MIGRATION CHARACTERISTICS OF MEANDERING CHANNELS BASED ON RIVER MORPHODYNAMICS

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ABSTRACT

Present research is aimed to test the possibility of using a mathematical model, based on river mechanics principles, as a tool to assess the migration characteristics of meandering rivers. Sand and silt bed rivers are dominating in Bangladesh. The rivers also carry a huge amount of sediment from the upstream reaches. These factors combined with seasonal change of flow discharge have contributed to the morphological characteristics of the rivers. Shifting of channel, excessive scour of fine bed materials, meander development and migration intensify bank erosion. Some difficulty for evaluating bank erosion hinders the proper planning for river management. Therefore, topics associated with channel shifting and bank erosion have been chosen for present study.

Scouring of curved channels and migration of meandering channels were studied using existing models in order to obtain information for river management. Special attention was paid for applicability of the models to the Madhumati River in Bangladesh. In order to evaluate local scouring resulting from curved flows, bed topography models developed by Engelund (1974) and Ikeda (1974) were reviewed and their validities were investigated. In those models, the secondary flow plays an important role on the relation among the direction of sediment particle migration, direction of fluid force and transverse bed slope and is taken into account through the transverse bed slope parameter. It was found that transverse bed profile can be computed fairly well by the model developed by Ikeda (1974). Maximum scour depth can also be predicted by means of this model supposing the side bank is composed of non-erodible wall.

Prediction of channel shifting using numerical simulations was identified as an important tool to conduct site adaptive countermeasures in river management. The meander migration models proposed by Ikeda et al. (1981) and by Hasegawa (1989) were applied to predict the migration of a meander bend of the Madhumati River and were examined by comparing the simulated results and corresponding field data. Ikeda et al.'s model which was proposed originally to evaluate dominant wave lengths of meandering channels is able to discuss the channel migration based on a linear relation between the excess velocity and bank erosion rate. Hasegawa's model, which is based on the same linear relation as Ikeda et al.'s, includes the erosion rate formula that is derived from integration of sediment continuity equation. It is found that the both model could be acceptable for evaluating the channel shift although some improvements may be necessary. Especially, Hasegawa's model will predict well the bank erosion and corresponding channel shift if the flow width is specified carefully. Nevertheless, such meander migration models provide a valuable and easy-to-use tool to analyze migration characteristics of meandering channels.

Keywords: Meandering channel, Migration characteristics, River morphodynamics.

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INTRODUCTION

Bangladesh is located in a low-lying delta where more than three hundred alluvial channels have made an intricate network of rivers. The total length of the river network including tributaries and distributaries is more than 150,000 km. The floodplains and river reaches consist mainly of recent alluvial deposits. The soil material is fine-grained and the ground is loosely packed or unconsolidated. The rivers also carry huge amount of sediment from the upstream reaches. These factors combined with seasonal change of flow discharge have contributed to the morphological characteristics. Shifting of channel, excessive scour of fine bed materials, meander development and migration frequently intensify bank erosion. Throughout the country about 1200 km of riverbanks are under severe erosion problem (Figure 1). Around eight thousand hectares of lands are eroded every year. The impact of land loss involves primarily the loss of homestead land, housing structures, crops, trees and households. Loss of homesteads force people to move to new places without any option and puts them in disastrous situation. The human environment, riparian ecosystem and the biological habitat in the rivers and floodplains are thus disrupted or destroyed. Therefore, river bank erosion has been identified as a type of disaster in Bangladesh.

