

Modeling Sediment Transport and River Bed Evolution in River System

Wanshun Zhang, Yanhong Xu, Yanru Wang, and Hong Peng

Abstract—The problem of sedimentation has significant impacts on the operation lifetime of the reservoir. A two dimensional numerical model has been developed to simulate the transport of sediment and the evolution of the river bed in river system. The model consists of hydrodynamic equations, sedimentological equations and bed deformation equations. Water-sediment conditions and the abrupt change of water level and flow, which are influenced by gate dams, were emphatically considered in the simulation. The field measurements of erosion-sedimentation thickness of 2006, 2007, 2008 and 2009 in three sections are used for the model validation and the simulation results agree with the measurements well. The model is applied to simulate the process of sediment deposition at the upper reaches of Three Gorges Reservoir Region. The model results can reflect the detailed changes of sediment deposition thickness of river channel in the next 70 year.

Index Terms—2D mathematical model, erosion and deposition, sediment, Yangtze River.

I. INTRODUCTION

The movement of sediment shows profound significance to river. The process of sediment transport and deposition can change the topography of the river bed [1]. And the sediment deposition is a key factor to limit the river development and management. However, ever increasing human activities, such as extensive damming have increased sediment deposition in the river channel and reservoirs [2], [3]. Take the Three Gorges Dam (TGD) as an example, the sediment discharge of Qinxichang and Yichang stations were similar, and net erosion or deposition along the channel between Qinxichang and Yichang was little before TGD impoundment; however, after impoundment, the average trapped sediment was approximately 118 Mt/y from 2003 to 2006 [4].

During the comprehensive using and regulation of reservoir, sedimentation and erosion is the key point of reservoir life and efficiency. With the running time growth of the reservoir, the operation of the project will result siltation in the upper reaches and erosion of the downstream river bed [5]. The problem of sedimentation will have significant impacts on the operation lifetime of the reservoir, the flood control capacity and the shipping. So it is very important to research the process of sediment transport, and its

significance mainly shows in the following aspects: overall problem, longer-term problem and complex problem.

Over the past decades, the development of sediment transport mathematical models has been receiving more and more recognition, because they can be applied to assess the process of river bed evolution [6], [7]. On the basis of the theories of overseas and domestic experts, the theoretical and applied researches of one-dimensional (1D) models are very mature, and the reliability and accuracy are good [1], [8], [9]. The 1D model can analyze the general changes of flow and riverbed from a macroscopic view, but cannot simulate the local sediment movement in detail. Then the two-dimensional (2D) models are developed to simulate the refine local riverbed deformation and sediment deposition process in vertical and horizontal [10]-[12]. These models represent an improvement in the description of the sediment erosion and deposition in river system. However, as more and more water projects have been built, the abrupt changes of river flow-sediment conditions that influenced by the hydro-junctions are growing [13], [14]. Then there is a need for a comprehensive modeling system that can realistically describe significant sediment erosion and deposition process.

In the present study, the flow velocity, sediments discharge and bed-load gradation composition form the focus of the study, with which the transport of sediment and the thickness of erosion-sedimentation can be simulated by the developed 2D numerical model in river system. The model contains the hydrodynamic sub model, and the sedimentological sub model together with the bed deformation sub model. After calibration and validation, the model is applied to simulate the erosion and deposition process of sediment in the Three Gorges region. The results should provide a scientific basis for the improvement of the sediment management, which is the primary objective of the study.

II. MATHEMATICAL MODEL

The mechanical migration and the physical migration are the main mechanisms of sediment transport, and the transport processes are very complicated. Meanwhile, suspended and bed sediments, which are transport by the river flows, can cause bed scouring and siltation, and then lead to bed deformation. Therefore, the hydrodynamic and hydrological conditions, such as water flow velocity, bed material grade and sediment concentration, are the main factors influencing sediment transport.

