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Characteristics of Sediment Transport with Alternate-Bar Migrating

CHARACTERISTICS OF SEDIMENT TRANSPORT WITH ALTERNATE-BAR MIGRATING

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ABSTRACT

Sediment control along river is very important for river management. In order to restore the continuity of sand interrupted by dam, countermeasures to deal with rotational degradation, e.g. placing sand at the downstream of the dam, have been taken in some rivers. To indicate significance of artificial sediment supply in river, we need to know where supplied sediment deposit, how sediment supply makes river morphology change, and so on. Therefore, we focus on the sediment transport on the bars which forms typical landscape of river. We took the experiments to estimate sediment discharge on the bar and to indicate differences between sediment transport on the bars and on the flat bed. As results, characteristics of sediment discharge and sediment transport on the bars are shown.

Keywords: alternative bars, sediment transport, sediment discharge

1. INTRODUCTION

These days, physical environment has dramatically changed in the downstream reach of dam. It is one of the reasons that sediment supply to downstream have decreased. Trial, which sediment supplies to the downstream reach of dam, has started in several rivers of Japan. Considering it, we need to know the optimum way to supply sediment to the downstream of the dam. Therefore, we need to grasp the characteristics of sediment movement and sediment discharge along river.

We can estimate equilibrium sediment discharge on the flat bed by using well-known formula. Although we usually use sediment discharge for plane bed to estimate longitudinal (1D) sediment discharge in river, we don't know the influence of bed shape on total sediment discharge along river. Therefore, we focused on the sediment transport on alternative bars, which form in many rivers, and indicated the differences between the sediment transport on alternative bars and on plane bed with flume experiments and numerical simulations.

2. FLUME EXPERIMENTS

In order to explain the characteristics of sediment discharge and movements along alternative bars, flume experiments were carried out in the laboratory flume (Fig.1), 19m long and 60cm wide. 2 series of experiments have been conducted under the hydraulics conditions that alternative bars can develop. In the first series of experiments, we focus on change of longitudinal sediment discharge with bar developing and characteristics of sediment discharge through alternative bars in equilibrium. In the second series of experiments, we focus on movement of sediment particle on alternate bars.

Experimental Set Up

Table 1

	Water discharge (m^3/s)	Bed slope	Aspect ratio B/H	mode
Pattern 0	0.002	1/100	59.3	1-2
Pattern 1	0.006	1/100	32.2	1

Fig. 1 shows experimental set up in all flume experiments. Bed material is uniform sand of diameter 0.88mm. The channel slope was kept at 1/100. Experimental hydraulic conditions are shown in Table 1. “Mode Number” in Table 1 indicates the initial number of bar mode (n) estimated from the linear instability analysis employed by Kuroki & Kishi(1984).

We grasped sediment discharge by the trial experiment, and decided amount of sediment supply in upstream area. Sediment supply had been done constantly in all series of experiments. In order to measure cross-sectional distribution of sediment amount in addition to total sediment discharge, sediment from outlet of channel had been caught with 6 boxes, which we placed in cross-sectional direction as Fig. 1 shows, each 10 minutes.

Bed elevation had been measured with laser plotter from middle area to downstream area of the channel to grasp the growth of alternative bars. And we had recorded the condition of alternative bars with digital video camera over the channel.

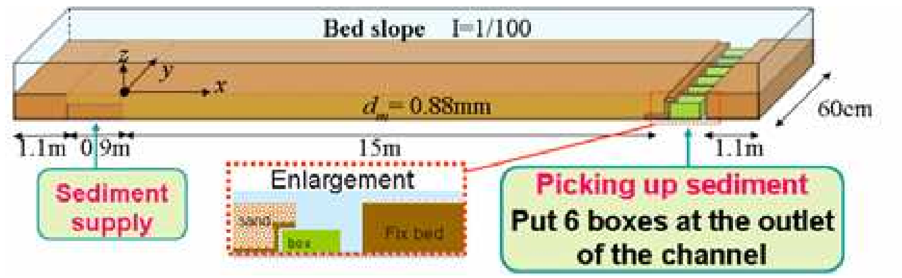


Figure 1 Experimental Set Up

Sediment discharge with bar migrating

In the first series of experiment, we focused on plane distribution of longitudinal sediment discharge through alternative bars. Under the pattern 1 of hydraulics condition in table 1 which alternative bars initially appeared and developed, we measured amount of sediment from outlet of channel.

