Iranica Journal of Energy & Environment 3 (4): 299-306, 2012
ISSN 2079-2115
IJEE an Official Peer Reviewed Journal of Babol Noshirvani University of Technology
DOI: 10.5829/idosi.ijee.2012.03.04.02

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River Channel Change Simulation of Khoshke Rud Farsan River and Bank Erosion Process Using a Numerical Depth Averaged Model, CCHE2D

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(Received: May 30, 2012; Accepted in Revised Form: December 23, 2012)

Abstract: Bank erosion in populated areas could cause fatalities and property damage if banks collapse abruptly, compromising the integrity of residential buildings and civil facilities. Bank erosion study is in general a very complex problem because of it involves multi-processes such as bank surface erosion, bank toe erosion and bank material mechanic failure, etc. Each of these processes is related to several parameters: sediment size distribution, bank material cohesion, slope, homogeneity, consolidation, soil moisture and ground water level, as well as bank height. The bank erosion rate is also related to the strength of the flow in the river indicated by the flow shear stress, water depth and channel curvature, etc. In this study, the numerical model CCHE2D has been applied to study real-world bank erosion cases in a mountain river, Khoske Rud Farsan River, Iran, which is a braided river with high sediment loads and channel mobility; the bank erosion of this river is dominated by floods during rainy seasons.

Key words: River · Bank Erosion · Numerical Model · Simulation · Sediment

INTRODUCTION

Bank erosion induced by alluvial river channel migration often causes problems of encroachment upon valuable farm land, downstream channel deposition and degradation water quality. Channel bed degradation increases bank heights and lateral erosion on bank surface makes the bank retreat. Khoske Rud Farsan River originated in the central mountains of Zardkuhe Bakhtiyari, it forms a large alluvial fan and then empties into Zayande Rud River. The channel slope in the mountain area is very steep. The flow discharge varies greatly, particularly during Rainy seasons. Sediment transport is dominated by the pattern of the flow discharge, forming a braided river channel. The valley of the river is very wide and a typical braided river pattern with multiple channels can be observed from aerial photos and satellite imagery. The multiple channels become a single one only when the discharge is very large during Rainy seasons. Due to the nature of the channel pattern, the main channel and braided channels in this reach change courses randomly and quickly. This study is to apply a computational model, CCHE2D, to simulate the bank erosion process in one stretch of the river from Eisy Abad Bridge to Goujan sand and gravel Factory. The reach is situated at the connection part of the mountain and the alluvial fan. The channel slope is about 0.1% for the mountain part and it reduces suddenly to about 0.43% over the alluvial fan. The characteristic of braided river changed somewhat and the number of channels is reduced over the alluvial fan. Alluvial rivers often have lateral movement or migration; braided rivers are formed by multiple irregularly curved channels with high mobility. Due to the complexity of the fluvial morphology of this river and the flow discharge variation range, single curved channel case will be encountered.

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Because of sediment transport in curved channels is affected by the secondary current, which creates a lateral sediment motion and channel change, the computational model should include this mechanism to reflect the correct transport processes. Even in a braided river, each sub-channel is a curved one and this mechanism applies. All the data needed for computation modeling was provided by the Department of Watershed Management and River Engineering, National Shahre Kord University, Iran and Water Research Center.

In this paper, a bank erosion model based on a general hydrodynamic and sediment transport model, CCHE2D, is presented. Bank surface erosion, basal erosion and mass failure are simulated based on the approaches of Osman and Thorne [1, 2] and Hanson and Simon [3]. The secondary helical current effects on suspended sediment and bed load sediment transport have been considered. Since this is a two dimensional model, computational mesh and domain can be adjusted when the bank boundaries move due to erosion. Numerical tests with fixed bank experiments are conducted to validate the secondary current effect and one movable bank experiment data was used to test the bank erosion and mesh stretching module. Nagata *et al*. [4] and Duan *et al*. [5] developed 2-D channel meandering models that adopt the moving grid techniques. In their approaches, flow, sediment transport, bed change and bank erosion are simulated on a mesh at each time step. After the bank lines have been moved by erosion and deposition, a new mesh conforming to the new bank lines is created and the flow field and bed topography are interpolated from the old mesh to the new one. The computations of flow, sediment transport, bed change and bank erosion are then continued on the new mesh at the next time step. CCHE2D is a depth-integrated 2D model for simulating free surface turbulent flows, sediment transport and morphological change. This is a finite element based model with the collocation method and quadrilateral mesh [6, 7].

