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MECHANICS OF SEDIMENT MOTION AS BED MATERIAL LOAD

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SYNOPSIS

Bed material load has been classified into bed load and suspended load, both of which have been studied separately. Studies of bed load and suspended load have mostly been based on the equation of motion and the diffusion equation, respectively. Such studies work fairly well in predicting sediment transport rate, but several serious problems arise. For example, in the range of intermediate tractive force where bed load and suspended load coexist, sediment motion has a different character from that of typical bed load or typical suspended load according to the experimental observation. An essential question still remains whether transport of suspended load is a diffusion phenomenon or not. So as to understand the moving characteristics of bed material load, a numerical simulation was carried out in the present study by using the modified saltation model in which the effect of flow turbulence on a sediment motion is taken into account. The generation model of turbulent velocity fluctuation adopted here is similar to the one by Ohmoto and Hirano (12), and was constructed based on the information by Nezu and Nakagawa (8). The mechanism of transition between bed load and suspended load was investigated, and the effect of turbulence on the moving trajectory of bed material load is clarified in this paper.

INTRODUCTION

Bed material load is the transport of sediment that inherently constitutes the river channel itself. The life of moving sediment as bed material load starts by being picked up from the bed and ends by being deposited on the bed. Therefore river channel deformation occurs due to the temporal and spatial imbalance of its transport rate. The studies on bed material load in literatures are reviewed briefly as follows.

In the region of a tractive force slightly larger than the critical value, sediment moves in the vicinity of the bed surface and its trajectory is relatively regular. Such sediment transport is named "bed load". Extensive studies have been performed by several researchers, and can be classified into the following three categories according to their manner of approaches; [1] a stochastic model by Einstein (3), Satoh, Kikkawa and Ashida (16) and Nakagawa and Tsujimoto(9), [2] a sliding type model by Ashida and Michiue (2) and Engelund and Fresoe (4), and [3] a saltation model by Tsujimoto and Nakagawa (22), Sekine and Kikkawa (17), (20), (21), Wiberg and Smith (25), Anderson and Haff (1), Gotoh, Tsujimoto and Nakagawa (6). The saltation model is the most refined model that enables us to understand the mechanics of sediment transport. The model is a typical particle-fluid model, and is based on the equation of motion for a sediment particle.

In the higher tractive force range, where the ratio of the frictional velocity to the terminal falling velocity u^*/w_o is much larger than unity, the dominant motion of the sediment is strongly affected by the turbulent motion of the water. The trajectory of moving sediment fluctuates randomly. Such type of sediment transport is named "suspended load" or "suspension". Due to the randomness, the transport of suspended load was mostly analyzed as a diffusion phenomenon. A pioneering work was done by Rouse (14) in 1937. He published the well-known "Rouse formula" of suspended sediment concentration, which enables us to predict the vertical distribution of relative concentration to the reference concentration in an equilibrium state. One year later, he also published the memorial experiment (15) on the vertical distribution of sediment concentration. The investigation was performed in a cylindrical tank with oscillating grid bars which generated turbulence, and the test sediment was supplied through the water surface. No sediment exists on the bottom of the tank. The reason why he developed the "Rouse formula" of the relative concentration and performed the above experiment was that he was not aware that the bed surface is the supplying source of sediment. The influences of his famous works still remain at the present, so most analyses on suspended load have been based on the diffusion equation, and no definite consideration was given to the interrelation between bed material and suspended load. The only exceptions are the works by Fujita and Ashida (5), Ohmoto and Hirano (12) and Sekine and Kikkawa (18) which were based on the equation of motion for a sediment particle. The above mentioned idea proposed by Rouse leads to the following problems which have been difficult to solve; the accurate predictions of [1] a reference concentration and [2] the diffusion coefficient of sediment concentration. An essential question arises whether it is possible to analyze suspended load in the same way for dissolved material like a dye, because the diameter of some sediment can be larger than the eddy size, and its mass density is larger than that of water, which results in its settlement.

