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NUMERICAL CALCULATION FOR BED LOAD SORTING IN MEANDERING CHANNEL

(蛇行水路における流砂の分布に関する数値計算)

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1. INTRODUCTION

The changes in river morphology don't occur independently, because water flows, bottom topography, bank erosion, sediment characteristics, and the roughness are mutually interrelated. And understanding the processes and mechanisms of channel morphology induced by such influences and responses quantitatively is very important for river engineering purposes to manage rivers and prevent disasters from flood. In the meandering channel with mixed sediment, the grain sizes are distributed in different proportion and directions in time and space. The bed materials on the inside near the bend are finer than the outside, and the sorting process starts at the upstream inflection point and is finished at the downstream inflection point.

Numerous attempts to estimate channel changes caused by aggradation or degradation of the riverbed without bank changes have been made on the basis of various theories and experiments, and also manynumerical models have been developed.

Ikeda et al.(1981) investigated the stability of a meandering channel with erodable banks to explain a bend instability. Paker et al.(1985) proposed a model to predict temporal changes of sediments with different grain sizes in the meandering channel. Ashida et al.(1991) developed a numerical model to simulate sediment distribution and the bed changes in meandering channel with mixed grain sizes, considering

the effect of bed slope and flow direction. Shimizu et al.(1995) established numerical model to estimate channel changes without bank erosion and also Shimizu et al.(1996) developed a 2-D numerical model to calculate temporal and special changes in the meandering channel with uniform grain size considering the bank erosion. Nagata et al.(2000) proposed to analyze river channel changes with bank erosion by a moving boundary fitted-coordinate system. Sun et al.(2001) developed a computer model to simulate the sorting of sediment and bar-bend interactions for meandering channel with mixed grain size with fixed bank.

However, the existing literature mostly concentrates on the mixed grain size with fixed bank or uniform sediment with bank erosion, while, on the contrary, the interaction of mixed sediment and bank erosion simultaneously is distinctive feature of natural rivers. Figure 1 shows an example of a meandering river keeping the channel width in nature: the Kushiro river in Hokkaido.

In this paper, a numerical model is proposed to simulate the channel deformation and bed load distribution in time and space simultaneously in the meandering channel as a preliminary study to develop a computer model for calculating the sediment characteristics and bank erosion simultaneously in alluvial channel. And this model was verified with laboratory experiments by Ashida et al.(1990).

2. NUMERICAL CALCULATION

A generalized coordinate system was used to calculate water flows, and the riverbed changes. At first, continuity and momentum equations for a two-dimensional shallow water flow were employed to calculate water flows. Momentum equation was separated into two parts, advection phase and non-advection phase, using the operator splitting method. Advection phase was calculated by the CIP method, high-order accuracy scheme, and non-advection phase was computed by the central difference method. Also, the riverbed changes were solved by the backward

Figure 1. An example of a meandering channel: the Kushiro river in Hokaido

difference method.

The bed load transport rate was calculated by the Ashida-Michiue's(1971) formula:

$$q_{ii} = 17P_i\sqrt{sgd_i^{\,3}}\,\tau_{*i}^{3/2}\left(1-\frac{\tau_{*ci}}{\tau_{*i}}\right)\left(1-\frac{u_{*ci}}{u_{*i}}\right) \quad (1)$$

in which q_{bi} is the bed load transport rate, s is the relative density of grain in water, g is the gravitational force, d_i is the sediment diameter in each size fraction, τ_{*ci} is the dimensionless critical tractive force, τ_{*i} is the dimensionless tractive force, u_{*ci} is the critical shear velocity, and u_{*i} is the shear velocity. P_i is the sediment size fraction i at the substratum, and is calculated by the sediment continuity equation per bed material size fraction in the generalized coordproposed by Hirano(1971) :

$$\delta\frac{\partial P_i}{\partial t} + P_i^*\frac{\partial z}{\partial t} + \frac{1}{J(1-\lambda)}\left[\frac{1}{d\xi}\frac{\partial q_{b\xi i}}{\partial \xi} + \frac{1}{d\eta}\frac{\partial q_{b\eta i}}{\partial \eta}\right] = 0 \quad (2)$$

$$p_i^* = p_i \quad \text{when} \quad \frac{\partial z}{\partial t} \geq 0$$

$$p_i^* = p_{i0} \quad \text{when} \quad \frac{\partial z}{\partial t} < 0$$

in which δ is the thickness of the exchange layer, J is the Jacobian, $q_{b\xi i}$ and $q_{b\eta i}$ are the bed load transport rate for sediment fraction i in the ξ and η direction in generalized coordinate system, respectively. p_i^* is the sediment size fraction i at the bed z, and is equal to p_i when the bed rise and p_{i0} when the bed is eroded.