Validation of Bed Morphological Change Simulation Using Flume Experimental Data: The sediment transport and bed morphological change simulation models were tested using physical model data. Four of the experiment test cases published by Struiksma *et al*. [8] were simulated. These are physical models with different channel geometry, curvature, flow conditions and sediment size distributions. The patterns of bed elevation in bend ways or meander channels, deeper near the outer bank and shallower near the inner bank, are correctly reproduced. The magnitude of the predicted erosion and deposition in the channels agreed very well to the measurement (Fig. 1). The agreements of the numerical simulation and the data indicated that the CCHE2D model can reproduce the flow and sediment transport physical process in laboratory flumes correctly. Because the flume channel provided by the paper are often short (just the part of the channel with curvature), the length and shape of the leading and tailing channel reaches are unknown; it may affect the specification of accurate boundary conditions especially the upstream boundary conditions. This may therefore affect the accuracy of the predicted bed elevation change and equilibrium bed forms.

Bank Erosion Modeling: Channel bed degradation increases bank heights and lateral erosion on bank surface makes the bank retreat. Once the stability criterion is exceeded, a bank mass failure would occur. The failed

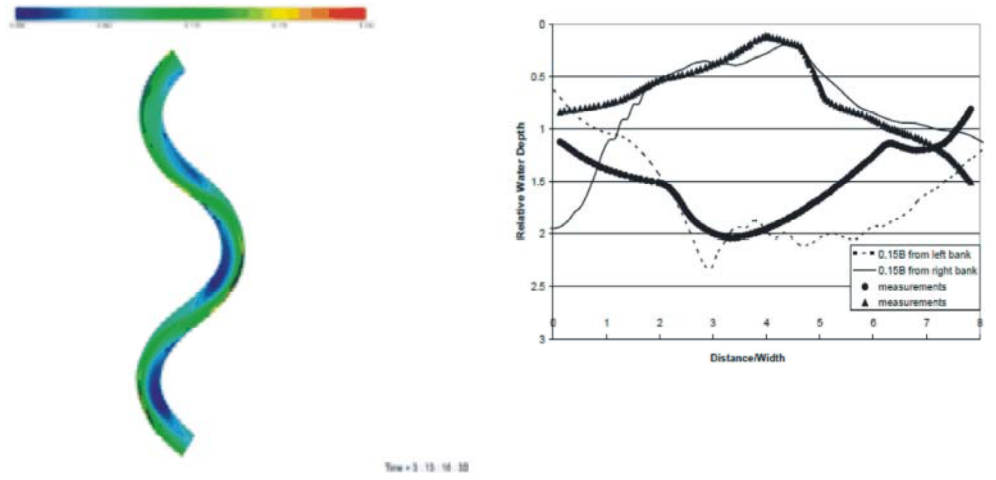

Fig. 1: Computed water depth and comparison of numerical results (curve) and experimental data (Case 3)