A. Hydrodynamic Sub Model

The hydrodynamics sub model based on the full set of 2D Saint-Venant equations are as follows:

Continuity equation:

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$$\frac{\partial z}{\partial t} + \frac{\partial(h+z)u}{\partial x} + \frac{\partial(h+z)v}{\partial y} = 0 \quad (1)$$

Momentum equations:

$$\frac{\partial hu}{\partial t} + \frac{\partial}{\partial x}(huu) + \frac{\partial}{\partial y}(hvu) + gh \frac{\partial z}{\partial x} + g \frac{n^2 u}{(h+z)^{1/3}} \sqrt{u^2 + v^2} = \frac{\partial}{\partial x}(h\gamma \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(h\gamma \frac{\partial u}{\partial y}) \quad (2)$$

$$\frac{\partial hv}{\partial t} + \frac{\partial}{\partial x}(huv) + \frac{\partial}{\partial y}(hvv) + gh \frac{\partial z}{\partial y} + g \frac{n^2 v}{(h+z)^{1/3}} \sqrt{u^2 + v^2} = \frac{\partial}{\partial x}(h\gamma \frac{\partial v}{\partial x}) + \frac{\partial}{\partial y}(h\gamma \frac{\partial v}{\partial y}) \quad (3)$$

where u and v are the components of the water velocity along the x - and y -axes directions in the Cartesian coordinates (m/s), respectively; z is the free surface elevation (m); h is the water depth (m); q_l is the discharge of lateral inflow along stream (m^3/s); g is the acceleration of gravity (m/s^2); γ is the turbulence viscosity coefficient (m^2/s); n is the Manning coefficient of roughness.

B. Sedimentological Sub Model

The transport of suspended sediments is described by the nonequilibrium suspended sediment transport equation.

Continuity equation of suspended sediments:

$$\frac{\partial s_i}{\partial t} + u \frac{\partial s_i}{\partial x} + v \frac{\partial s_i}{\partial y} = \varepsilon_s \left(\frac{\partial^2 s_i}{\partial x^2} + \frac{\partial^2 s_i}{\partial y^2} \right) + \alpha_{s_i} \omega_i (s_i^* - s_i) \quad (4)$$

where subscript i indicates the i -th size group of suspended sediments; s_i and s_i^* are the depth-averaged suspended sediment concentration, respectively (kg/m^3); ε_s is the diffusion coefficients of sediment; ω_i is the setting velocity of sediment (m/s); a is the recovery coefficient of suspended sediment, with $a = 1.0$ for the erosion process ($s_i^* > s_i$) and $a = 0.25$ for the deposition process ($s_i^* < s_i$).

The sediment transport capacity s_i^* is calculated as [15]:

$$s_i^* = K_s \left(U^3 / gh \omega_i \right)^m \quad (5)$$

where U is magnitude of flow velocity, $U = \sqrt{u^2 + v^2}$; K_s and m are empirical coefficients.

The sediment-transport rate of bed load is as follows:

$$q_{sb} = \frac{k_1}{c_0^2} \frac{\rho_s \rho}{\rho_s - \rho} \frac{(u - u_c) \bar{u}^3}{gh \omega} \quad (6)$$

in which q_{sb} is the exchange of sediment material between bed and suspension; ω is the setting velocity of bed sediment average particle size (m/s); ρ_s and ρ are the density of sediment and water (kg/m^3); u_c is the initiating setting velocity of bed sediment average particle size (m/s), $c_0 = h^{1/6} / n \sqrt{g}$.

C. Bed deformation sub model

The bed deformation sub model describes the process of bed deformation because of erosion and deposition by suspended sediments and bed sediments.