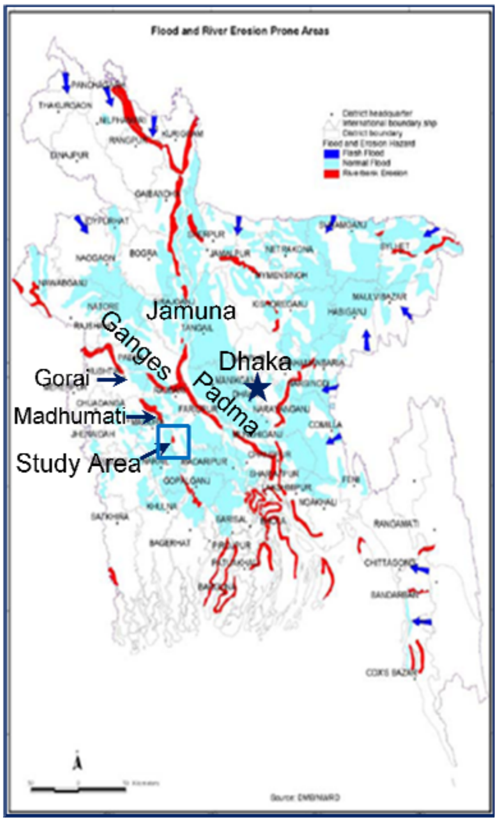

Fig. 1 River bank erosion and flood prone areas

Difficulties in river bank erosion control in Bangladesh arise both from economical or financial and technological reasons. Economic and financial constraints appear due to very low return from the investment. This implies that only the priority sites can be brought under structural measures. However the location and extent of bank erosion is not yet predictable in reasonable time ahead. Some difficulty for evaluating bank erosion hinders the proper planning for river management. Therefore, topics associated with channel shifting and bank erosion is chosen for present study. Present research is aimed to test the possibility of using a mathematical model, based on river mechanics principles, as a tool to assess the migration characteristics of meandering rivers.

STUDY AREA

The Madhumati River originates from the Ganges River and its channel length is 199 km. It passes through the south-western region in Bangladesh. The Madhumati River showed a typical meandering behavior and migrated very actively throughout the period of record. The study area is Mallikpur bend on the river (Figure 2). It is approximately 1.88 km long. The bend is becoming

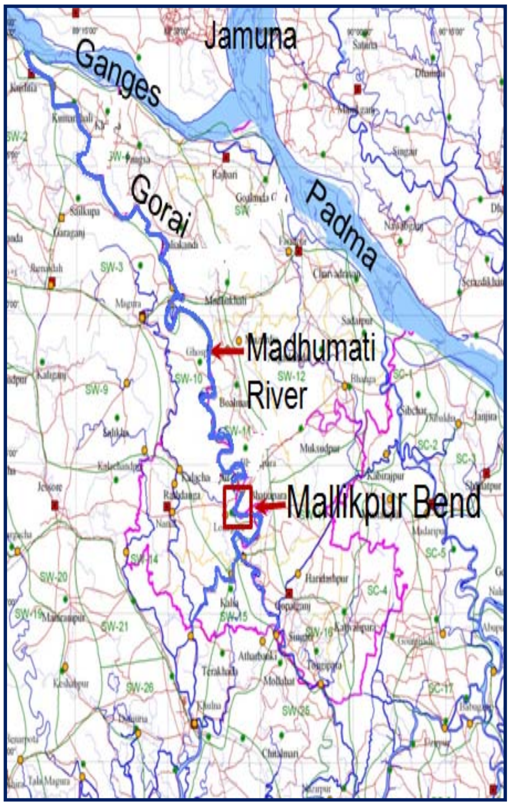

Fig. 2 Location of study area

sharp year by year resulting from severe bank erosion. The river has shown a tendency to coincide with the neighboring Naboganga River through this bend. The morphological changes of the river are shown in Figure 3. In 1973, the shortest distance between these two rivers was 3.85 km. This distance has been reduced to 2.64 km in 1984 and 1.7 km in 1997 (Sarker et al. 1999). The meander bend migration is still active. The reach has shown a considerable amount of migration for latest several years.