In the range of intermediate tractive force where "bed load" and "suspended load" coexist, sediment motion appears to be the combination of typical bed load and suspended load, and the transition from one to the other occurs. But most notable is that there exists an intermediate type of motion that is neither typical bed load nor suspended load. In such a case, the accurate way to evaluate the concentration and the moving velocity of sediment at the interface that locates at the upper edge of the bed load layer is indispensable so as to predict the total sediment transport rate more accurately. But no definite investigation has been made yet except for the works by Tsujimoto and Nakagawa (23), Nakagawa, Tsujimoto, Murakami and Gotoh (10).

Tsujimoto and Nakagawa (23) have also pointed out the problems on suspended sediment concentration described above, and investigated the transition process from bed load to suspended load. Physical meanings of a reference concentration and the diffusion coefficient for suspended load were explained in the same paper (23). Nakagawa, Tsujimoto, Murakami and Gotoh (10) studied the mechanism of transition, and following points were made clear; [1] the transition process from bed load to suspended load can be defined as an instability problem of particle trajectory, [2] the mechanism of transition is described by a logistic equation deduced from the equation of particle motion, [3] the relationship between transition probability and dimensionless tractive force was proposed.

In the present paper, the motion of bed material load is simulated on the basis of the equation of motion by using a modified saltation model in which the effect of turbulence is considered, in order to understand the motion itself more clearly. The result presented here is expected to constitute the foundation toward the understanding of the transportation mechanism of bed material load.

NUMERICAL SIMULATION MODEL OF BED MATERIAL LOAD

Summary

The model presented here is the "particle-fluid model" in the field of multiphase flow which has been clearly introduced by Ashida, Egashira et al. (13) recently. The model was restricted to be a simple "1-way model", in which the interaction between the particle phase and the fluid phase was not considered. This constraint is due to the fact that no acceptable way to quantify the interaction term in governing equations of water flow has been established yet now, though Gotoh, Tsujimoto and Nakagawa (6) proposed their model. So the model presented here was kept to be in the simplest form and some space are left open for further extension.

The present model is an extension of the 3-D saltation model constructed by Sekine and Kikkawa (20). The bed materials are modeled to be composed of a uniform sediment in size, and are arranged to constitute a flat bed from a macroscopic point of view. But the uneven bed surface is generated on a diameter scale from the microscopic point of view. Such a generation model of random bed surface was developed in a previous paper (20) on the basis of an experimental observation. Only the newly included sub-models are described in the later pages, and the rest of the numerical model is referred to the previous paper (20).

Equation of motion

The equation of motion that governs sediment transport as bed material load is written in the vectorial expression as follows;

$$\rho\sigma_s V\frac{\partial \vec{u}_p}{\partial t}=\rho(\sigma_s-1)V\vec{g}+\rho V\frac{\partial \vec{u}_f}{\partial t}+\frac{1}{2}\rho C_D A|\vec{u}_r|\vec{u}_r+\rho V C_M\frac{\partial \vec{u}_r}{\partial t}+\frac{1}{2}\rho C_L A\left((u_{rx}^2)_T-(u_{rx}^2)_B\right)\vec{i} \qquad (1)$$

in which ρ = mass density of water, A and V = projected area and volume of the particle, respectively, which are equal to $\pi D^2/4$, $\pi D^3/6$ in case of the spherical particle whose diameter is D. $\vec{u}_r$ = relative fluid velocity exerting on the moving particle $\vec{u}_f-\vec{u}_p$ ($\vec{u}_f$ = fluid velocity, $\vec{u}_p$ = particle moving velocity), and its components are defined as $\vec{u}_r=(u_{rx}, u_{ry}, u_{rz})$. The brackets $(\ )_T$ and $(\ )_B$ in the fifth term on the right hand side indicate the values at the top and the bottom of the moving particle, respectively. The gravitational acceleration vector is defined as $\vec{g}=(g\sin\theta,\ 0,\ -g\cos\theta)$ in which g = the gravitational acceleration, θ = the angle of bed slope in streamwise direction, $\vec{i}$ = the unit vector whose components are $(0,0,1)$. C_M= coefficient of added mass (= 0.5), C_L = the lift coefficient which is assumed to be constant (= 0.2) referring to the study by Wiberg and Smith (25). C_D = the drag coefficient which has a functional relationship with the particle Reynolds Number $R_{ep}=|\vec{u}_r|D/\nu$ (ν = fluid kinematic viscosity). The following approximate relation is used in this study; $C_D=24/R_{ep}+3/\sqrt{R_{ep}}+0.34$. The Basset term is neglected in Eq. 1 referring to the study by Sekine and Kikkawa (19).