To calculate bed load transport rate in the transversal direction to primary flow in the meandering channel, secondary flow due to centrifugal force and the slope in the transverse direction were considered. However, the computation of suspended sediment transport rate was excluded in this study.

The velocity near the bed was assumed to the following relation of depth-averaged velocity.

$$\tilde{u}_b^s = \beta V \quad (3)$$

in which $\tilde{u}_b^s$ is the velocity near the bed in the stream line direction, V is the resultant velocity, and using the flow velocity which was the parabolic distribution along a depth, according to Engelund(1974), β becomes as follows.

$$\beta = 3(1-\sigma)(3-\sigma), \quad \sigma = \frac{3}{\phi_0\kappa + 1} \quad (4)$$

where ϕ_0 is the velocity coefficient, κ is the Karman universal constant(=0.4).

In general, when the streamline is curved, a secondary flow is induced by the centrifugal force in the orthogonal direction to the streamline. The sediment transport rate in the orthogonal to the streamline was calculated by considering the secondary flow on the riverbed. The following equation is the water velocity near the bed in the stream line and transversal direction, written as $\tilde{u}_b^s$ and $\tilde{u}_b^n$, respectively :

$$\tilde{u}_b^n = \tilde{u}_b^s N_* \frac{h}{r^s} \quad (5)$$

in which $N_* = 7$ proposed by Engelund(1974) was used, h is the averaged-water depth, and r^s is the radius of a streamline curvature and was given as follows.

$$\frac{1}{r_s}=\frac{1}{V}\left[u^2\left(\xi_x\frac{\partial v}{\partial \xi}+\eta_x\frac{\partial v}{\partial \eta}\right)+uv\left(\xi_y\frac{\partial v}{\partial \xi}+\eta_y\frac{\partial v}{\partial \eta}\right)\right.$$
$$\left.-uv\left(\xi_x\frac{\partial u}{\partial \xi}+\eta_x\frac{\partial u}{\partial \eta}\right)-v^2\left(\xi_y\frac{\partial u}{\partial \xi}+\eta_y\frac{\partial u}{\partial \eta}\right)\right] \qquad (6)$$

where V $(=\sqrt{u^2+v^2})$ is the resultant velocity of u, horizontal flow velocity component in the Cartesian coordinate system, and v, the vertical component in the system.

3. CALCULATION RESULTS

This numerical model was applied to reproduce laboratory experiments of a meandering channel by Ashida et al.(1990) for the purpose of validation. The experiment was conducted in the initial sine-generated-meandering channel with an angle of $\theta_{\max}=35°$ on the initial channel slope I of 0.009. The meandering length, L, was 220cm, and the channel width, B, was 20cm. Water discharge Q of 3.6(l/s) was maintained, and the channel bed consists of bed materials with mean diameter $D_m=1.7mm$, and $D_{90}=4mm$.

Figure 2(a) is the bed load distribution in mean diameter after experiment, and the bed materials are finer at the inside near the bend apex than at the outside. Figure 2(b) shows the channel bed deformation, and the bed is degraded at the outside covered with coarse materials, and aggraded at the inside with fine bed materials. Figure 3(a) is the calculation results of the sediment sorting. The bed changes are shown in Figure 3(b). And these simulation results are quantitatively agreement with the experimental results.

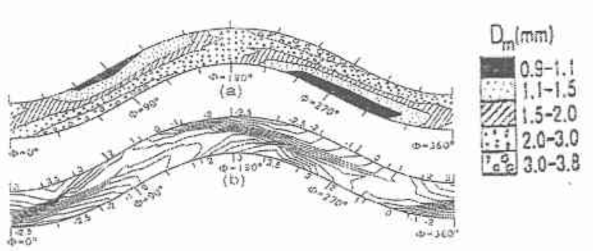

Figure 2. Experimental results by Ashida et al. (1990) ; (a) bed load distribution (mean diameter), (b) the channel bed deformation in equilibrium state.