Fig.2 shows sediment discharge at the outlet of channel and Fig.3 shows bar height. Sediment discharge increased and fluctuated with the growth of alternative bars as shown in Fig.2 and 3. The averaged value of sediment discharge from 5 minutes to 30 minutes is little less than the averaged sediment discharge after 30 minutes in Fig 2 and 3, and the difference between maximum and minimum value of sediment discharge increased after 30 minutes pass.

We show cross-sectional distribution of sediment unit discharge in Fig.4 and bed elevation in Fig.5. Plane distribution of sediment flow becomes clear with growth of alternative bars. Flow of sediment concentrates near left- and right-side walls by turns as shown in Fig.5. When the peak of sediment flow appeared near one side, sediment flow was almost zero near the other side wall. After the place where bed elevation was high, the peak of sediment flow appeared near side-wall.

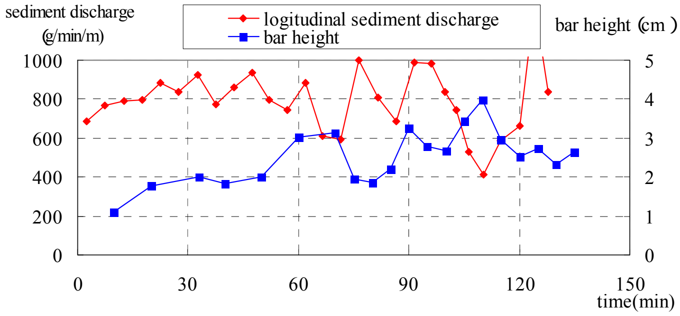


Figure 2 Sediment discharge and bar height in trial experiment (Pattern 1)

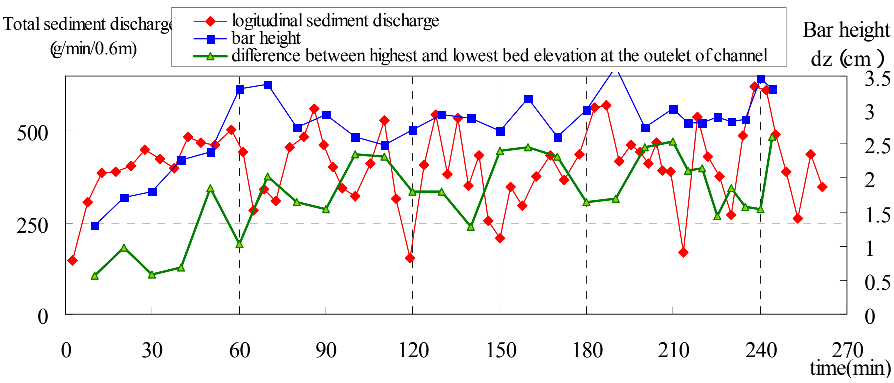


Figure 3 Sediment discharge and bar height, dZ (Pattern 1)