bank material deposits first on the bed near bank toes and then is eroded away by the flow. The bank erosion process can significantly affect sediment balance in a channel and channel morphology evolution. Rinaldi *et al*. [9] proposed a numerical simulation of hydrodynamics and bank erosion. Depending on geometries and soil properties, river banks may fail by various mechanisms, which may be planar, rotational, cantilever, piping-type and sapping-type. Planar and rotational failures usually occur on the homogeneous, non-layered banks; cantilever failures usually happen on the layered banks; while piping- and sapping-type failures most likely occur on the heterogeneous banks where seepage flow is often observed. Osman and Thorne [1] analyzed the planar and rotational failures. Usually, the failed material deposits first on the bed near the bank toe and then is disaggregated and eroded away by the flow if the flow is strong enough. For large rivers, the failed material depositing near the bank toe does not strongly disturb the flow, but for small rivers and streams, this influence may disturb the flow distribution. In the current approach, the failed bank material is considered as an input to the bed load. Since the time step for bank erosion is much larger than sediment transport, this side input is set uniform through the next bank erosion step. This input will result in highly near bank sediment concentration or bed load. If the bank erosion is too fast, near bank bed elevation would increase to slow down the bank erosion. In Osman and Thorne's model, a bank has an initial slope; after the first collapse occurs, a new slope will be established and the bank will then keep this slope. The mass failure that occurs later will not change the slope (parallel retreat). Considering that the river banks one studies have been experiencing bank failures for a long time, the bank slope observed is likely to be the bank mass failure slope. It is reasonable to assume that the bank slope is a known value and only the parallel retreat processes are needed to be simulated. In Osman and Thorne's model [1], the bank surface erosion was proportional to the difference of the shear stress and the critical stress; the difference was then normalized by the critical stress. Erosion due to excessive shear and gravity both have been implemented in the CCHE2D-BANK model [8-15].

Moving Boundary Problem: A bank erosion problem is a moving boundary problem: the bank moves in time and the shape of the computational domain varies accordingly. Along the bank erosion side of the channel, the mesh line moves with the bank and the computational mesh should be stretched to widen the channel as the channel bank lines move due to bank erosion. The distance of the bank movement is comparable to or even larger than the channel width for a channel migration study. One should point out that this stretch is not completed in one step, but was done in many finite steps and each was caused by a small step of bank erosion. Mass and momentum conservation may be affected if the distance of a bank movement is too large.

Once the mesh line along the bank line is moved, the mesh in the entire domain should be changed. Normally, the mesh lines along the channel are moved in the same direction toward the eroded bank line with a distance. The mesh is in this way "stretched" wider to conform to the new domain. Because the discretization of the computational model is based on the mesh, the computational model discretization should be updated once the mesh is changed. One has to re-compute all the numerical parameters and differential operators again every time a mesh stretch is performed. Interpolation of the computational results from the previous mesh to the stretched one is required before re-computing the flow if the stretching is significant. Usually bank materials are much less erodible than the bed materials. The bank lines are therefore much less mobile than the bed. The time scales to compute bank erosion are normally much larger than that for the bed change and the flow. Therefore, although computation of bank erosion is complicated, its associated computation cost is not very high, particularly if the quasi-steady approaches is adopted using a channel forming flow discharge.

Figure 2 shows the development of simulated channel morphology. In the process of development, the outer bank line retreats gradually and the main channel of this bend shifts accordingly. The cross-section form of the channel also changes, particularly at the beginning stage and the water depth near the outer bank becomes larger while that near the inner bank becomes smaller. This change makes it possible to form a point bar near the inner bank; then the point bar later becomes dry. Although the distance of the two banks increases, the width of the wetted channel remained approximately the same. Another feature of the simulated results is that when the main channel moves toward the outer bank due to bank erosion, a small channel near the inner bank is formed behind the point bar. This probably is because the small channel shortcuts from one bend to the next, the local water surface slope and sediment transport capacity are not small. This phenomenon appears in many natural meandering rivers [3, 8, 12, 16-22].