Turbulence Generation Model

The most important factor in simulating the motion of bed material load is the turbulence of flow. Nezu and Nakagawa (8) performed extensive theoretical and experimental investigations on turbulent structures. Referring to their study, the following turbulence generation model was constructed, which is similar to the one by Ohmoto and Hirano (12). Streamwise and vertical components of turbulent velocities of fluid surrounding a moving sediment particle are generated in Lagrangian space. The transverse component is neglected because no serious influence on sediment transport is expected, and also because no definite information about the correlation between it and the other two components has been obtained.

According to the theory of Markov chain, the streamwise turbulent velocity $u'_f(t)$ at time t can be expressed in the following equation with the velocity $u'_f(t-\delta t)$ at the time $t-\delta t$,

$$u'_f(t) = \rho_t \times u'_f(t-\delta t) + \phi_u \qquad (2)$$

in which ρ_t = auto correlation coefficient which is defined by $\rho_t = \exp(-\delta t/T_L)$, T_L = the Lagrangian eddy life time and is written in relation with an Eulerian time scale T_E as follows (7), (24);

$$T_L = 0.4\frac{u}{\sigma_u}\times T_E \qquad (3)$$

in which u = temporally averaged primary velocity, σ_u = turbulent intensity in streamwise direction. Considering that ϕ_u in Eq. 2 is a random component, $u'_f(t)$ can be generated by using a normal random number in accordance with the following probability density function:

$$p\left(u'_f(t)\middle|u'_f(t-\delta t)\right) = \frac{1}{\sqrt{2\pi}\sigma'_u}\exp\left\{-\frac{\left(u'_f(t)-m_u\right)^2}{2\sigma'^2_u}\right\} \qquad (4)$$

where $\sigma'_u = \sqrt{1-\rho_t^2}\times\sigma_u$, $m_u = \rho_t u'_f(t-\delta t)$.

The vertical turbulent velocity $w'_f(t)$ is known to have a mutual correlation with $u'_f(t)$. Considering this correlation, $w'_f(t)$ can be generated in a similar manner as $u'_f(t)$ in accordance with the following function;

$$p\left(w'_f(t)\middle|u'_f(t)\right) = \frac{1}{\sqrt{2\pi}\sigma'_w}\exp\left\{-\frac{\left(w'_f(t)-m_w\right)^2}{2\sigma'^2_w}\right\} \qquad (5)$$

