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Erosion Threat Analysis for the Stability of a Sedimentary Deposit in a Tidal River

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Abstract

Erosion-deposition which is the outcome of flow-sediment interaction, is very complex in a tidal environment because of dynamic nature of tidal flow and varying physiochemical properties of sediment particles. Tidal environment always attracts human settlements by its valuable ecosystem and natural resources. Any unplanned anthropogenic intervention may intervene the natural flow-sediment regime and exacerbate the complexity of erosion-deposition dynamics which may cause instability to the tidal river course and damages infrastructure built therein. In this study, detail flow and sediment measurements are done in a tidal reach of the river Pyra located in the southern region of Bangladesh to assess future erosion threat for a sedimentary deposit alongside the river bank. The analysis revealed that flow induced mobilizing force is much stronger than the resisting force offered by the bed and bank materials which consists of sand-mud mixtures. It is also learnt that the site remains in sediment deficit condition whose intensity varies with time and space. This deficit sediment is supplied from bed and bank erosion which is a great concern for the stability of the site and installations therein unless any protection measures are undertaken. Therefore, the availability of new landmass/sedimentary deposit should not be the only criterion for selecting a project site and residual flow-sediment regime need to be consider as an additional parameter for such decision-making process.

Keywords: *erosion-deposition, flow-sediment interaction, sediment transport, anthropogenic intervention, sediment deficit and surplus condition*

1. Introduction

Tidal river courses are the most distinctive and important features of coastal environments. For its valuable ecosystems and natural resources tidal river basins are always being attracted by human settlement and development activities which in turn put on stresses on eco-morphology of this delicate environment (Cox et al., 2022). When the equilibrium flow-sediment regime of a river reach is disturbed by any natural or anthropogenic interventions, the river responses in different ways by changing its biophysical process through aggradation, degradation and planform changes. As part of wider development plan, the Government of Bangladesh has planned to establish a large build up area on a sedimentary deposit developed in last 40 years alongside the right bank of a tidal river located the southern region of Bangladesh. It is observed that the said sedimentary deposit already experiences intermittent erosion. This intervention to the natural system may change the flow-sediment regime and exacerbate the erosion scenario and consequently imposes serious threat to the stability bank/sedimentary deposit and infrastructures built therein.

The sediment transport process which is the outcome of both flow and sediment interaction, can be regarded as the threshold to cause erosion or deposition. (Chen et al., 2021a). When flow induced mobilizing force is greater than stabilizing force offered by the bed or bank materials, erosion occurs. Tidal river is characterized by continuous spatial and temporal variation of flow velocity, tidal height, discharge, slack period etc. which in turn, changes the mobilizing fluid force. Again, most of the natural fluvial bed material and sedimentary deposits consist of non-uniform particles of varied physiochemical properties (Chen et al., 2021b) and hence they exhibit different erosion-deposition/transportation behavior. Coarse-grained sediment particles (>0.063 mm) exhibit non-cohesive behavior and primarily transported as bed load (in the form of sliding, rolling, jumping/saltating) (Bisschop et al., 2016) whereas fine-grained sediment particles (<63 μm) exhibit cohesive behavior (Zuo et al., 2017) and primarily transported as suspended load (Guo et al., 2018). Again, most of the natural bed materials exist as sand-mud mixtures which behave as cohesive particle when mud fraction is dominant otherwise they behave like non-cohesive particles (Chen D; 2021b). In summary, the sediment transport / erosion-disposition process is very complex in a tidal river because of dynamic nature of tidal flow and varying physiochemical properties of bed and bank materials. Therefore, before undertaking any settlement or development project (any physical intervention) in a delicate tidal environment, it is essential to know the erosion-deposition dynamics of the site. From such perspectives, the objectives of this study is set to measure relevant flow and sediment parameters of the study site and analyze those parameters for predicting future erosion–deposition threat/potential and its impact of on any settlement projects with a view to protect the infrastructures therein.

