bank. Planting large willow cuttings (10 to 30 cm dia; 2 to 4 m long) has been widely practiced in the United States for halting bank erosion and restoring riparian zones (Watson et al. 1997; Shields et al. 1995). Willow posts are emplaced along the stream bank from the water edge landward using 3-5 rows spaced nominally 1 m apart.

(iv) ***Bandallings***: Bandals are placed on the principles that bandals provide partial lateral and vertical obstruction to the approach flow and induce fewer disturbances to the river flow. The key issues of bandals for the control of water and sediment are non-uniform vertical distribution of suspended sediment. Within the lower half of the flow depth, major portion of the sediment flow is concentrated.



(a) Wooden Piling (b) Crisscross porcupines

Figure 7: Biological protections

(v) ***Crisscross porcupines***: Bamboo or wooden porcupines are placed across the river, which sometimes work to dredge and stabilize the bank by depositing sediments

(vi) ***Log hard points***: The log hard points are composed of log bundles 20 m in length buried 10 m into the bank with approximately 25 tons of stones placed around the toe of the structure to protect against scour. Fig.7 shows different types of biological protections.

8. IMPORTANCE OF PHYSICAL SCALE MODEL STUDY IN BANK PROTECTION WORKS

Due to its numerous advantages, scale model is a widely practiced reliable tool to optimize alternative structures and design parameters, particularly for river training and bank protection works. Scale model study on protection of Kazipur area from the erosion of Jamuna River is discussed here to justify the argument.

Kazipur is situated on the right bank of Jamuna River suffered from flooding and continuous bank erosion. To mitigate the flood problem, Bangladesh Water Development Board (BWDB) constructed a flood embankment along the right bank. But due to continuous bank erosion, this flood embankment was also under threat and partly had washed out. The shifting of the bank line was a continuous process and from the past history of bank line shifting it was easily understood the devastation nature of bank erosion. To save the valuable land and properties BWDB had decided to construct a T-head groyne to divert the flow towards the midstream. A scale model study was conducted at River Research Institute (RRI) to find out the effectiveness of this hard measure and also find out an appropriate hydraulic structure and its location to stop the bank erosion. But after a series of test runs in the scale model, three groynes were recommended instead of single groyne along with the optimum design parameters of the groynes, size of the riprap and length of the falling apron (Details may be foun in RRI, 1996). But considering huge cost, series of spurs were proposed by the client and then tested in the scale model. Based on the test results, seven spurs were recommended to protect 5 km area (Details may be found in RRI, 1998a) as shown in Fig.8. The type of model spur is shown in Fig.9.

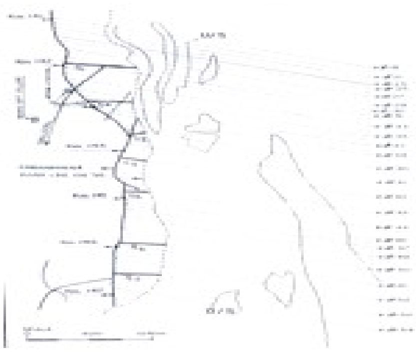


Figure 8: Location of spurs at Kazipur based on physical model study

Figure 9: Scale model run showing a spur at Kazipur

In physical scale models, recent bathymetries are used and the future bank line shifting is considered to recommend suitable bank protection works. For site selection of structures length and extent of bank erosion is prerequisite.

9. ECONOMIC ANALYSIS

The optimum design of a bank protection work, the height of a revetment along riverbank for example, will be when the difference between the benefit and the cost of protection (net-benefit) is maximum. Conceptually, if the structure is constructed larger than the optimum design the 'net-benefit' will be reduced and if the structure is smaller, the net-benefit also will be reduced. So, over-design or under-design both have the similar shortcomings. At one extreme, if the costs actually exceed the benefits we have so over designed the structure that the design would be criticized under any sensible policy of public spending. On the other hand, if the costs are less than the benefits we have under designed the structure to a similar extent. But this may be inevitable if there are no public funds.

The cost of protection is assumed to have a fixed component and to then increase proportionally with the cube of the height. The annual value of a protection may be estimated from the damage-probability relationship based on a probability of exceedence of a certain height, *h* (details presented in Ahmed, 1994). A plausible cost model as proposed by Ahmed (1994) is given by,

$$C = a + bh^3 \tag{7}$$

where, C is the cost, a is the fixed cost element, b is a constant of variable cost component and h is the height of protection work.

Fig.10 shows a typical cost-benefit relationship when probability of exceeding a height is h. Based on simulation results, Ahmed (1994) proposed optimum and sub-optimum design strategies for selection of bank protection works as shown in Fig.11.