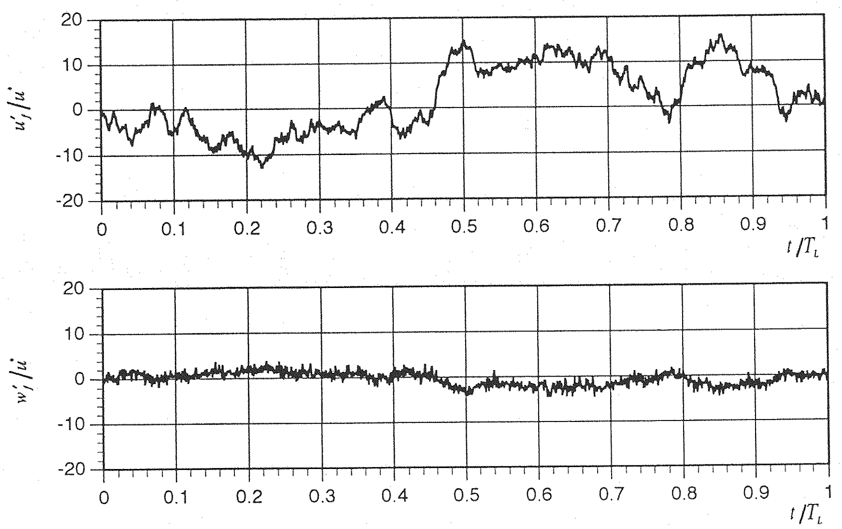

Fig. 1 Time-series of turbulent velocities generated by the present model

in which ρ_{uw} = mutual correlation coefficient, and $\sigma'_w = \sqrt{1-\rho_{uw}^2}\times\sigma_w$, $m_w = \rho_{uw}\left(\sigma_w/\sigma_u\right)u'_f(t)$.

Turbulent intensities σ_u and σ_w are set equal to the depth averaged value of the following equations by Nezu and Nakagawa; $\sigma_u = 2.30u^*\exp(-z/h)$ and $\sigma_w = 1.27u^*\exp(-z/h)$. T_L and ρ_{uw} are also set to be the depth averaged value, and therefore $\rho_{uw} = -0.375$. The effect of the vertical distribution of these variables on sediment movement has been investigated in the paper (11).

Some examples of the time-series of turbulent velocities generated by using the present model are depicted in Fig. 1.

MECHANISM OF TRANSITION FROM BED LOAD TO SUSPENDED LOAD

Nakagawa and Tsujimoto (10) studied the mechanism of transition from bed load to suspended load by using a stochastic technique. In this paper, the mechanism is investigated by simulating a particle motion dynamically. The motion in the first jump was analyzed to clarify the effect of turbulent motion of water on the transition. In Fig. 2, typical examples of calculated results are shown, which were obtained under the condition that $D = 0.366\ (mm)$, $u^*/w_0 = 1$ and the initial velocity vectors $\vec{u}_{p\ initial} = 20.0\times\ (\cos(\pi/3), \sin(\pi/3))\ (cm/\sec)$. The trajectories of sediment particle, the instantaneous vertical velocity components of fluid and sediment particle, the accelerations, and each term in governing equation (Eq. 1) are depicted respectively for three cases. Fig. 2 (a) shows the calculated result without any consideration of turbulence in water. Figs. 2 (b) and (c), on the other hand, are the results obtained by considering the effect of turbulence, and show that the particle trajectory deviates upward or downward from the deterministic trajectory, respectively. From the results of extensive numerical simulation, the followings are clarified; [1] the critical value of u^*/w_0 at which the deviation from the deterministic trajectory of saltation occurs is about 0.4 or 0.5, [2] the gravitational term, the fluid acceleration term and the drag term (the first, second and third terms on the right hand side of Eq. 1) are dominant in the vertical movement except for the initial motion, [3] the acceleration of sediment movement correlates strongly with that of fluid, but the sediment cannot respond to the velocity fluctuation of fluid whose frequency is high enough to exceed some critical value , [4] even if the frequency of fluid velocity fluctuation is less than the critical, a sediment particle needs some lag distance or time before it can fully respond to the fluid motion, [5] the upward deviation in trajectory, for example, does not occur immediately after the action of an instantaneously high upward velocity of fluid, but occurs after a series of relatively high upward velocities and accelerations.