2. Study Area

The study site is a tidal reach of the river Pyra, located at Lebukhali which is about 60 km upstream from the mouth of Bishkhali/Burishwar estuary. The river flows between the district of Barisal and Patuakhali in the southern region of Bangladesh. In the upstream, the river is connected with the Meghna River through the Tentulia river via the Karkhana river in the east and Kirtankhola river in the north and finally falls into the Bay of Bengal by the name of Pyra River and Galachipa river (Figure 1a). The site falls in the central estuary system of GBM delta and transports enormous fresh water and sediment under the influence of tidal exchange and other fluvial and marine processes.

(a) (b)

Figure 1: (a) Overall study area with surrounding districts, river system and estuary, (b) Study site details, 22.274490°N, 90.173525°E to 22.301957°N, 90.214919°E. ADCP run lines (—) and sediment sample, water level data location (●), Inset: Bank line erosion scenario

3. Materials and Methods

3.1 Erosion-suspension-deposition dynamics

During accelerating flow when the flow induced bed shear velocity (u_*) exceeds a critical value for motion ($u_{*,cr,motion}$), erosion is initiated and particle moves as bed load by sliding or rolling or jumping/saltating along the bed in a thin layer. With further increase of velocity, when u_* exceeds the critical shear velocity for suspension ($u_{*,cr,suspension}$), the particle goes into suspension and moves as suspended load (Bagnold, 1966; Hinze, 1975; Guo et al., 2018). These suspension/movement continue till u_* induced by decelerating flow become less than or equal to particle fall velocity (w_s). With $u_* \leq w_s$, the suspended particles start settling, first coarser then finer particles. The settling process continues during the slack water period until the start of a new erosion cycle. The critical shear velocity for motion and suspension can be calculated from the following equations (van Rijn, 1984, 2022):

$$u_{*,cr,motion} = \sqrt{\theta_{cr,motion}(s-1)gD_{50}} \quad (1)$$

$$\text{and } u_{*,cr,suspension} = \sqrt{\theta_{cr,suspension}(s-1)gD_{50}} \quad (2)$$

$$\text{where, } \theta_{cr,motion} = \frac{0.3}{1+D_*} + 0.055[1 - e^{-0.020D_*}] \quad \text{for } D_* > 0.2 \quad (3)$$

$$\text{and } \theta_{cr,suspension} = \frac{0.3}{1+D_*} + 0.1[1 - e^{-0.05D_*}] \quad \text{for } D_* > 1 \quad (4)$$

Here D_* is the dimensionless grain size parameter, $D_* = [\frac{(s-1)g}{\nu^2}]^{1/3} D_{50}$, with ν = kinematic viscosity of fluid, s = specific density ($s = \rho_s/\rho_w$), and D_{50} = median grain sizes. (Shields, 1936; Soulsby, 1997; van Rijn, 2020). There are many empirical relations developed for the determination of settling velocity (Cheng, 1997). Among them following formulae) may be useful for marine environment (Soulsby, 1997; Dorrell, 2021):

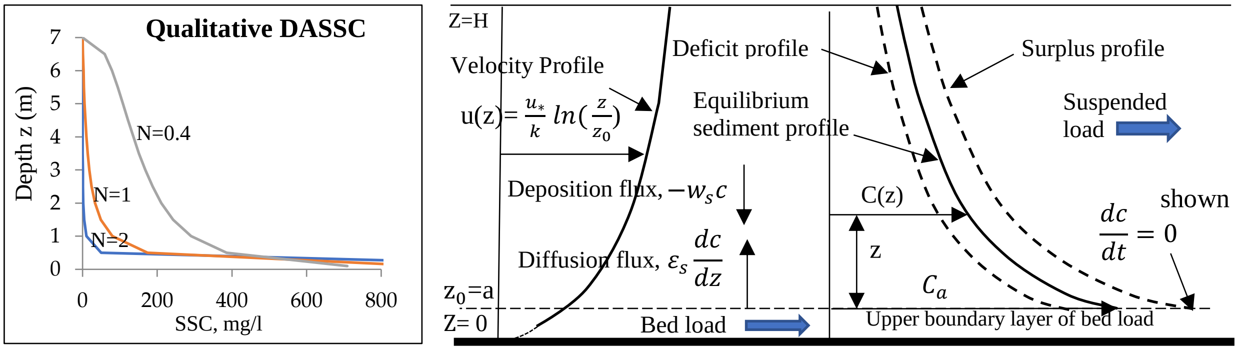
$$w_s = \frac{\nu}{D}[(10.36^2 + 1.049D_*^3)^{\frac{1}{2}} - 10.36] \quad (5)$$

where, D is the mean grain size assumed as D_{50}.

