NUMERICAL COMPUTATION OF ANTIDUNE MIGRATION USING 3D FLOW MODEL

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ABSTRACT

Corresponding to hydraulic condition, various types of micro scale sand waves form over a sand bed and flow resistance is changed in the development or transition processes of sand waves. Consequently, prediction of flow resistance is of great importance in river engineering. In this study, formation process of antidunes is simulated by coupling the 3D flow model which solves simultaneously surface and seepage flows in the Cartesian coordinate and equilibrium sediment transport model. Water surface variations are calculated by using the density function method, and porous media approach is applied to simulate both surface and seepage flows. The numerical model is applied to the previous experiments by Inoue et al., and the characteristics of water surface and sand waves, and migrating direction are examined. The numerical model can simulate the development process of antidunes from the flat bed, and the downstream migration of antidunes can be reproduced reasonably, by considering the effect of seepage flow.

Keywords: antidunes, numerical simulation, sediment transport, migrating direction

1. INTRODUCTION

Various types of micro scale sand waves form over a sand bed, corresponding to hydraulic condition, and flow resistance is varied in the development or attenuation processes of sand waves. Therefore, for risk management, it is of great importance to understand the mechanism of the development process of sand waves and predict flow resistance. In this study, we focus on the formation process of 3D antidunes and migration direction in this process. To predict the development process of antidunes, a depth averaged flow model considering the effects of vertical acceleration and local flow patterns is used in the previous study (Iwasaki et al., 2018; Uchida and Fukuoka, 2013). However, the formation process of antidunes migrating the downstream are not simulated so far. Consequently, numerical simulation is carried out by coupling the 3D flow model which solves simultaneously surface and seepage flows in the Cartesian coordinate and equilibrium sediment transport model. Applicability of the numerical model is verified, comparing the previous experimental results.

2. NUMERICAL METHOD

2.1 Flow model

To simulate development process of antidunes, a 3D flow model (Onda et al., 2019) and equilibrium sediment transport model are coupled. In the flow model, to calculate water surface variations in unsteady flows, a density function method which solves advection equation of volume fraction in liquid phase is applied. In addition, the concept of volume fraction in the solid phase based on a porous media approach is used. The basic equations are described in the following:

$$\frac{\partial(1-c)\Phi}{\partial t}+\frac{\partial(1-c)u_j\Phi}{\partial x_j}=0 \tag{1}$$

$$\frac{\partial}{\partial t}\{(1-c)u_i\}+\frac{\partial}{\partial x_j}\{(1-c)u_iu_j\}=(1-c)g_i-\frac{(1-c)}{\rho}\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left\{-(1-c)\overline{u'_iu'_j}\right\} +\nu\frac{\partial}{\partial x_j}\left\{(1-c)\frac{\partial u_i}{\partial x_j}\right\}-\frac{\nu(1-c)^2u_i}{K_d} \tag{2}$$

$$\rho=\Phi\rho_{liq}+(1-\Phi)\rho_{gas} \tag{3a}$$

$$\mu=\Phi\mu_{liq}+(1-\Phi)\mu_{gas} \tag{3b}$$

where, x_i = Cartesian coordinate; t = time; u_i = velocity vectors in the x_i directions; Φ = density function; c = volume fraction in the solid phase; p = pressure; ρ = density of fluid; ρ_{liq} = density of water; ρ_{gas} = density of gas; μ = viscosity of fluid; μ_{liq} = viscosity of water; μ_{gas} = viscosity of gas; ν = kinematic viscosity of fluid; g_i = gravitational acceleration vector; $-\overline{u'_i u'_j}$ = Reynolds stress; K_d = intrinsic permeability. The subscript indexes i and j denote the value of 1, 2 and 3 indicating the x, y and z directions, respectively. The last term in equation (2) is resistance force and Darcy's law is applied for simplicity in this study.

The second order nonlinear $k-\varepsilon$ model is used for turbulence model (Kimura and Hosoda, 2003). The details of model constants are described in Kimura and Hosoda (2003).