METHODOLOGY

Local scouring and bed topography in curved channels of constant curvature with non-erodible banks were studied in order to obtain important results for river improvement works. Models developed by Engelund (1974) and by Ikeda (1974) were reviewed and applied to local scouring to test their validities (Table 1). Secondary flow is the key factor for the asymmetric cross-sectional profiles in curved channels. In those models, the secondary flow plays an important role on the relation among the direction of sediment particle migration, direction of fluid force and transverse bed slope and is taken into account through the transverse bed slope parameter. Application of the methods is conducted assuming fully developed flow in the meander bend. The width of the equivalent rectangular channel was estimated from the bankfull geometry and flow properties using a definition equation as $B_{eq} = Q/(UH)$ and found equal to 287m. The channel centerline curvature was obtained from planform analysis of satellite images and estimated to be 0.00148/m (radius = 677m). In order to apply Engelund's model, the transverse bed slope parameter A was supposed to be 4 according to his experimental results. Whereas a calibrated value of A was 6 in Ikeda's model. With this calibrated value, the best possible agreement is obtained between the calculated and the measured bed topography.

The meandering channel migration process results from the interaction between flow, sediment transport and bank erosion as shown in Figure 4. Linearized 1-D models are widely used to simulate morphodynamic processes of natural meandering rivers. The meander migration models proposed by Ikeda et al. (1981) and by Hasegawa (1989) are reviewed and applied to channel shifting to test

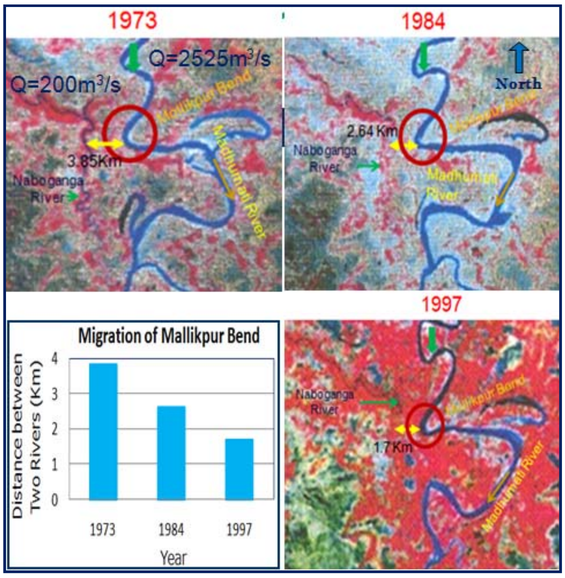

Fig. 3 Morphological changes of the Madhumati River

Table 1 Overview of bed topography models

Engelund (1974)	$\frac{\eta}{H} = \left(\frac{\tilde{r}_0 + \tilde{n}}{\tilde{r}_0}\right)^A - 1$
Ikeda (1974)	$\frac{\eta}{H} = \exp\left\{\frac{1}{2}A\left(\frac{\tilde{r}^2}{\tilde{r}_a{}^2} - 1\right)\right\} - 1$

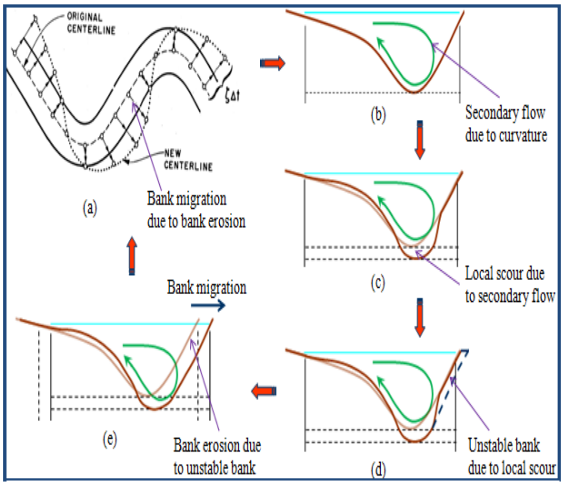

Fig. 4 Bank migration process: (a) planform of a meandering channel (Johannesson and Parker, 1985); (b) secondary flow is generated due to channel planform curvature; (c) secondary flow carries the near bottom sediment from the outer bank to the inner bank region in the downstream and progressively local scour takes place; (d) the outer bank is undermined and becomes unstable; and (e) unstable bank collapses, and causes bank erosion. Finally the outer bank migrates.