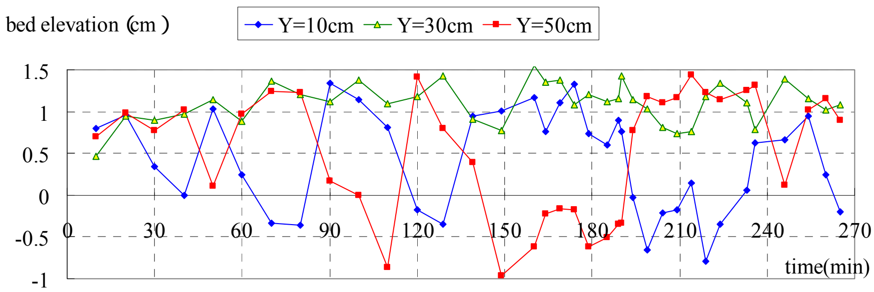


Figure 4 Bed elevations at the outlet of channel

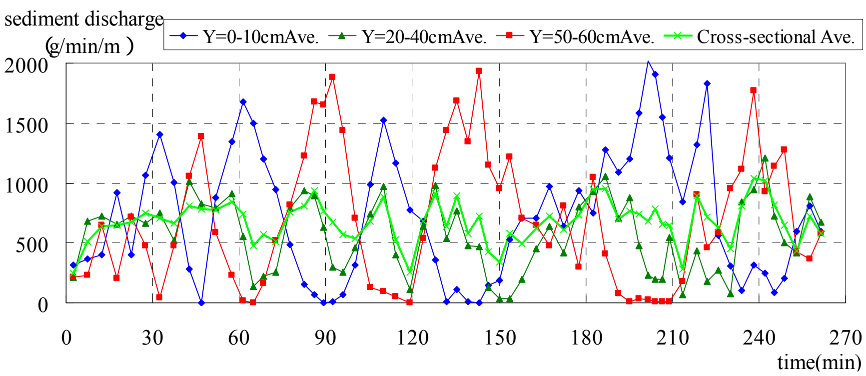


Figure 5 Amount of x-directional sediment transport at outlet of the channel

Fig.6 shows cross-sectional bed shape which averaged longitudinally bed elevation within one or two pair of bars and minimum bed elevation, and also described cross-sectional distribution of sediment discharge which averaged longitudinally within one or two pair of bars. Longitudinal sediment discharge was accumulated near side-wall, while bed elevation was higher at center of the channel. As alternative bars develop, sediment accumulates to center of the channel. Then bed elevation at the center of channel becomes higher than near wall. And longitudinal minimum bed elevation is also lower near wall in Fig.6.

Sediment movement on the bars

In the second series of experiments, we focused on sediment movement through alternative bars and flat bed. In order to investigate movement of sediment particle, we had supplied coloured sands to channel. CaseB11 is that coloured sediment was supplied after alternative bars migrated in equilibrium in the pattern 1 of hydraulics condition as shown in Table 1. We had also supplied coloured sands to flat bed under the pattern 1 and 0 of hydraulics conditions (CaseB01 and CaseB00). Coloured sand were supplied for 10-15 minutes.

In this series of experiments, we try to indicate the characteristics of sediment-particle movement through bars. After stopping water supply, we had measured ratio of colour sediment cover and thickness of coloured sands. A ratio of coloured sand cover was estimated with the pictures of bed surface. Thickness of coloured sand was measure as shown in Fig. 7.

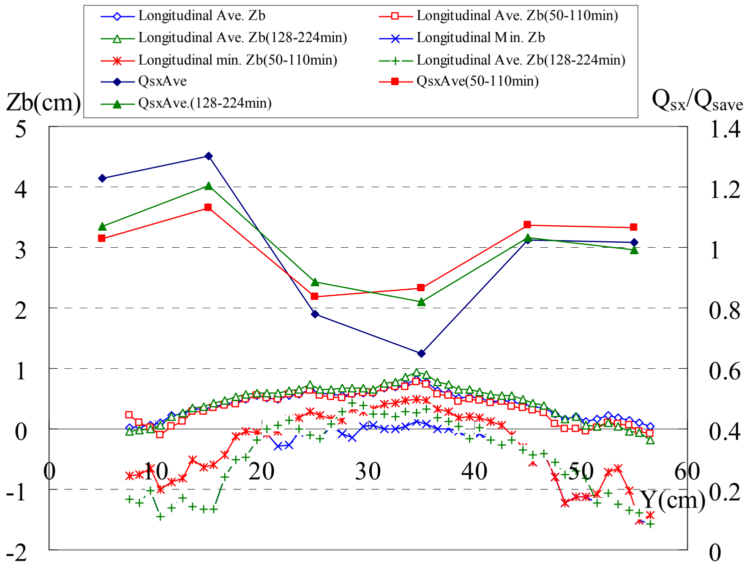
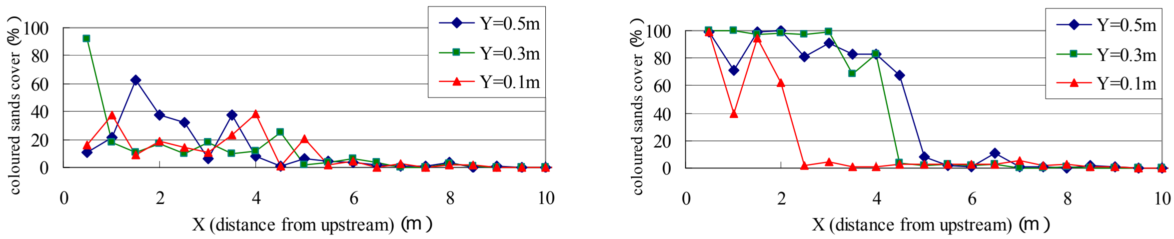