2.2 Bed deformation model

In this study, only bed load is considered as sediment transport, and an equilibrium sediment transport model is applied. The equations proposed by Kovacs and Parker (1994), and Hasegawa (1984) are used for bed load fluxes in the streamwise and transversal directions, respectively

$$q_{bs} = \frac{u_p/u_*}{\mu_k\left(1+\frac{\partial z_b}{\partial s}/\mu_k\right)}\left[\tau_* - \tau_{*c}\left(1+\frac{\partial z_b}{\partial s}/\mu_k\right)\right] \times\left[\tau_*^{1/2} - \tau_{*c}^{1/2}\left(1+\frac{\partial z_b}{\partial s}/\mu_k\right)^{1/2}\right]\sqrt{\left(\frac{\sigma}{\rho}-1\right)gd^3} \tag{4a}$$

$$q_{bn} = q_{bs}\left(-\sqrt{\frac{\tau_{*c}}{\mu_s\mu_k\tau_*}}\frac{\partial z_b}{\partial n}\right) \tag{4b}$$

$$\frac{\partial z_b}{\partial t} + \frac{1}{1-\lambda}\left(\frac{\partial q_{bx}}{\partial x} + \frac{\partial q_{by}}{\partial y}\right) = 0 \tag{5}$$

where, q_{bs} = bed load flux in the streamwise direction; q_{bn} = bed load flux in the transversal direction; τ_* = dimensionless tractive force; τ_{*c} = dimensionless critical tractive force (calculated by Iwagaki equation) ; σ = density of sand material; d = grain size of sand material; z_b = bed level; μ_s = coefficient of static friction of sand; μ_k = coefficient of dynamic friction of sand.

After converting q_{bs} and q_{bn} to q_{bx} and q_{by}, bed variations are calculated by using continuity equation of sediment transport represented by equation (5).

3. APPLICATION OF NUMERICAL MODEL

3.1 Computational condition

The numerical model is applied to Run7 in the experiments conducted by Inoue et al (2015). In the experiment, a channel is 25 m long, 0.5 m wide, the bed slope is 0.018, and flow discharge is 0.0429m^3/sec. The ration of width to depth in Run7 is 6.7 and the number of waves in the lateral direction is constantly 1~2 throughout the experiment. Water surface is in phase of bed surface and both waves migrate to downstream.

In terms of computational time, it is difficult to simulate the flow fields in the same scale with the experiments, and computational flow domain is set as shown in Figure 1. Additionally, to stabilize the calculation, fixed bed areas are installed in both upstream and downstream sides. As boundary conditions, flow discharge and water depth are determined at upstream end, and gradient for hydraulic parameters are set to be 0 at downstream end. In the initial condition, small disturbance is given for the bed level, to initiate the formation of sand waves. The thickness of sand layer is 0.06 m, and grid size in the streamwise, transversal and vertical directions are 0.05 m, 0.05 m and 0.003 m, respectively. Time interval is 0.0001 s.

In this study, the effect of seepage flow on migrating characteristics of antidunes is examined, by comparing two cases of the calculations; Case1 and Case2. In Case1, the calculation is started from the flatbed and the effect of seepage flow is considered throughout the calculation. On the other hand, in Case2, the calculation is started from flatbed, then from 35 s, the effect of seepage flow is not considered, by changing the value of hydraulic permeability. By comparing the results in Case1 and Case2 in terms of the characteristics of water surface and sand waves, and migrating direction, we examine the effect of seepage flow.

3.2 Results and discussion

Figure 2 shows temporal change of bed level for Case 1. The formation of 3D antidunes are observed and the number of sand waves in the lateral direction is about 1~2. Figure 3 presents the temporal change of flow fields at the center section (t = 35 s, 40 s, 45 s), and the color contour represents the volume fraction in the liquid phase. By checking the waves indicated by arrows, it can be confirmed that surface waves and sand waves migrated to downstream in the same phase.