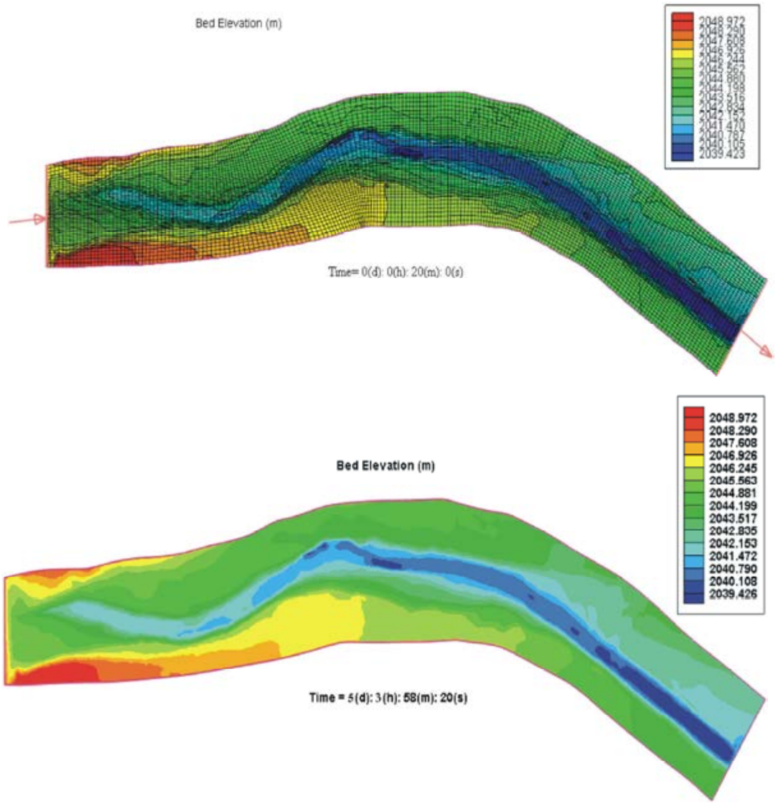

Fig. 2: Simulated bank erosion and channel morphologic change using bankfull discharge (The color contour indicates flow velocity magnitude)

Table 1: Computed bank erosion and tested bank critical shear stresses

Maximum Erosion width (m)	Length of eroded bank (m)	Bank cohesion	Bank material Specific Weight (N/m^3)	Friction angle (degree)	Critical Shear Stress (dyne/cm^2)	Time Step for Flow (second)	Time Step for Bank (second)	Bank
98	3000	500	25500	30	10	30	3600	Left
55	4500	500	25500	30	10	30	3600	Right

Application of the Bank Erosion Model to a Field Case in Khoshke Rud River: The Khoshke Rud River between Eisy Abad Bridge to Goujan sand and gravel Factory is used as a test site for the bank erosion model. Figure 3 shows the channel pattern of this river in 2010. The nature of the braided river is clearly seen. The old channel is less braided and that of 2010, the flows are in less number of sub-channels. The flow discharges for these two figures are unknown. It is certain that the braided river process is very active. To simplify the bank erosion process simulation, only high flows (110cms) in 2004 and 2010 are considered. Most of these flows are due to intensity rainfalls and snow in this region. The accumulated flooding time of these high flows are approximately 2 days and 5 hours. The aforementioned numerical model CCHE2D-BANK was applied.

Figure 4 shows the upstream boundary condition, flow discharge and downstream boundary condition and water surface elevation used for the computation. To simplify the problem, only high flow events (Q>=4000cms) were considered. Rating curves for sediment transport rate were used for sediment boundary conditions with wash load being removed.

Table 1 shows some parameters of the computation. Bank material specific weight and friction angle were measured values. The bank material has no cohesion; a small cohesion was used. Bank critical stress was unknown in this study. It shows in the tests that bank erosion is sensitive to this parameter. The bank erosion width (encroachment) and length along the channel increase when the bank critical shear stress is less. The critical stress used was consistent with the field data [3, 23] for low cohesive bank materials. Because no bank erosion data are available, the computational study was focused on testing model capabilities.

Fig. 3: Channel form of Khoske Rud River and present condition of it in 2010

Figure 5 shows the comparison of computed and measured bed elevation along several cross-sections. As shown, the general agreement of the computed bed elevation distribution along cross-sections agrees well with the measured. Because the river is braided, the number and location of sub-channels vary in time due to high flow and sediment transport. The model can compute braided channel pattern but the number and location of these channels may not be the same. As a result, the location of erosion and deposition in a cross-section may not be the same as the data, but the trend of channel change, aggradation or degradation, is consistent to those observed.

Figure 6 shows the computed bank erosion and the channel bed change from 2004 to 2010. Large bed change along the channel indicates the bank erosion.

