

RIVER BANK EROSION AND SUSTAINABLE PROTECTION STRATEGIES

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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. Treatment of bank erosion is usually expensive and is not particularly susceptible to engineering analysis. Because diagnosis and prediction of bank erosion is often difficult as it may be caused by a number of factors operating separately or together. Engineers play a dominant role to design the optimum bank protection works, which sounds justified both technically and economically. 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.

Key Words : river bank erosion, sustainable strategies, bank protection works

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



Fig.1 Typical Bank erosion along the Jamuna Right Bank

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.

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 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 embankments 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 & MECHANISM

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; Thorne 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:

- 1) Steepening of bank slopes caused by erosion of lower part of the slope and riverbed near the slope toe.
- 2) Slip failure of the steepened bank slope by losing its stability.
- 3) Movement of failed bank material toward riverbed along the slip surface.
- 4) 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.

4. FACTORS TO CONSIDER IN BANK EROSION ASSESSMENT

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

1. Hydraulics (stage-discharge, flow structures, flow resistance, maximum near-bank velocity, distribution of shear stress, secondary currents and turbulence, water level variations).
2. Morphology (Riverbed deformation by computing bed shear stress, bed topography, channel planform, migration of bar and bed shear stress).
3. Sediment transport (suspended sediment, bed load, wash load).
4. Stability of banks and riparian structures (vegetation, bank angle, critical bank height is a function of bank angle, tension crack depth).
5. 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, gives 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

$$E = f(\Omega, \gamma_b, h, R_c, w) \quad (1)$$

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

$$\Omega = \gamma Q i \quad (2)$$

where, $\gamma (= \rho g)$ is the specific weight of water, Q is discharge, i is slope. Eq.1 may be expressed by a non-dimensional form as

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

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

$$\frac{Eh}{w} = k \frac{\Omega}{\gamma_b} \quad (4)$$

Measurements on the Beaton 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)

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

in which Δw = bank erosion distance (m) in one bank; τ_c = critical shear stress (dynes/cm²) for cohesive soils; v = soil unit weight (KN/m³) ; τ = average shear stress (dynes/cm²) and Δt = computational time interval in minutes.

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

$$\tau = \mu \frac{du}{dy} + \rho \varepsilon \frac{du}{dy} \quad (6)$$

where, $\frac{du}{dy}$ 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.

Prediction of bank erosion rate along Jamuna River, Bangladesh

The bank line migration of the Jamuna left bank downstream of Bahadurabad calculated from SPOT images indicate 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

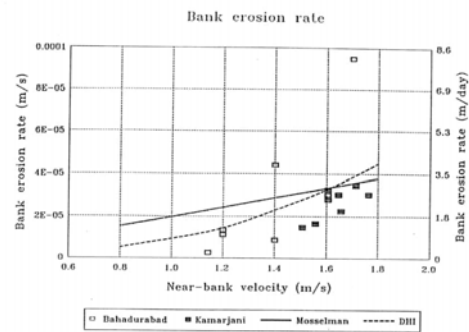


Fig.2 Comparison of bank erosion rate estimates in relation to near bank velocity

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.

Failure due to piping in non-cohesive riverbank have 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 1975-2000.

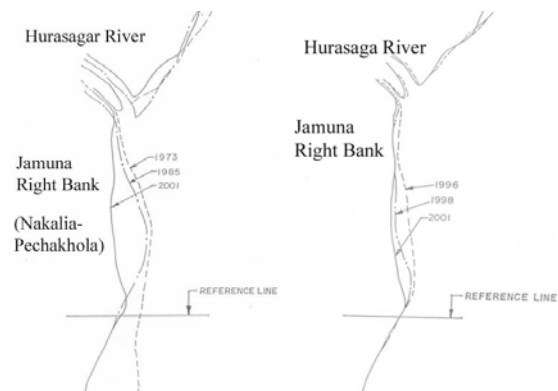


Fig.3 Bank shifting at Nakalia-Pechakhola (1973-2001)

River Research Institute, 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 1975-2001 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).

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.

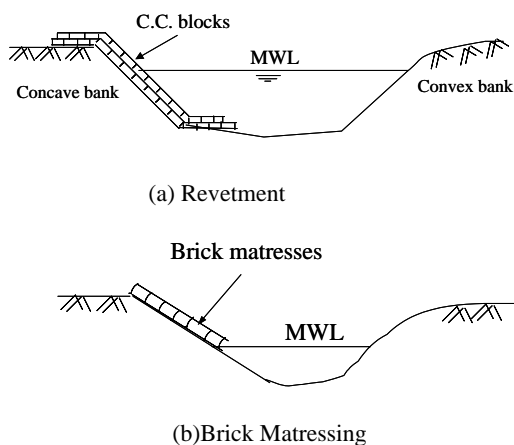


Fig.4 Hard material protections

Barrier across the river

This method is known as 'redirectional bank stabilization method'. The objective is to redirect 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.