From the concept of equilibrium sediment concentration profile at upper boundary layer of bed load ($-\boldsymbol{w_s C(z)} = \boldsymbol{\varepsilon_s \frac{dC(z)}{dz}}$, Figure 2a), the depth averaged SSC profile can be derived as follows (Rouse, 1937; Van Rijn, 1984; Keetels et al., 2018; Shiqian et al., 2017):

$$c(z) = c(a)\left[\left(\frac{h-z}{z}\right)\left(\frac{a}{h-a}\right)\right]^N \quad (\text{with } N = \frac{w_s}{\beta\kappa u_*}) \quad (6)$$

where, $c(a)$ = reference concentration at reference level a above river bed, h = flow depth, z =height above the bed level, κ = von Karman constant and β = dimensionless proportionality coefficient related to diffusion of sediment particles. Here, N is known as suspension number or Rouse number which determine the relative distribution of SSC over the depth of fluid (van Rijn, 1984). The lower the value of N, the more uniformly sediment is distributed over the depth of flow. For N=5, SSC is more in near-bed layer (z<0.1h); for N=2, SSC remain spread up to mid depth (z<0.5h); for N=1, SSC remains distributed up to water surface (z<h); for N=0.1, SSC is almost uniformly distributed over whole water depth (van Rijn, 2022). Qualitative SSC profile for different N values are shown



(a) (b)

Figure 2: (a) Qualitative SSC profile for different Rouse Number, N. (b) Concept of equilibrium, deficit and surplus sediment concentration profiles (Islam & Rahman, 2022)

Figure 2b.

Quantitatively, if the measured sediment concentration profile follows or lags the equilibrium concentration profile (estimated by Eqn. 6), the hydraulic condition is recognized as sediment deficit (SD) condition which would be subjected to erosion, and if the measured sediment concentration leads the estimated equilibrium concentration profile, the condition is considered as sediment surplus (SS) condition which would be subjected to deposition.

3.2 Flow and sediment data measurement

In this work, different sensors were deployed to measure the temporal and spatial changes of flow and sediment parameters. Flow velocity and discharge data were measured using ADCP and water level data were measured using total station with RTK GPS and gauge staff at locations shown in Figure 1b. The instrument was run from right bank to left bank and all measurements were made following Win River II manual. Measurements were taken at 30-minute interval for 12 hours to capture the variations within one complete tidal cycle.

Sediment concentration at 2 m height from the bed were measured through turbidity measurement by OBS at two locations (shown in Figure 3) covering a period of a complete tidal cycle from 7.00 a.m to 7.00 p.m. Water samples were also collected from same locations and height using improvised sample collector. These samples were tested on the laboratory for SSC which were used for calibrating the turbidity measurement recorded by OBS-3A. Water samples were also collected manually from different depth to know the depth average suspended sediment concentration DASSC) during full tide, full ebb, half tide and half ebb. Bed and bank materials were collected from river bed and banks of two locations of the study site and gran size distribution were done in the laboratories.

4. Result and discussion

Table 1: Grain size limit classifications (ASTM D 7928-17) and median grain size (D_{50})

Location	Gravel (>4.75)	Sand (4.75 - 0.075 mm)			Silt (0.075 -0.005)	Clay (0.005-0.001)	D_{50} (mm)
		Coarse sand (4.75-2.00)	Medium sand (2.00-0.425)	Fine sand (0.425-0.075)			
Bed Soil	0%	0.0%	2-3%	67-70%	22-25%	1-8%	0.1049
Bank Soil	0.0%	0.0%	0.0%	4-5%	80-86%	10-15%	0.0205

Riverbed and bank material samples were analyzed in the laboratories and the result are shown in Table 1.