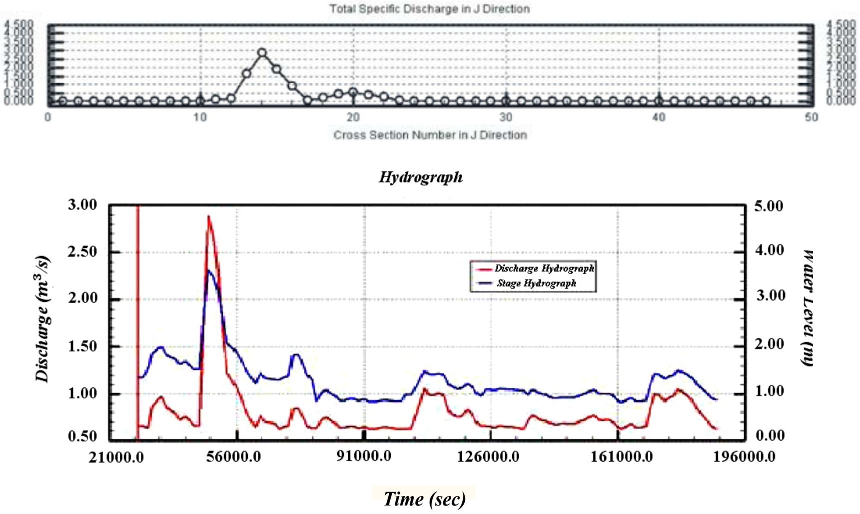

Fig. 4: Discharge hydrograph at Khoske Rud River

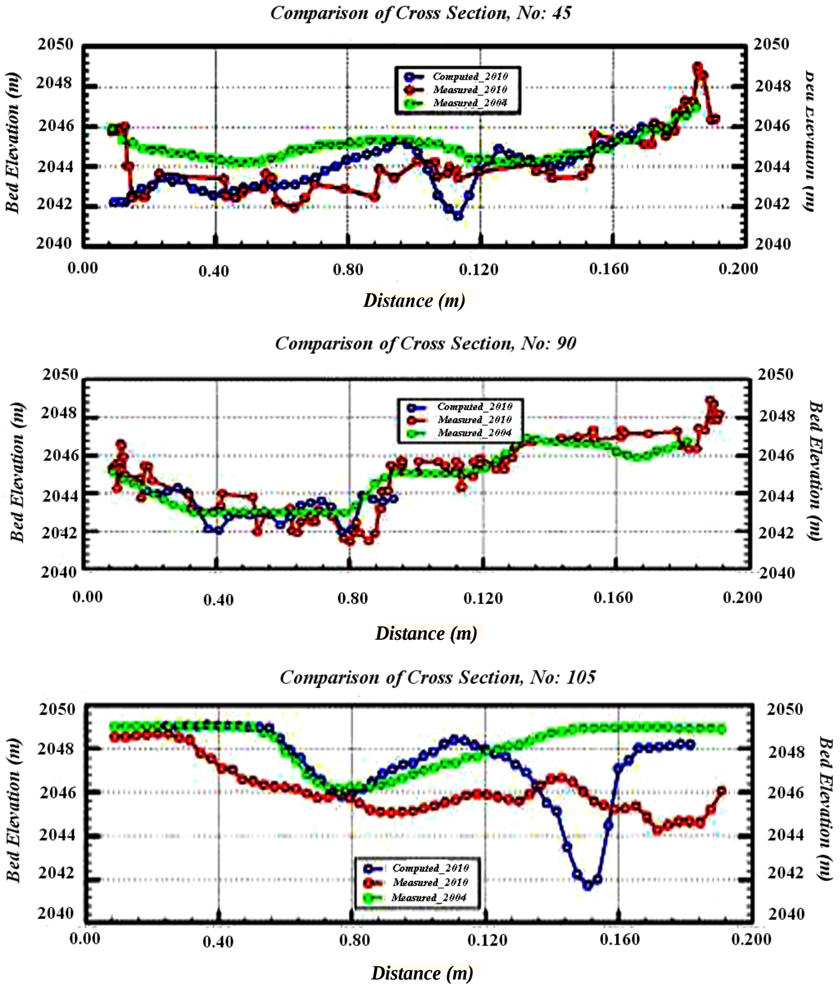

Fig. 5: Computed and measured cross-sections. The 2010 DEM data was used as initial bed