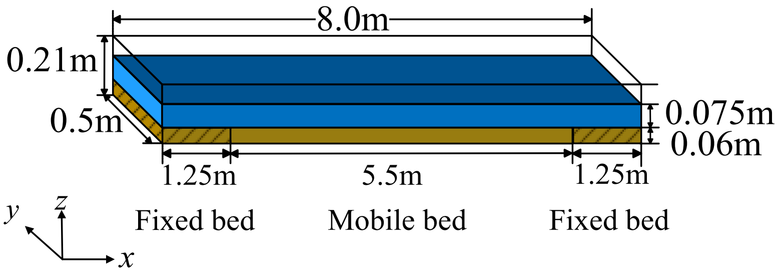
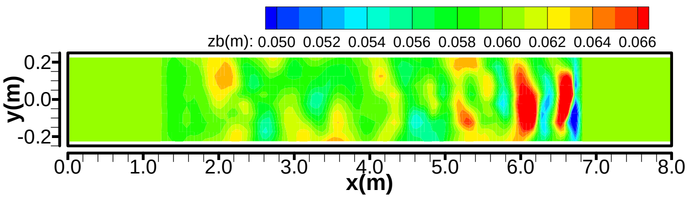
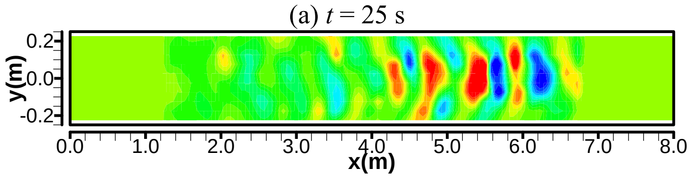


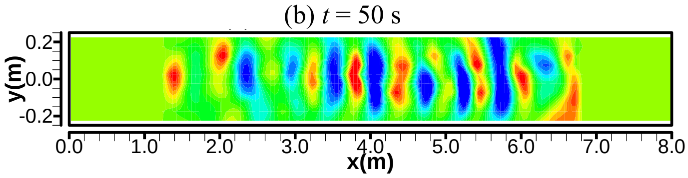
Figure 1. Computational flow domain



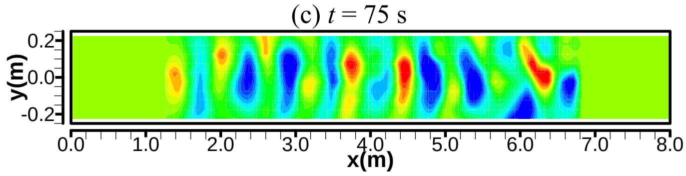
(a) $t = 25$ s



(b) $t = 50$ s

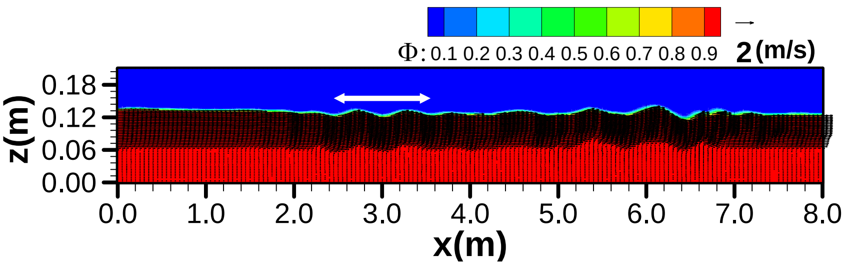


(c) $t = 75$ s

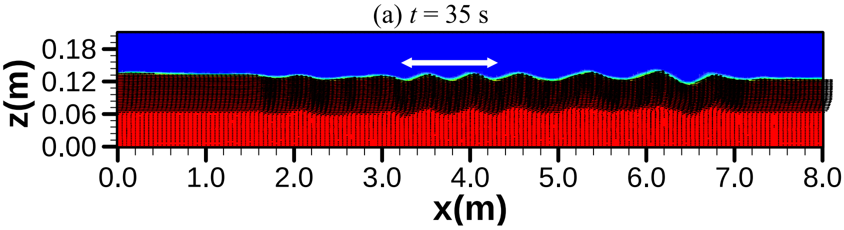


(d) $t = 100$ s

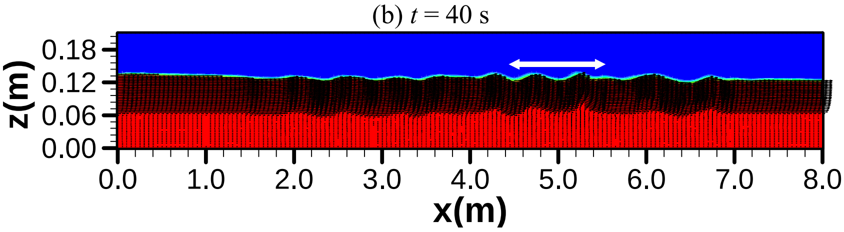
Figure 2. Temporal change of bed level (Case1)