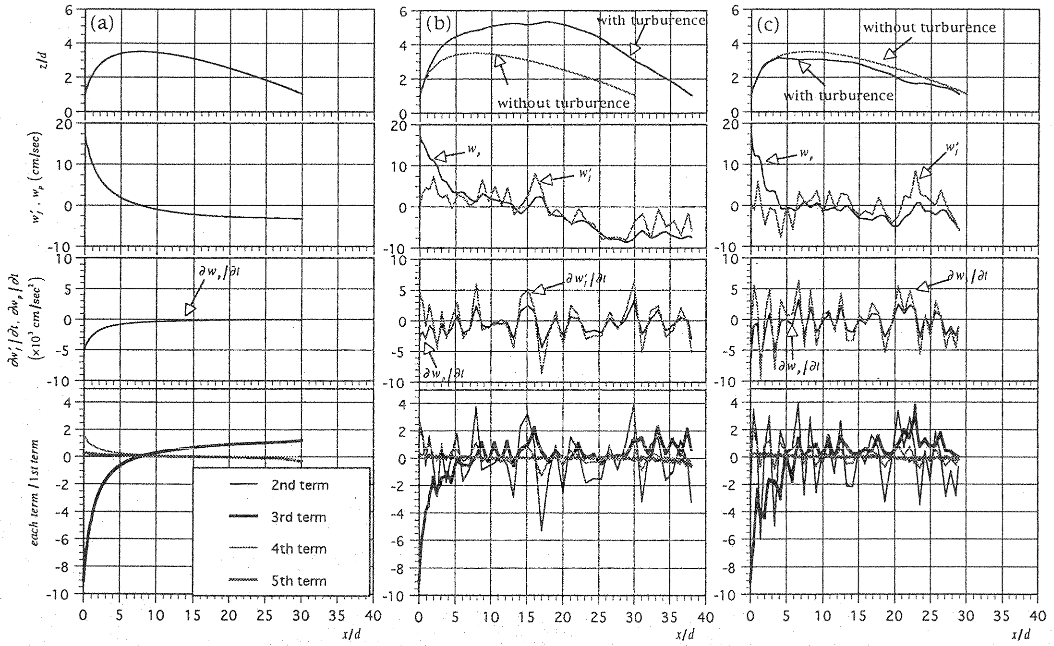

Fig. 2 Analysis of the effect of turbulence on the moving trajectory of sediment particles; (a) without turbulence, (b) and (c)with turbulence, at $u^*/w_0 = 1$. The bottom figure in each case shows the magnitude of each term in Eq. 1 as the dimensionless values normalized by the 1st. term.

EFFECT OF TURBULENT VELOCITY ON MOVING TRAJECTORY

The moving trajectory of bed material load is analyzed by changing the parameter u^*/w_0 under the condition that sediment size and bed gradient are constant; $D = 0.366\ (mm)$ and $i_b = 1/500$. Typical trajectories for different values of tractive force u^*/w_0 are shown in Fig. 3. These trajectories were obtained by tracing a sediment particle moving on or over the randomly generated bed. As is seen from Fig. 3 (a) where $u^*/w_0 = 0.4$ ($\tau^* = 0.10$), the trajectory shows no fluctuation in each jump even though the height and the distance of each jump is random due to the irregular collision with bed particles. Such a trajectory is known to be that of typical saltation which is not affected by the turbulent motion of water. In Fig. 3 (b) where $u^*/w_0 = 0.5$ ($\tau^* = 0.166$), the transition between a typical "bed load" and a typical "suspended load" appears in a series of trajectories, and each trajectory shows a deviation from the regular path as is seen in Fig. 3 (a). As the value of u^*/w_0 increases, the trajectory becomes the larger and more fluctuating one because the effect of turbulence on the particle motion becomes substantial. In Fig. 3 (c) where $u^*/w_o = 1.0$ ($\tau^* = 0.662$), randomly fluctuating motion becomes dominant which is equivalent or similar to the motion of suspended sediment. It can be concluded that the transition occurs under the condition that u^*/w_o is larger than 0.5, and suspended load becomes dominant under the condition $u^*/w_o \geq 1.0$.

CONCLUSION

The motion of bed material load is investigated by using a modified version of saltation model, in which the effect of turbulence is taken into account. As a result of the present study, the following points are made clear or reconfirmed; [1] the trajectory of bed material load appears to be composed of that of typical bed load and suspended load, and the transition from one to the other occurs naturally, but there exists an intermediate type of motion that is neither typical bed load nor suspended load, [2] the transition occurs under the condition that $u^*/w_0 \geq 0.4$ or 0.5 due to the strong influence of turbulent acceleration of fluid, [3] the typical motion of "suspended load" is dominant in the range that $u^*/w_0 \geq 1.0$. In the present numerical model, the following problems still remain to be solved in order to clarify more detailed characteristics quantitatively; [1] the effect of interaction between a sediment particle and a fluid, [2] the interparticle collision, [3] the refinement of the turbulent generation model. The turbulent generation model has been refined in the paper (21) by considering the vertical distribution of parameters σ_u, σ_w and T_L.