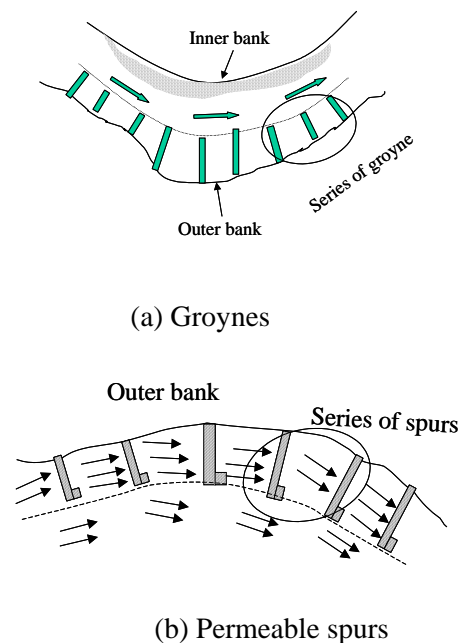


Fig.5 Barriers across the river

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.

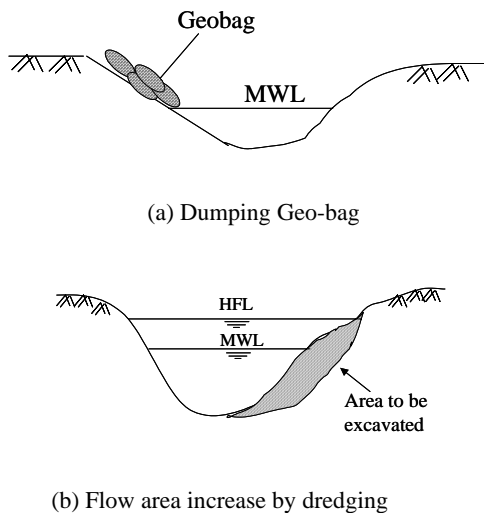


Fig.6 Non-structural bank protection measures

(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 bandalls 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. 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.

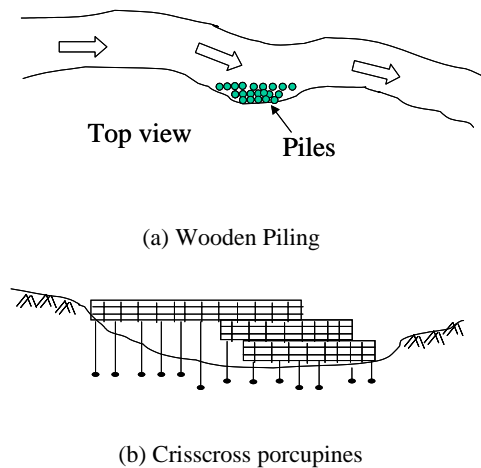


Fig.7 Biological protections

8. PHYSICAL SCALE MODEL NEEDS 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 found 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.

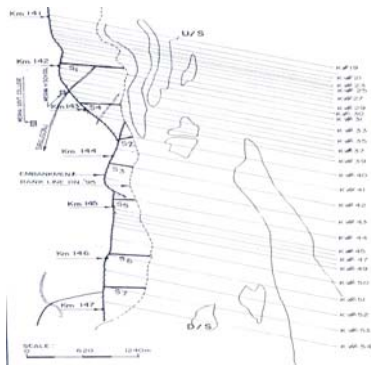


Fig.8 Location of spurs at Kazipur based on physical model study



Fig.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 of structures, length and extent of bank erosion is prerequisite. The study suggests carrying out scale model investigations prior to choice a technically sound and economically justified protective measures.

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,

$$C = a + bh^3 \quad (7)$$

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

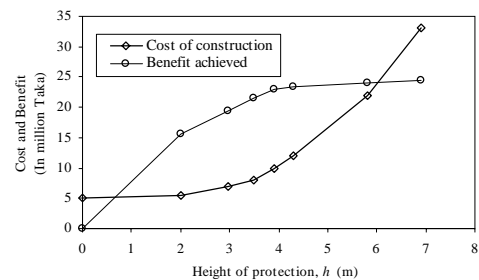


Fig.10 Benefit-cost relationship when $\text{Pr}(X>h)$

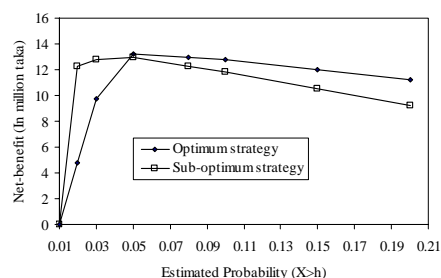


Fig.11 Comparison of optimum strategy and sub-optimum strategy with estimated probability of exceedence

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.

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