Bed deformation equation of suspended sediments:

$$\rho'_s \frac{\partial z_{si}}{\partial t} = \alpha_s \omega_i (s_i - s_i^*) \quad (7)$$

Bed deformation equation of bed sediments:

$$\rho'_b \frac{\partial z_{bi}}{\partial t} + \frac{\partial q_{bxi}}{\partial x} + \frac{\partial q_{byi}}{\partial y} = 0 \quad (8)$$

Equation of bed material gradation:

$$\rho'_s \frac{\partial E_m P_{mi}}{\partial t} + \alpha_s \omega_i (s_i^* - s_i) + \frac{\partial q_{bxi}}{\partial x} + \frac{\partial q_{byi}}{\partial y} + [\varepsilon_l P_{mi} + (1 - \varepsilon_l) P_{mi,0}] \rho'_s \left(\frac{\partial z}{\partial t} - \frac{\partial E_m}{\partial t} \right) = 0 \quad (9)$$

where Z_{si} and Z_{bi} are the thickness of sediment generated by suspended sediment and bed sediment, respectively (m); ρ'_s and ρ'_b are the dry density of suspended and bed load, respectively (kg/m^3); α_s is the recovery saturation coefficient of suspended sediment; $P_{mi,0}$ is the initial bed material grade; q_{bx} and q_{by} are the sediment-transport rate of bed load along the x - and y -axes directions in the Cartesian coordinates, respectively (t/d); E_m is the depth of mixed layer (m), when the initial bed is washed, then $\varepsilon_l=0$, otherwise $\varepsilon_l=1$.

D. Initial and Boundary Conditions

The initial values of flow velocity, water level, suspended sediments discharge and bed-load gradation composition are set for each grid at the start time.

Two types of boundary, open and closed boundaries, are prescribed along the boundary of the computational domain. For open boundaries, river flow, flow velocity, sediment discharge and bed-load transport rate are given at the upstream boundary; and the water level is given at the downstream boundary. For closed boundaries, flow velocity and all fluxes are set to zero to the solid boundaries.

E. Numerical Discretization and Solution

The equations are discretized in the framework of the Finite Volume Method (FVM). The upwind scheme is utilized to compute the convection items on non-orthogonal, quadrilateral grids [16]. The coupling of pressure and velocity on non-orthogonal grid arrangement is obtained by using the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm and the momentum interpolation procedure [17].

III. VALIDATION

A. Study Area

The ongoing Three Gorges reservoir is located in the Yichang City, Hubei Province of China. As one of the largest water-power engineerings, the total storage of the Three Gorges reservoir is 39.3 billion m^3 , and the flood control capacity is 22.15 billion m^3 . The Three Gorges reservoir has put into operation in 2009. Because of the large sediment charge of the Yangtze River, the mean sediment content is 1.19 kg/m^3 , and average annual sediment discharge is 53 million kg. The research results of the preliminary design stage of Three Gorges Project showed that the time of reservoir sedimentation would last more than 100 year.

Though some methods have been carried out to reduce the sediment charge, the sediment deposition is still the most important problem affect the development of reservoir’s synthetic benefit in some degree. The study area is outlined in Fig. 1.

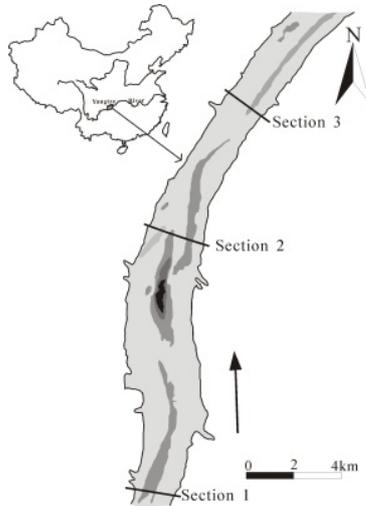


Fig. 1. Map of the study area.

B. Parameters

The inflow and downstream boundary conditions and the water and sediment data are obtained from historical hydrological measurements of the Zhutuo, Wulong and Beipei gauging station. The roughness n is based on the observed water flow of the simulated reach from 2009 to 2010 within a range of 0.028-0.030. The coefficients of suspended sediment transport of K ranges from 0.9 to 1.5 and m adopts 0.95.