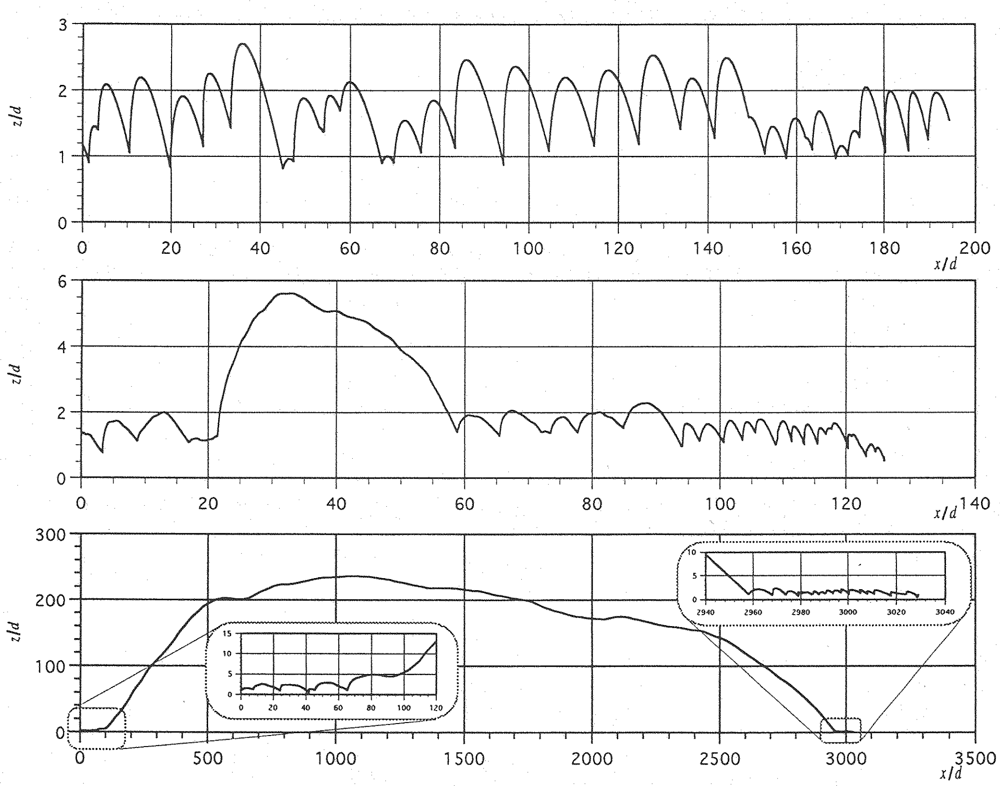

Fig. 3 Typical moving trajectory of bed material load; (a) $u^*/w_0 = 0.4$, (b) $u^*/w_0 = 0.5$ and (c) $u^*/w_0 = 1$

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APPENDIX - NOTATIONS

The following symbols are used in this paper:

A	=	projected area of sediment particle;
C_D, C_L, C_M	=	drag coefficient, lift coefficient and added mass coefficient, respectively;
D	=	sediment diameter;
$\vec{u}_f$	=	velocity vector of a fluid;
$\vec{u}_p$	=	velocity vector of a moving sediment particle;
$\vec{u}_r$	=	relative velocity $\left(\equiv \vec{u}_f - \vec{u}_p\right)$;
T_L, T_E	=	Lagrangian time scale and Eulerian time scale of turbulence, respectively;
u^*	=	frictional velocity;
V	=	volume of sediment particle;
w_o	=	terminal falling velocity of sediment particle;
ρ	=	mass density of water;
ρ_t	=	auto correlation coefficient;
ρ_{uv}	=	mutual correlation coefficient of turbulence;
σ_s	=	specific gravity of sediment;
σ_u, σ_w	=	turbulent intensities in streamwise and vertical direction, respectively;
τ^*	=	dimensionless tractive force.

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