their validities for river management. Ikeda et al.'s model is based on shallow water (St. Venant) flow model coupled with the assumption that bank erosion rate is linearly related to the near-bank excess velocity. Hasegawa's model, which is based on the same linear relation as Ikeda et al.'s, includes the erosion rate formula that is derived from integration of sediment continuity equation. Three different numerical simulations are carried out using meander migration models; methods 1 to 3 (Table 2).

In the meander migration models, near-bank excess velocity u is computed by the linear solution of the flow field (Eq. 1).

$$u = -\chi C(s) + \int_0^S C_f \left\{(A+2)\chi^2 + F^2\chi^5\right\} C(s')\exp\left\{-2\chi C_f (s-s')\right\} ds' \quad ...(1)$$

The parameter χ, which is the cube root of the ratio of the equivalent straight channel length aligned along the valley axis to the meandering channel length, is computed using the channel centerline coordinates. The spacing of the digitized coordinates is of one width-equivalent.

In Method-1, the erosion coefficient is calculated for the period 2002 to 2004 from the map of time sequential bank line diagrams. Bankfull geometry and flow parameters are used as input data (Table 3). The time step equal to 0.25 years is employed in the computations. In addition to bankfull geometry and flow parameters, sediment characteristics and transport parameters are required by Method-2 (Table 4). The time step is specified as the duration of bankfull discharge of different flood events. In Method-3, observed near-bank excess flow depths are used.

RESULTS AND DISCUSSION

The results computed by Engelund (1974) and by Ikeda (1974) model are shown with the measured cross-sectional shape in Figure 5. Correspondingly, the results can be interpreted as follows: If the side bank of the reach is composed of non-erodible wall, the bed will be eroded like a predicted curve. Taking such matters into consideration, it is suggested that the transverse bed profile can be computed fairly well by Ikeda's model.

The migration models were applied to predict the migration of a meander bend of the Madhumati River and were examined by comparing the simulated results and corresponding field data

Table 2 Overview of meander migration methods

Method	Equation	Comments
Method -1	$\zeta = E_0 u$	$E_0 = \frac{\sum_{i=1}^{n}(u_i \cdot \zeta_i)}{\sum_{i=1}^{n}(u_i)^2}$
Method -2	$\zeta = E_0 u$	$E_0 = \sqrt{C_f}\, \chi^3 I_0 \left[\frac{3KT\tan\theta_k}{(1-\lambda)\left(\frac{\rho_s}{\rho} - 1\right)\sqrt{\emptyset_*}}\right]$
Method -3	$\zeta = E_0 \left\{u - \chi^2\left(\frac{1}{6} + \frac{1}{3\emptyset_*}\right)\frac{\eta}{H_0}\right\}$	$E_0 = \sqrt{C_f}\, \chi^3 I_0 \left[\frac{3KT\tan\theta_k}{(1-\lambda)\left(\frac{\rho_s}{\rho} - 1\right)\sqrt{\emptyset_*}}\right]$

Table 3 Bankfull geometry and flow parameters

Parameter	Meander Channel	Equivalent Straight Channel
Bankfull discharge	$Q = 2525\text{m}^3/\text{s}$	$Q = 2525\text{m}^3/\text{s}$
Average channel top-width	$B = 470$ m	$B = 470$ m
Average channel bed slope	$I = 0.00004$	$I_0 = 0.000069$
Average channel depth	$H = 8.00$ m	$H_0 = 6.655$ m
Average flow velocity	$U = 1.10$ m/s	$U_0 = 1.322$ m/s
Transverse bed slope parameter	$A = 6.00$	$A = 6.00$
Froude number	$F = 0.12417$	$F = 0.16365$
Friction factor	$C_f = 0.002594$	$C_f = 0.002576$