The grain size classification shows (Table 1) that both bed and bank materials consist of sand-mud mixtures with more than 90% finer particles which implies the eroded particle will easily move as suspended load. Particle size <0.063 mm is more than 10-15% for bed material and more than 60-80% for bank material. Again sand particle (>0.063 µm) is more 60% for bed material and very less for bank materials. Therefore, bank material will behave like cohesive and bank material will behave like weakly cohesive (Chen D et al., 2021; van Rijn L C 2007).

From the sediment data, D_* are calculated as 2.4 and 0.47 for bank and bed materials respectively. Here s = 2.6, ν for $15°\text{C} = 1.15 \times 10^{-6} m^2 s^{-1}$ [Islam and Rahman, 2022). Average $\theta_{cr,motion}$ and $\theta_{cr,suspension}$ are determined as 0.10 and 0.21 for bed and bank respectively (Eqn. 3 and 4). Particle settling velocity w_s is determined 0.73 cm/s (Eqn. 5). $u_{*,cr,motion}$ and $u_{*,cr,suspension}$ are also calculated as 1.2 cm/s and 1.3 cm/s for bed materials and 080 cm/s and 0.82 cm/s for bank material respectively (Eqn. 1 and 2).

Vertical velocity profiles of two locations at about 20 m away from the bank line were retrieved from ADCP records during both ebb and flood peaks and shown in Figure 4. Flow induced bed shear velocity (u_*) is determined by the well-known law of the wall (van Rijn, 1984) $u_* = \frac{uk}{\ln(\frac{z}{z_0})}$, where $u =$ time-averaged near-bed velocity, $k =$ von Karman's constant usually taken as 0.41, z_0 = 0.1 m (Islam and Rahman, 2022). From the measured data, u_* are found to vary from 5.4 cm/s (peak flood) to 6.3 cm/s (peak ebb) and 7.4 cm/s (peak flood) to 8.5 cm/s (peak ebb) for upstream and downstream locations respectively.

From the analysis of flow and sediment data, it is revealed that flow induced bed shear velocity $u_* > both\, u_{*,cr,motion}$ and $u_{*,cr,suspension}$, for the whole site (upstream and downstream), therefore, both erosion and suspension followed by transportation of bed and bank materials occurs in the study reach. Again, from measured flow and sediment data, it is found that Rouse number N varies from 0.22 to 0.35 which is less than. This implies that most of the eroded particles remain distributed over the depth of water and moves as suspended load which is evident from field measured depth average SSC (DASSC) shown in Figure 5. Again, peak ebb velocities are greater than peak flood velocities (Figure 4), therefore the site is a peak current asymmetric site which causes the suspended sediment to move in downward direction.

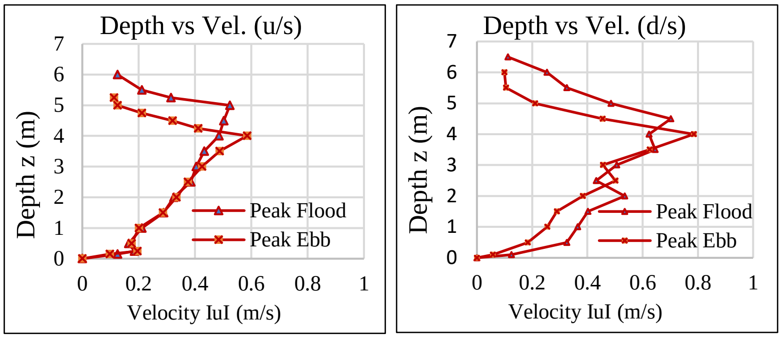


Figure 4: Depth average flow velocities of upstream (VIP ghat) site and downstream (OBM ghat) site