(a) $t = 35$ s

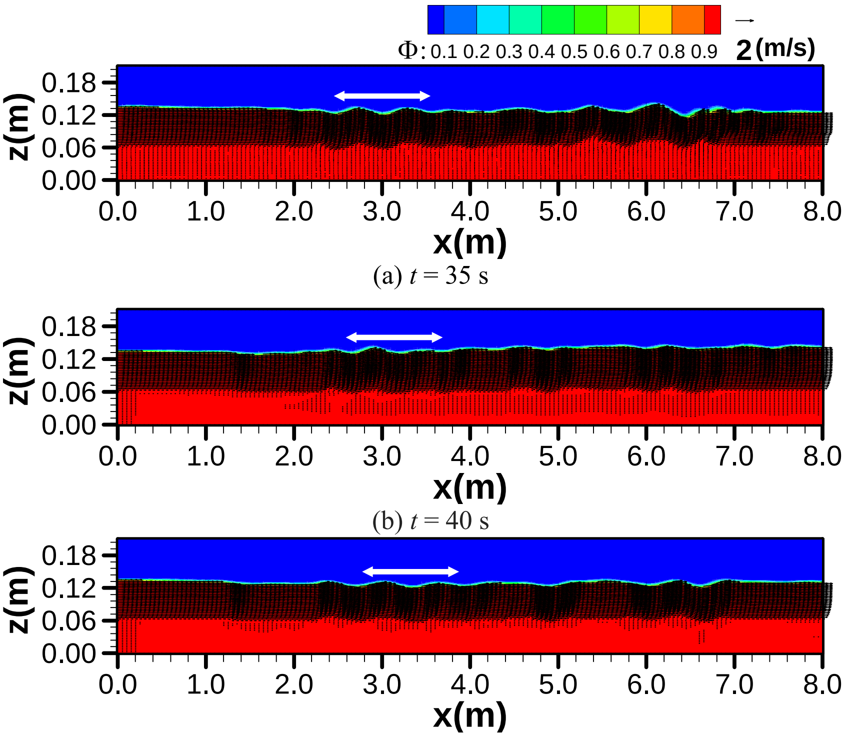


(b) $t = 40$ s



(c) $t = 45$ s

Figure 3. Temporal change of flow fields (Case1)



(a) t = 35 s

(b) t = 40 s

(c) t = 45 s

Figure 4. Temporal change of flow fields (Case2)

Figure 4 presents the temporal change of flow fields at the center section(t = 35 s, 40 s, 45 s). Comparing with Case1, migrating speed of surface and sand waves is drastically slowed down in Case2. Thus, it can be said that the effect of seepage flow is a key role in migrating direction of antidunes in the numerical simulation. In previous numerical analysis, antidunes migrating downstream has not been reproduced yet. On the other hand, in this study, antidunes migrating downstream are satisfactorily reproduced by using the 3D flow model which solves both surface and seepage flows.

The following is the supposed reason of downstream migration of antidunes. In the simulation of Case1, seepage flow with low velocity joins surface flow with high velocity at the downstream of crest, considering the effect of seepage flow. This makes the flow velocity there slowed down, and bed load fluxes behind the crest are reduced. Then, by applying the continuity equation of sediment transport, the characteristics of antidunes migrating downstream are reproduced.

4. CONCLUSIONS

In this study, a numerical simulation in the formation process of 3D antidunes is carried out by coupling a 3D flow model and equilibrium sediment transport model. Applying the previous experimental study, it is concluded that the formation process of antidunes migrating downstream is reasonably simulated in this model.

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