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EFFECTS OF NON-UNIFORM SEDIMENT ON DUNE FORMATION

Wandee THAISIAM[1], Yasuyuki SHIMIZU[2] and Ichiro KIMURA[3]

[1]Student Member of JSCE, Doctoral Student, Dept. of Hydraulic Research, Hokkaido University (North 13, West 8, Kita-ku, Sapporo 060-8628, Japan)
[2]Member of JSCE, Dr. Eng., Professor, Dept. of Hydraulic Research, Hokkaido University (North 13, West 8, Kita-ku, Sapporo 060-8628, Japan)
[3]Member of JSCE, Dr. Eng., Associate Professor, Dept. of Hydraulic Research, Hokkaido University (North 13, West 8, Kita-ku, Sapporo 060-8628, Japan)

The numerical model for non-uniform sediment is performed to simulate the characteristics of sand dunes. With the use of the concepts of bed layer model and size fractional transport, the mechanism of grain sorting at various locations of sand dunes can be investigated. It is found that the sand wave formation and its migration process can be reproduced. Using the experimental results, the model provides the satisfactory agreement in grain sorting and wave height. In addition, the effect of non-uniform sediment is studied. Under the same hydraulic conditions and mean grain size, the numerical simulations of the non-uniform sediment case are compared with that of the uniform sediment case. Again, the simulated results are consistent with the experimental results that the migration velocities of sand dunes in the non-uniform sediment case are faster than those of the uniform sediment case, and the wave heights of sand dunes of the non-uniform sediment case are smaller than those of the uniform sediment case.

Key Words : *non-uniform sediment, dune formation, grain sorting, numerical model*

1. INTRODUCTION

In the natural rivers, bed material and sediment transport are generally non-uniform. In practice, the modeling with the consideration of non-uniform sediment is too complicated and time-consuming. As a result, most of the models in the field of river engineering are considered only one grain size of sediment that can represent the non-uniformity of sediment such as a median size. However, many studies found that considering only one grain size cannot explain some important mechanisms of river morphology sufficiently such as the geometry of bedforms and their evolutions. One of the essential factors that one grain size cannot represent realistic bedforms is the effect of grain sorting.

Miwa and Daido[1)] performed the experiment of dunes and compared the migration process and sand dune geometries between uniform and non-uniform sediment cases. They also investigated grain sorting at various locations of sand dunes in the experiments of non-uniform sediment. Their experimental results showed that grain sorting on the upstream part of sand dune crests causes the sediment coarsening on the lee side and, finally, affects wave height. As a result, with the same mean diameter and hydraulic conditions, wave height of the non-uniform sediment case was found to be smaller than that of the uniform sediment case, but the migration speed of the non-uniform sediment case is faster. Kleinhans[2)] studied on sediment sorting at the lee side of sand dunes. He concluded that the sorting process can be modeled by considering the following variables: the statistic parameters of sediment mixture (standard deviation, skewness, bimodality) delivered to the brink point, the height of sand dunes or bars relative to the average grain size of the mixture, the flow velocity above the brink point relative to the settling velocity for all grain size fractions, and the frequency of the grain flows. Recently, Blom et al.[3)] indicated that the vertical sorting profiles are downward coarsening trend within sand dunes. All mentioned studies show that non-uniform sediment not only holds a complicated process which is difficult for modeling, but also affects sand dune morphology significantly.

In order to analyze sand dune morphology, Lansoni and Tubino[4)] proposed that the deformation of bedforms can be analyzed by using the selective transport of each size fractions of non-uniform bed material. With the use of the concepts of bed layer model and size fractional transport[5), 6)], it was found that the non-uniform sediment transport and bedforms in the case of non-uniform sediment can be properly estimated.

The numerical model for micro-scale bedforms of uniform sediment have been extensively developed in the past few years. Onda and Hosoda[7)] performed the depth averaged flow model considering the effects of vertical acceleration and coupling with a non-equilibrium sediment transport model. They succeeded to reproduce the micro-scale sand wave migration process, sand wave geometry characteristics and flow resistance. Giri and Shimizu[8)] proposed a vertical two-dimensional morphodynamic model with non-hydrostatic and free surface flow. The model adequately reproduced flow and vorticity field in the separation region and succeeded simulating some features of the bed form evolution.