Figure 6 Longitudinal averaged cross-sectional bed shape and minimum bed elevation and ratio of sediment amount averaged within bar length

Figure 7 Measurement for thickness of coloured sands



Case B01 (supplied for 10min.) Case B11 (supplied for 16min.)

Figure 8 Ratio of coloured sands covering bed

Table 2 Spread speed of coloured sand (m/min)

	Case00	Case01	Case11
Y=0.5m (left-side wall)	0.346	0.292	0.306
Y=0.3m (center)	0.244	0.355	0.275
Y=0.1m (right-side wall)	0.565	0.387	0.166
Maximum velosity of sand	0.565	0.387	0.306
Averaged velosity of sand	0.385	0.345	0.249

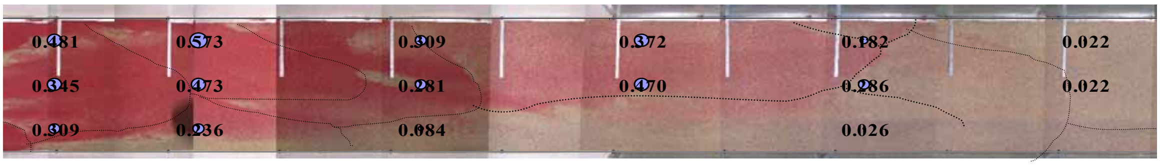


Figure 9 Plane view of channel after coloured sand supply and relationships between bar front and thickness of coloured sands

The results of second series of experiments show that behaviour of sand through alternative bars is really different from on flat bed. Compared with sediment movement on flat bed, sediment through bars moved to downstream one-sidedly in Fig.8. And spread speeds of sand on flat bed are faster than through bars as shown in table 2.

Although thicknesses of coloured sand in CaseB00 and Case B01 are around two millimetres, thicknesses of coloured sand in Case B11 relate to the front of bars as Fig.9 show. Thicknesses of coloured sand are deeper at the upstream of bar front. On the other hands, these of coloured sand are very shallow at the downstream of bar front.

As results, it was found that sands which flow down through bars stop at the front of bars. Therefore, we conclude that sediment through bars move slower than on flat bed. In other word, speed of sediment particle on bars equals to bar-migration speed.

3. NUMERICAL SIMULATION

In order to make us understand the phenomena, which we found in experiments, better, numerical simulation has been done by using NH2D model developed by us at Nagoya University(Pornpronmin *at el.*,2002; Teramoto & Tsujimoto, 2003).

NH2Dmodel

The NHSED2D model comprises two main parts: the flow model and the sediment transport and bed variation model. Firstly, the flow is computed over an initial bed configuration until it converges. Then, the sediment transport and the resultant bed variation are calculated using the pre-calculated flow field. After the bed is renewed, the flow is re-calculated on the modified bed. These procedures are repeated to obtain successive bed deformation.

3.1.1 Flow model of NHSED2D model

The 2D depth-averaged flow model has the following significant features:

- The finite volume method is employed to describe the governing equation.
- The fractional step method is employed in order to obtain the stable and accurate flow field (Ferziger, *at el.*(1997)).
- To prevent numerical oscillation due to collocated grid arrangement, the approach proposed by Rhie and Chow (1983) to interpolate the flux of mass at the cell surface is used.
- The QUICK scheme is employed to interpolate the convection of momentum at the cell surface.