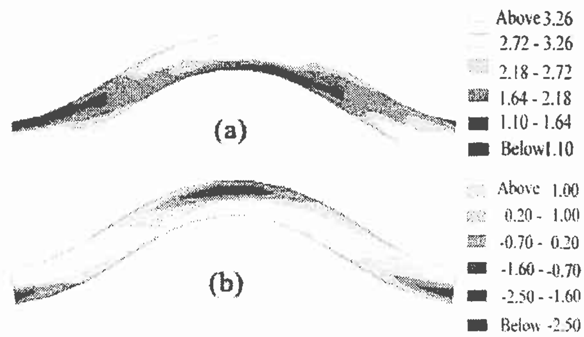

Figure 3. Calculation results; (a) bed load distribution (mean diameter), (b) the channel bed deformation in equilibrium state.

Figure 4 is the calculation results of the bed changes in the natural shaped-channel with uniform bed materials. Figure 5 is the results of the bed changes and the bed load sorting in the channel with non-uniform bed load.

The calculation conditions are that the initial channel slope I is 1/161, the bed is composed of mean diameter $D_m=1.1mm$, and $D_{90}=1.8mm$. Water discharge Q is 1.5(l/s). This calculation results show that the bed with uniform bed load is deeper than with non-uniform bed load.

The bed is scoured deeply in the outside of concave part and narrow width (Fig. 4(b)), and also flow velocity is large (Fig. 4(a)). Figure 5(a) is flow velocity, Figure 5(b) is bed load distribution, and Figure 5(c) is bed deformation. The bed with uniform grain size (Fig. 4(b)) is scoured deeper than with non-

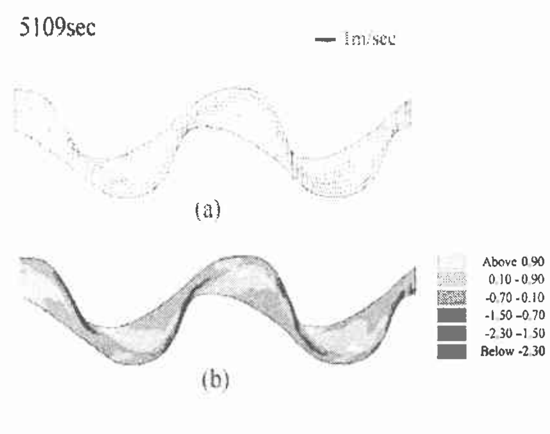

Figure 4. Calculation results in the natural shaped-channel with uniform bed load ; (a) the flow velocity distribution, (b) the bed change

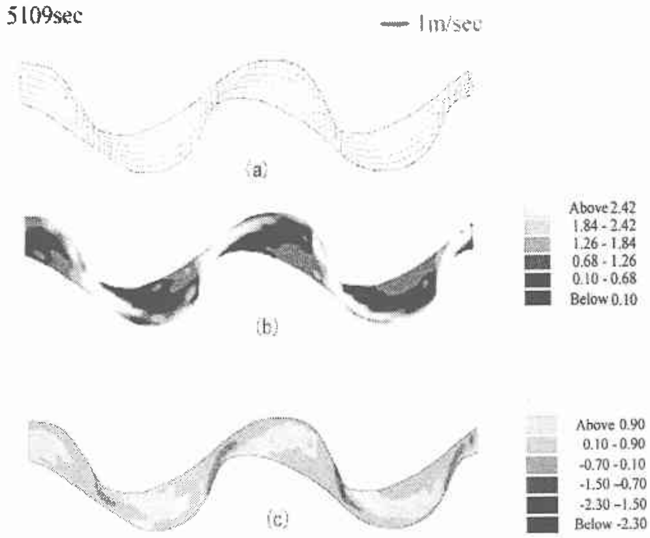

Figure 5. Calculation results in the natural shaped-channel with non-uniform bed load ; (a) the flow velocity distribution, (b) bed load distribution, (c) the channel bed deformation

uniform grain size (Fig. 5(c)), and this is relatively similar to the experimental results by Ashida et al. (1990). As time progresses, the point bar shows up in the inside near the bend, and the bed materials are finer. Although there is no available data to compare the bed deformation and bed load distribution in space and time, the simulation results show relatively good trends.

4. CONCLUSIONS

In this paper, a numerical model is proposed to simulate the channel deformation and the spatial and temporal distribution of bed load simultaneously. The simulation results are compared with laboratory experiments of a meandering channel by Ashida et al. (1990) and are quantitatively agreement with the experimental results. In the natural shaped-channel, the results of the bed changes and the bed load sorting in the channel with non-uniform bed load show the characteristics of natural river with non-uniformity materials, although their applicability was not verified.

In the future a numerical model has to be developed considering the sediment characteristics and bank erosion simultaneously in the meandering channel.

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