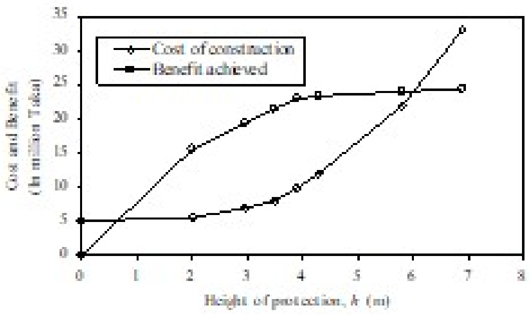


Figure 10: Benefit-cost relationship when Pr(X>h)

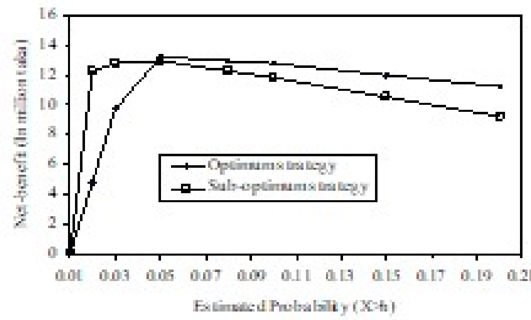


Figure 11: Comparison of optimum strategy and sub-optimum strategy with estimated probability of exceedence

10. CONCLUSIONS

Before design of appropriate bank protection measures, bank erosion should be assessed by available predictive methods and tools using required hydraulic data, morphological data, sediment data, soil properties and bank characteristics. Near bank flow velocity and shear stresses are two governing parameters to consider while predicting bank erosion. To take appropriate bank protection measures, on-site assessment of the bank erosion and failure should be considered, as there might have several mechanisms those needs due attention and further research. Physical scale model study has been proved to be a useful tool for sound engineering judgment in selecting technically feasible structures. The recommendations based on physical model study results should be timely and properly implemented and post-construction maintenance should be done so as to make it sustainable. As the flood intensity and frequency varies temporally, no structure should be implemented based on assumptions or experiences from the other projects. Finally, economic analysis must be done to select cost-effective structures.

ACKNOWLEDGEMENT

The author is grateful to Dr. Engr. A.M.M Motaher Ahmed, Ex .Senior Scientific Officer, River Research Institute for his support in preparing the manuscript.

REFERENCES

Ahmed A. M. M. M; "Economic benefit of improving the accuracy and precision of flood predictions", M.Sc. Eng. Thesis (unpublished), University of Newcastle-upon-Tyne, England, 1994

Bagnold R. A.; "Some aspects of the shape of river meanders", US Geological Survey: Professional Paper 282E, pp.135-144, 1960

Darby S. E. and Thorne C. R.; "Numerical simulation of widening and bed deformation of straight sand bed channels", I: Model development, J. of Hydraulic Engineering, ASCE, Vol. 122 (4), pp.184-193, 1996

DELFT/DHI: River Survey Project, Final Report – Annex 5, Morphological Characteristics, Dhaka, Bangladesh, pp. 10.1-10.22, 1996

Hagerty D. J. and Hamel J. V.; "Geo-technical aspects of riverbank erosion) In Proceedings of the 1989 National conference on Hydraulic", Engg. (Micheal A. Ports eds.), pp.118-123, 1989

Hickin E. J. and Nanson G. C.; "Channel migration and incision on the Beatton River", Journal of Hydraulic Eng. ASCE, vol. 109, No. 3, Mar, pp. 327-337,1983

Hickin E. J. and Nanson G. C.; "Lateral Migration Rate of River Bends", Journal of Hydraulic Eng. Asse. Vol. 110, No.11, November, pp 1557-1567, 1984

Hickin E. J. and Nanson G. C.; "The character of channel migration on the Beatton River", Northeast British Columbia, Canada, Geological Society America Bulletuin, Vol. 86, pp. 487-494,1975

Klaassen, G. J. and Masselink, G.; “Planform changes of a braided river with fine sand as bed and bank material”, Proc. Fifth Intl. Symp. on River Sed., Karlsruhe, pp.459-471,1992

River Research Institute: Physical model study to investigate the extent of bank erosion along east and west bank at the downstream of the Jamuna Bridge, Final Report, Faridpur, Bangladesh, 1998b

River Research Institute: Scale model investigation for the protection of Kazipur area from the erosion of Jamuna river, Draft Final Report, Faridpur, Bangladesh, 1996

River Research Institute: Scale model study for the protection of Kazipur area from the erosion of Jamuna River (additional tests), Final Report, Faridpur, Bangladesh, 1998a

River Research Institute: Study of bank erosion at Nakalia Pechakhola, Bera, Pabna from the erosion of the Jamuna River, Research Report, Faridpur, Bangladesh, 2000

Shields Jr., F. D., Bowie A. J. and Cooper C. M.; “Control of stream bank erosion due to bed degradation with vegetation and structure”, Water Research Bulletin, Vol. 31(3), pp. 475-489, 1995

Thorne C. R. and Osman A. M.; “River bank stability analysis”, II: Applications, J. of Hydraulic Engineering, ASCE, 114 (2), pp.151-172, 1988