Table 4 Sediment characteristics and transport parameters

Parameter	Value
Median diameter of sediment particles, d	0.179 mm
Porosity of bed and bank material, λ	0.44
Transverse slope angle of eroding Bank, θ_k	26.64^0
Critical Non-dimensional Shields stress, τ_{*c}	0.073
Static Coulomb friction Coefficient of sediment particles, μ_s	1.00
Dynamic Coulomb friction Coefficient of sediment particles, μ_k	0.70
Constant of bed load transport rate, K	8.00
Density of sediment particles, ρ_s	2650 kg/m^3

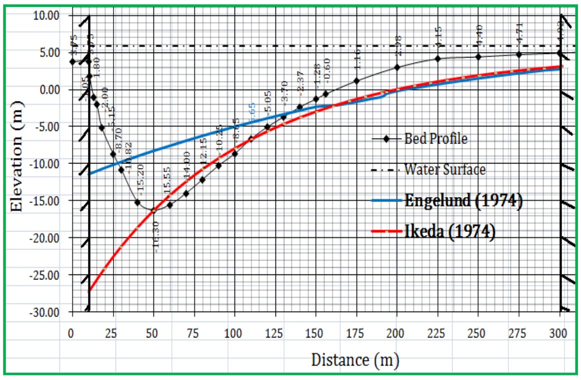

Fig. 5 Simulation of transverse bed topography: Side bank is composed of non-erodible wall.

(Figure 6). The results suggest that Method 1 & 2 are able to simulate well lateral migration, however these cannot evaluate downstream migration. Method 3 is able to simulate the downstream migration well. In this method an influence of the near-bank excess flow depth on the bank migration is added to the Method 2. Maximum velocity is predicted at the bend apex whereas the largest water depth is observed downstream of the bend apex. Although the near-bank excess velocities and observed near-bank excess flow depths were out of phase (Figure 7), they together amplified the bank migration rate. This might be a possible reason for shifting the migration towards the down-stream direction. However, this method cannot predict the lateral migration in the upstream of bend apex. It is suggested that there are two reasons for the deviations. One possible cause for the deviation was considered to be the length scale of spatial discretization. However, it is suggested that the smaller length scale of spatial discretization does not yield much better results.

The second and most important reason was considered to be the large flow width of the channel. The flow width was determined including the very shallow water zone near the inner bank in the study reach. If the flow width is estimated to be large in comparison with the real one, the near bank excess flow depth will be large. Figure 8 shows that near-bank excess flow depth effect is much larger than the near-bank excess velocity on the bank migration rate. As the near-bank excess flow depth effect was large in the upstream of bend apex, the lateral migration was over predicted. Correspondingly, the prediction of bank shifting will be improved by determining the flow width carefully.

CONCLUSION

Scouring of curved channels and migration of meandering channels are studied using existing models in order to obtain information for river management. Special attention is paid for applicability of the models to the Madhumati River in Bangladesh as well as for testing validations.

It has been found that transverse bed profile can be computed fairly well by the model developed by Ikeda (1974). Maximum scour depth can also be predicted supposing the side bank is composed of non-erodible wall. The results show that local scour