C. Validation Results

The numerical model is verified by comparing the simulation results with the field data. The topographic data on November 1, 2006, October 1, 2007, April 1, 2008, April 1, 2009 and October 1, 2009 are used for the verification. Fig. 2- Fig. 4 shows the comparison of the thickness of erosion-sedimentation between the model results and the observation at Section 1, Section 2 and Section 3, respectively. It can be seen that in general the calculated thickness of erosion-sedimentation of different years agree well with the measured data for the three sections. Therefore, the validity of the model is determined and the model can be used to forecast the sediment deposition at the upper reaches of Three Gorges Reservoir Region.

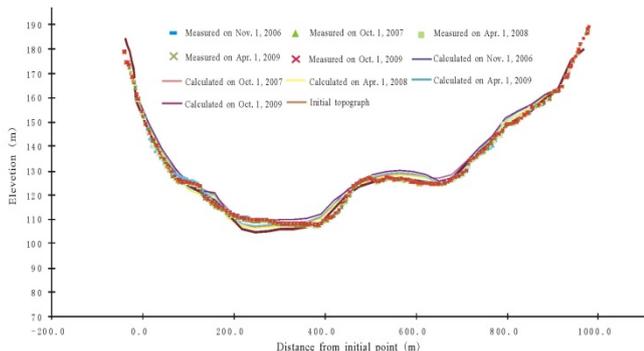


Fig. 2. Comparison of the thickness of erosion-sedimentation at Section 1.

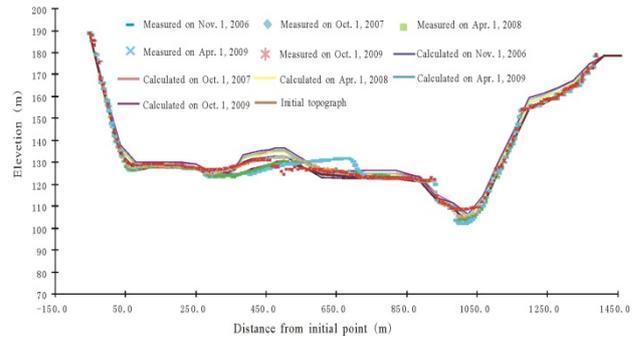


Fig. 3. Comparison of the thickness of erosion-sedimentation at Section 2.

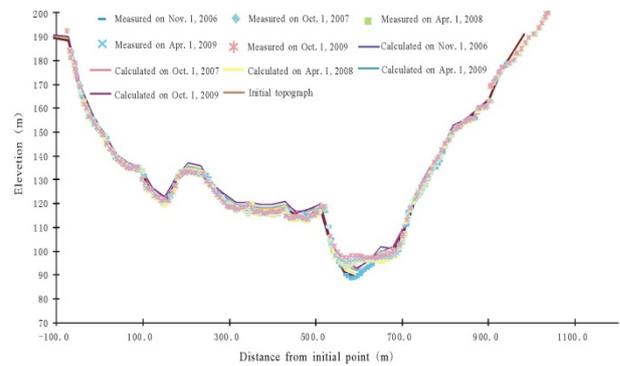


Fig. 4. Comparison of the thickness of erosion-sedimentation at Section 3.

IV. MODEL APPLICATION

A. Scenario Description

The model used in this study aims at calculating the thickness of erosion-sedimentation in the next 70 year under the influence of water control project. The time series of flow discharge and sediment concentration by Zhutuo hydrological station are used as the input conditions in the study (Fig. 5). In the figure the discharge is a long series (ten-year) of natural hydrology processed between 1961 and 1970. At the same time, from the River discharge and sediment concentration data, it would seem that the sediment concentration in river between 1961 and 1970 is quite large. The measured river topographic in 2006 is used for simulation.

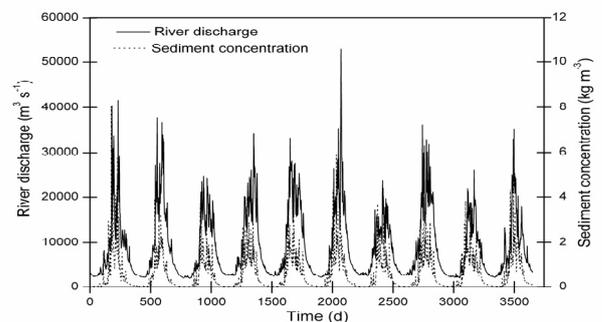


Fig. 5. River discharge and sediment concentration between 2001 and 2010.