The governing equations of 2D depth-averaged surface flow can be described by the following equations:

$$\frac{\partial q_x}{\partial t} + \mathrm{div}\left(q_x \frac{\mathbf{q}}{h} - \frac{\mathbf{T}_x}{\rho} \right) = -gh\frac{\partial \zeta}{\partial x} - \frac{C_f}{h^2} q_x |\mathbf{q}| \qquad (1)$$

$$\frac{\partial q_y}{\partial t} + \mathrm{div}\left(q_y \frac{\mathbf{q}}{h} - \frac{\mathbf{T}_y}{\rho} \right) = -gh\frac{\partial \zeta}{\partial y} - \frac{C_f}{h^2} q_y |\mathbf{q}| \qquad (2)$$

$$\frac{\partial \zeta}{\partial t} + \mathrm{div}\mathbf{q} = 0 \qquad (3)$$

where t = time; (x, y) = the streamwise and lateral coordinates respectively; (q_x , q_y) = the x and y components of line discharge; $\boldsymbol{q}$ = the line discharge vector, z is the water surface elevation; h = the flow depth; (T_x , T_y) = the x and y components of the Reynolds stress tensor; g = the gravity acceleration; and C_f = the resistance coefficient of bed surface.

3.1.2 Uniform sediment and bed variation models of NHSED2D model

The time variation of bed elevation can be described by the following sediment continuity equation:

$$(1-n_e)\frac{\partial z}{\partial t} = -div\mathbf{q}_b \qquad (4)$$

where n_e = the porosity; z = the bed elevation; and q_b = the sediment flux vector, which is estimated using the formula from Ashida & Michiue (1971). The x and y components of the sediment flux (q_{Bx},q_{By}) are estimated by the following equation:

$$q_{Bx} = q_B \cos\varphi , \qquad q_{By} = q_B \sin\varphi \qquad (5a,b)$$

where $\boldsymbol{q}_B$ = the total bed load transport rate per unit width; and j = the angle of bed-load movement.

The effect of transverse bed slope on the sediment transport is taken into account following Nakagawa *et al* (1986). The model also includes the effect of secondary flow caused by the curvature of streamlines using Engelund's equation (1974). The angle of bed load movement is expressed by the following equation:

$$\varphi = \tan^{-1}\left(\frac{V}{U} - N_*\frac{h}{r}\right) - \tan^{-1}\left(\sqrt{\frac{\tau_{*c}}{\mu_d \mu_f \tau_*}}\frac{\partial z}{\partial n}\right) \tag{6}$$

where (U, V) =the velocity components in the x and y directions respectively; N_* = the coefficient of the strength of secondary flow (=7.0 as given by Engelund (1974)); r = the curvature radius of the streamline; μ_f and μ_d =respectively the static and kinetic friction coefficients of sand grains respectively, τ_* = the Shields number; τ_{*c} = the critical Shields number; and n = the coordinate normal to the stream line.

After calculating bed variation, the bed slope angles $\tan^{-1}(\Delta z/\Delta x)$ and $\tan^{-1}(\Delta z/\Delta y)$ between adjacent grids on the bed are compared with the angle of repose ϕ (about 45 degrees). In the case where the bed slope angle is greater than the angle of repose ϕ, the bed is assumed to collapse to an angle corresponding to ϕ.

3.1.3 Method of numerical simulation on bar formation process

To describe bar formation numerically, some type of disturbance is necessary to be presumed. To discuss sediment discharge, we chose the cyclic boundary condition that potential bars appear in equilibrium (Teramoto & Tsujimoto, 2003). Disturbance applied to initial bed elevation is enough to describe bar formation in numerical simulation with cyclic boundary condition.

Domain length for cyclic condition should be careful to choose because physical condition of bars must depend on boundary length. We used averaged value of bar length in experiments as domain length for numerical simulation.

Characteristics of sediment discharge through bars

In numerical simulation, sediment discharge increase a little and fluctuate with bars developing as shown in Fig.10 and 11. Mean value of sediment discharge through bars is more than on initial flat bed by 5 percent, and Maximum value of sediment discharge is more by 15 percent.

Distribution of sediment transport and water discharge is clearly defined as alternative bars grow. Fig. 12 gives vector of sediment, and Fig.13 gives water flow through bars in numerical simulation. Compared Fig. 12 with 13, the place where sediment move activity is different from the place where water flow concentrates. The place where peak of sediment discharge appear is opposite side wall of the top of bar front. Distribution of sediment transport is almost same as in experiment.