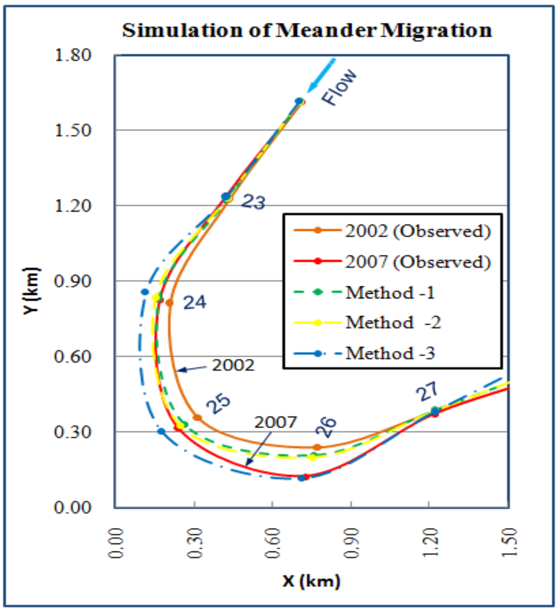

Fig. 6 Simulation of meander migration – Madhumati River (Bangladesh): The digitized coordinates of the channel centerline in 2002 is used as the initial location for simulation. The nodes are numbered to facilitate further discussion in Figure 7 and 8. Channel centerlines as predicted in 2007 by method 1, 2 & 3 are shown with the dashed, long-dashed and long-dash-dotted lines. Predicted channel centerlines are compared with the observed location in 2007.

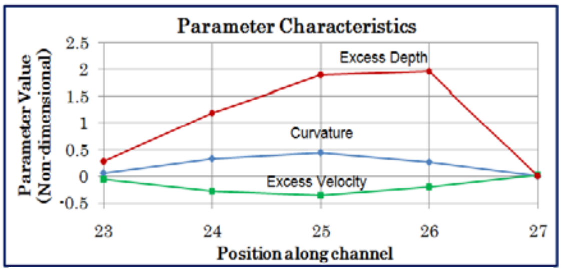

Fig. 7 Parameter characteristics: X-axis is position in bend measured downstream in width-equivalent units. Y-axis is non-dimensional local curvature, near-bank excess velocity and near-bank excess flow depth. Non-dimensional near-bank excess velocity is predicted by Eq. (1). Curvature is half-width normalized. The near-bank excess flow depth is measured and normalized by H_0. Curvature is defined as positive for anticlockwise turning of river channel, viewing from upstream. Curvature and near-bank excess velocities have opposite sign. Therefore, bank migration is directed towards outer bank. Node no. 25 is the bend apex.

depths in meandering channels can be evaluated roughly and efficiently by means of such simple methods.

It is found that the meander migration models proposed by Ikeda et al. (1981) and by Hasegawa (1989) could be acceptable for evaluating the channel shift although some improvements may be necessary. Specially, Hasegawa's model will predict well the bank erosion and corresponding channel shift if the flow width is specified carefully. Since the cross-sectional shapes of rivers in Bangladesh are highly asymmetric, special attention is necessary to determine the flow width. In this way it is possible to improve the predictions. Nevertheless, such meander migration models provide a valuable and easy-to-use tool to analyze migration characteristics of meandering channels.

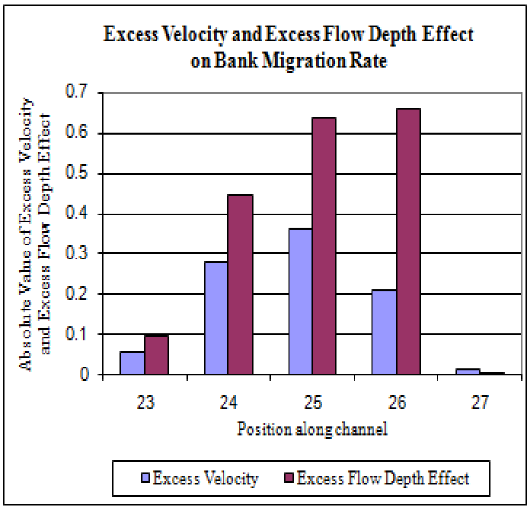

Fig. 8 Excess velocity and excess flow depth effect on meander migration: X-axis is position in bend measured downstream in width-equivalent units. Y-axis is absolute value of non-dimensional near-bank excess velocity and near-bank excess flow depth effect. Non-dimensional near-bank excess velocity is predicted by Eq. (1). Non-dimensional near-bank excess flow depth effect is computed as $\chi^2\left(\frac{1}{6}+\frac{1}{3\emptyset_*}\right)\frac{\eta}{H_0}$.

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