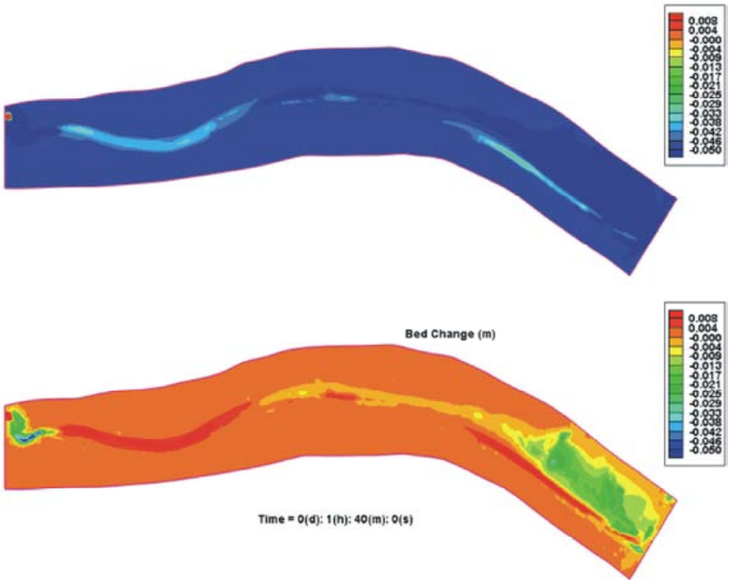

Fig. 6: Computed and observed bank erosion location. Major bank erosion areas along the right and left bank are close to that reflected in channel change data

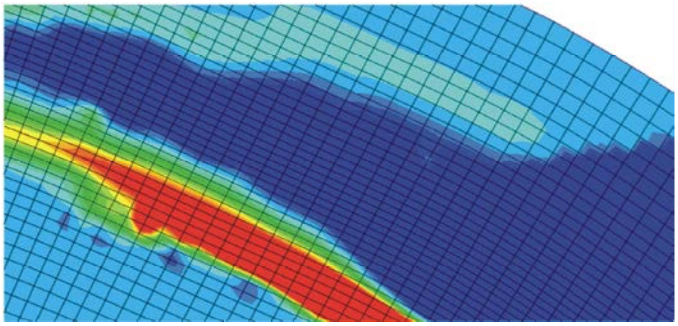

Fig. 7: Computed Bank Erosion process near the left bank

The simulated bank erosion zones are close to that of those indicated in the bed change data. This comparison is qualitative because there is no measured bank erosion data.

Figure 7 shows the simulated process of bank line retreat. Each line represents a bank location. The spacing between the lines is the bank erosion distance in one bank erosion time step. It is seen that the line spacing is not uniform, they are wider when the near bank flow is strong and vice versa.

CONCLUSIONS

Bank erosion is a complex fluvial processes and it causes so problems like as soil loss, water pollution and other disasters. Numerical models can be applied to simulate bank erosion by computing all the involved physical processes, such as main and secondary flow, sediment transport processes and mass failure.

The capabilities for simulating the secondary flow effects on suspended sediment and bed load sediment transport have been developed and implemented to the CCHE2D model. The bank surface erosion and mass failure mechanisms have been also developed with the eroded bank materials being transported as bed load. The mesh stretching technique was used to dynamically vary the mesh and handle the moving boundary (banks) problem. Several sets of experimental data were used to validate the developed sediment transport capabilities in curved channels with good agreements. Bank erosion capabilities were tested using a field case of Khoshke Rud River, Iran. Calculated channel bed change in the period of 2004-2010 was compared with the measured data with reasonable agreement. The computed bank erosion in one reach of the river is also compared with the bank erosion estimated using the difference of 2004 and 2010 DEM data.

ACKNOWLEDGEMENTS

This search is supported by Water Research Center of Shahre Kord, Iran. The authors appreciate Dr. Yoaxin Zhang for him technical support, data and valuable suggestions in this research.

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