Fig. 14 gives cross-sectional shape of longitudinal averaged bed elevation, and also gives cross-sectional shape of longitudinal averaged value of water and sediment discharge. In this figure, sediment and water discharge concentrate near wall through bars. On the other hand, averaged bed elevation is highest at the center of channel. It is clear that sediment gather to the center of channel as bars develop as shown in experiment.

Characteristics of sediment movement through bars

Results of numerical simulation indicate distribution of sediment discharge through bars and support experimental results as shown in the second paragraph of Chapter 3. In this paragraph, we focus on the sediment movement through bars with both results of numerical simulation and experiments.

Sands, which move to downstream through bars, are clear to stop at the front of bars in experiment. Flow line of numerical results is cross to the front of bars as shown in Fig.15. Time variation of bed elevation (dz/dt) have a peak at the front of bar in Fig.16. However, numerical results doesn't show that sediment discharge is 0 at the front of bar as experimental results shown. Numerical simulation doesn't explain movement of sand near bar front because it doesn't include process of non-equilibrium sediment transport. Therefore, we try to estimate speed of sand movements through bars by numerical simulation results. We compare speed of bar migration with speed of sands which calculated the cross-sectional total sediment discharge and volume of a bar. Volume of a bar is calculated as volume of sands above longitudinal minimum bed elevation. As a result, we found that speed of sand particle almost equals to bar-migration speed. This result indicates that the bar front trap most sediment, and that sediment trapped by bar front cannot move until erosion occur at the point where it trap.

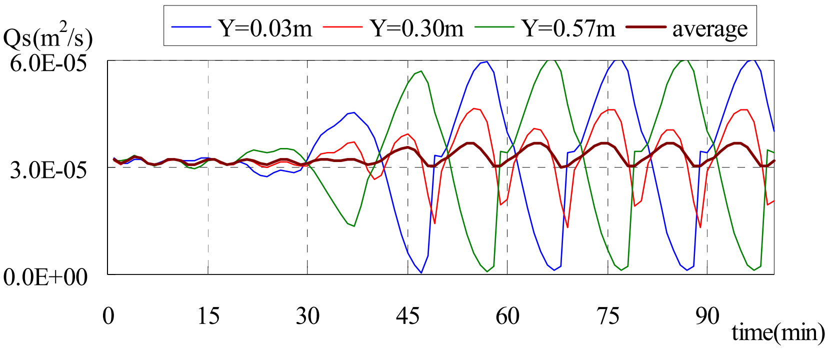


Figure 10 Amount of x-directional sediment transport (side-wall and center and average)

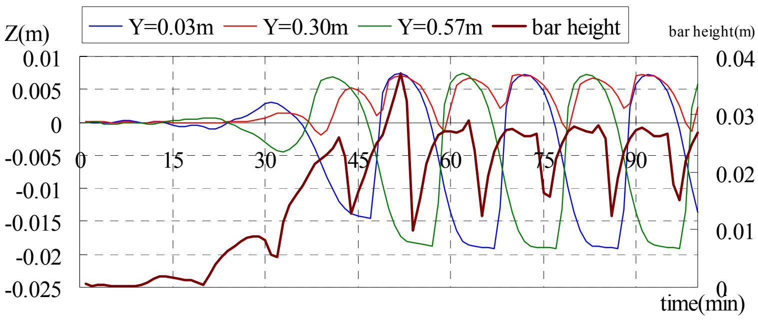


Figure 11 Bar height and Bed elevation(side-wall and center)