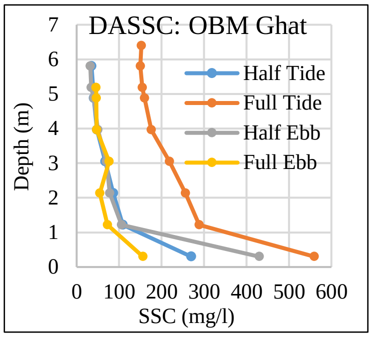
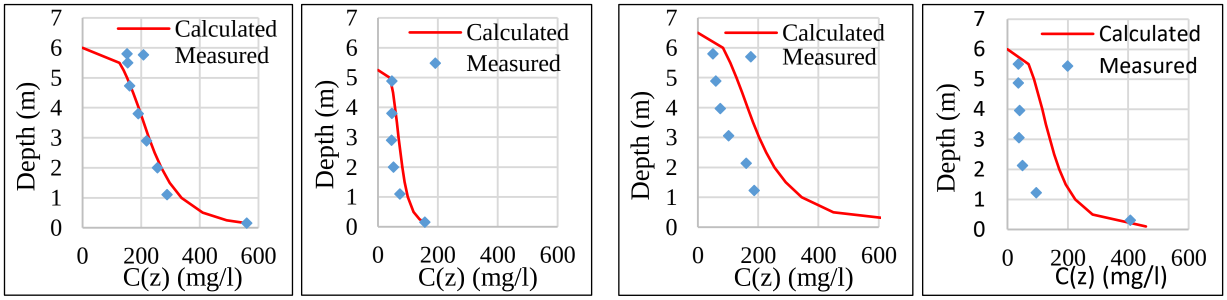


Figure 5: Measured DASSC at downstream location

The equilibrium profiles for SSC are calculated using Equation (6) for both the upstream and downstream locations for full tide (FT) and full ebb (FE) conditions. The profiles are compared with the measured SSC profiles (Figure 6). The selection of reference level 'a' and corresponding reference concentration 'C(a)' are important to have an accurate distribution profile and those are discussed in details by Islam and Rahman (2022).

DASSC profiles: Measured profile vs. Estimated profile



(a1) (a2) (b1) (b2)

Figure 6: DASSC profiles: measured profiles vs. calculated/estimated oncentration profiles. Upstream VIP Ghat: (a1) full tide (FT), (a2) full ebb (FE) and downstream OBM Ghat: (b1) full tide FT, (b2) full ebb FE

The profiles show that the measured concentration profiles lag the equilibrium concentration for all conditions and all locations which implies the whole study site is in SD condition and subjected to erosion. Again, the difference between measured concentration and equilibrium concentration is less in the upstream location (Figure 6 a1 & a2) with lesser water depth, but more in the downstream location (Figure 6 b1 & b2) with greater water depth. Besides, in both locations, the differences between measured and equilibrium concentrations are found less during full tide than full ebb. Thus the analysis revealed that the whole reach remains in SD condition with higher margin in downstream location and during ebb phase than upstream location and flood phase. To balance this deficit condition, required sediment is supplied through bank or bed erosion, and the upstream location and during flood phase.

5. Conclusion

The analysis of flow and sediment data reveals that flow induced bed shear velocity is much higher than the critical shear velocity to cause erosion and suspension of both bed and bank materials which are consist of sand-mud mixtures with greater parentage of fine particles (>90%). Besides, suspension number is found < 1 (i.e., 0.22-0.35).

Therefore, most of the eroded particle remains in suspension over the whole depth of water and moves as suspended load. And peak current asymmetry (ebb asymmetric) character of the study site causes this movement in seaward direction.

The analysis also found that the study site remains in SD condition throughout the tidal cycle with bigger deficit during ebb phase than flood phase as well as in downstream location with higher depth than upstream location with lower depth. These deficit sediments are supplied from bed and bank erosion which consequently make the channel unstable (leading towards the failure/unsustainability of the project site).

The methodology adopted in the present study to evaluate erosion-deposition dynamics through sediment deficit-surplus condition can identify the river reach whether it will be an eroding or siltation dominated site which in turn will create the ground for technical justification in selecting a settlement/development project site and in deciding whether the site needs any protection measures to ensure the physical stability of the project.

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