B. Results and Discussion

The upper reservoirs play an important role to block the role and make the rate of deposition reduce, so the trend of deposition becomes slow as time goes on (see Fig. 6). Fig. 6(a) shows the prediction of micro deposition trend in the simulative reach for the 10th year. There is a slight silting in the left of upstream of the simulative reach. In the middle

tortuous reach, the number of erosion-sedimentation belt is more than the upstream reach, because of the topographic factor. And some deposition also exists in the downstream reach. Fig. 6(b) presents the predicted deposition of sediment for the 30th year. The simulation results show that the range of erosion-sedimentation is larger than the 10th year, and the scope of deposition in the middle reach has the relatively large change. The erosion-sedimentation plumes at the 50th year are showed in Fig. 6(c). For this time, the simulation results show that the thickness of erosion-sedimentation plumes have increased significantly compared with the situation of the 30th year. Meanwhile, the range of erosion-sedimentation belt in the middle reach has greatly expanded. Fig. 6(d) shows the prediction of erosion-sedimentation thickness for the 70th year. At this time, the map shows that the deposition trend at the 70th year is more obvious than that of the 50th year, embodied in the elongation of river deposition scope and the increase of river deposition thickness.

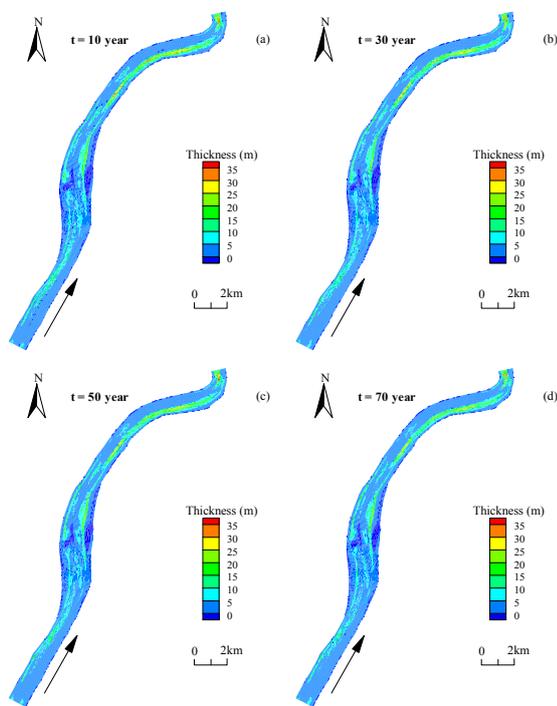


Fig. 6. The thickness of erosion-sedimentation on the 10th, 30th, 50th, 70th year.

V. CONCLUSION

The erosion and deposition of the sediment is one of the focus questions in the Three Gorges region. Therefore, the assessment of the sediment deposition thickness requires a model to simulate hydrodynamic, sedimentological and bed deformation processes. In the research, a 2D model, which was based on the combination of the hydrodynamic sub model, the sedimentological model and the bed deformation sub model, was developed to simulate the erosion and deposition process of sediment. A series of simulation results were compared with field measurements on November 1, 2006, October 1, 2007, April 1, 2008, April 1, 2009 and October 1, 2009, and it is shown that the model is applicable to the sediment transport in the river. Then the model is used to calculate the thickness of erosion-sedimentation in the next 70 year in Fengdu of Three Gorges Reservoir. The simulation

results can reflect the detailed changes of sediment deposition thickness in the next 70 year. The model developed in this study can be regarded as a basic tool for assessing the sediment transport process in the natural river system, and the research also can provide technical support for the project construction and support the Three Gorges cascaded hydropower scheduling.

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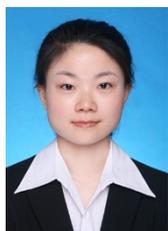
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