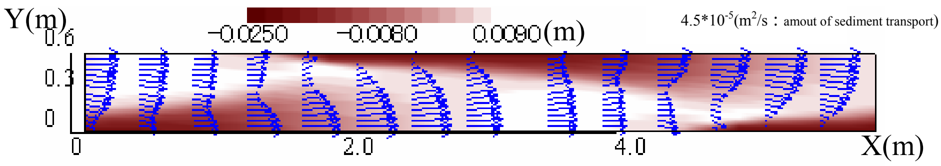


Figure 12 Bed topography and vector of sediment discharge

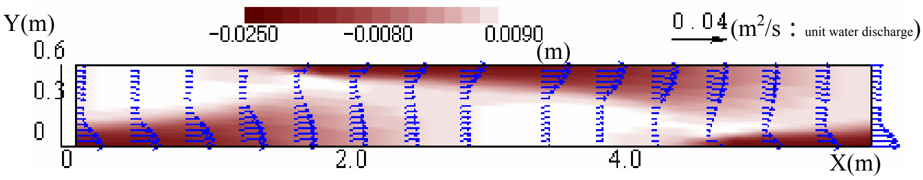


Figure 13 Bed topography and vector of water discharge

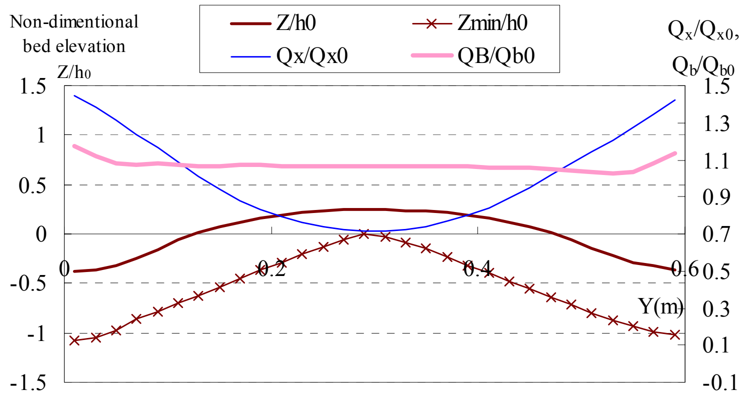


Figure 14 Cross-sectional shape of longitudinal averaged value of bed elevation and sediment and water discharge

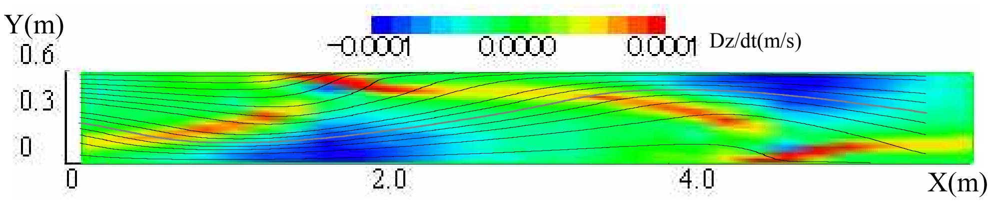


Figure 15 Contour of dz/dt(m/s) and sediment flow line

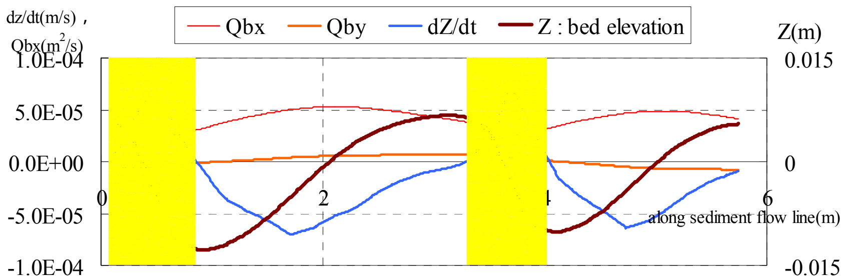


Figure 16 Bed elevation and sediment discharge and dz/dt along sediment flow line

4. RESULTS

We focus on sediment discharge and sediment movement through alternative bars in the condition that bars migrate on the bed consisted of uniform sediment. By experiments and numerical simulation, we could grasp the following characteristics of sediment discharge through bars.

- Total sediment discharge on the bars is little more than on plane bed.
- Alternative bars make sediment discharge distributed.
- Although bed elevation becomes higher at center of the channel longitudinally as bars develop, water and sediment discharge concentrate near side-wall on the bars.
- The speed of sand on flat bed is faster than through bars because sand trap at the front of bars.
- The speed of sand particle is almost same as that of bar migration.

The movement of sand through bars and sediment discharge are very important for river management, which focused on sediment control, because it is different from that on the plane bed. For the next step, we will focus on sediment discharge on the bed consisted of mixture sediment. And we will also focus on sediment movement in the condition that non-equilibrium bar change.

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