Recently, numerical models considering the non-uniform bed materials have been introduced in a meso-scale geomorphology (the scale of river channel)[9),10),11)]. For simplicity, those numerical studies, thus, used the depth-averaged shallow water equations for the flow simulation. However, in order to extend our understanding for the inside mechanism of the non-uniform sediment transport and its response to morphology, the micro-scale bedforms should be also investigated. In the case of the micro-scale bedforms such as dunes, the simplified version of flow equations such as the shallow water equations are no longer applicable, and more sophisticated equations are needed.

In the present study, we performed the numerical simulation of sand dunes (micro-scale bedform in the low flow regime) for both the uniform sediment case and the non-uniform sediment case. A vertical two-dimensional flow model with non-hydrostatic and free surface flow proposed by Giri and Shimizu[8)] is employed. For the uniform sediment case, we also used the same sediment transport model by Giri and Shimizu[8)]. For the non-uniform sediment case, the concepts of bed layer model and size fractional transport are applied. Thus, the sediment transport model is divided into two submodels which are a non-uniform sediment transport model and a bed layer model. In this study, we verify our new non-uniform sediment model with the experimental results. Then, the effect of non-uniform sediment will be discussed by comparing the simulation results of the uniform sediment case and the non-uniform sediment case.

2. SEDIMENT TRANSPORT MODEL

The sediment transport model explicitly takes the turbulence flow into account during the morphodynamic computation. The non-uniform sediment transport model is employed for sediment transport calculation which includes sediment pickup rate, sediment deposition rates, and bed deformation. The bed layer model is applied for grain sorting simulation. The total bed material transport can be modeled by two different approaches, either dividing the model into bed load and suspended load transport, or considering only the bed load transport. Presently, our sediment transport computation considers only the bed load transport which same sediment transport condition as all experiments. In all experiment cases, the suspended load did not significantly dominate in the sediment transport process.

(1) Non-uniform Sediment Transport Model

The sediment transport of non-uniform bed materials normally depends on a potential size fraction transport and is influenced by complicated flow features. The concept of size fraction transport is to divide bed material into size fractions which consider each size fraction as a uniform material. The sediment transport rate is determined by the summation of the potential transport rate of each size fraction which is in turn related to its concentration existing in the bed material. The bed material transport rate can be calculated by multiplying the potential transport rate corresponding to a given size fraction with the percentage of material which can be read as follows:

$$q_b = \sum_{k=1}^{nk} q_{bk} = \sum_{k=1}^{nk} P_k . q_k \tag{1}$$

where q_b is the bed load transport rate per unit width, q_{bk} is the bed load transport of sediment size fraction k per unit width, P_k is the concentration of sediment fraction size k, q_k is the potential transport rate for a given size fraction k, subscripts k and nk are the number and the total number of size fraction respectively.

An Eulerian stochastic formulation of sediment transport, proposed by Nakagawa and Tsujimoto [12)], is used in our model for the bed load transport calculation and it can be expressed in term of the dimensionless pickup rate of sediment size fraction k as:

$$p_{sk} = \frac{0.03\tau_k^*\left(1-0.7\tau_{ck}^*/\tau_k^*\right)^3}{\sqrt{d_k/(\rho_s/\rho-1)g}} \quad (2)$$

where p_{sk} is the pickup rate of sediment size fraction k, ρ and ρ_s are fluid and sediment density respectively, τ_k* is dimensionless local bed shear stress of sediment fraction size k, and τ_{ck}* is dimensionless critical bed shear stress of sediment fraction size k.

The sediment deposition rate is expressed as:

$$p_{dk} = \int p_{sk} f_s(s) \quad (3)$$

where p_{dk} is the deposition rate of sediment fraction size k and $f_s(s)$ is the distribution function of step length.

The exponential distribution function of step length by Nakagawa and Tsujimoto[12] is written as:

$$f_s(s) = \frac{1}{\Lambda}\exp\left(-\frac{s}{\Lambda}\right) \quad (4)$$

where Λ is the mean step length and s is the distance of sediment motion from the pickup point. On the basis of probability theory, Einstein[13] proposed $\Lambda = \alpha d$, in which α is an empirical constant proposed to be 100.

Then, the bed deformation is computed by using the sediment continuity equation which is

$$\frac{\partial z_b}{\partial t} + \frac{1}{1-\lambda}.\frac{\partial}{\partial x}\left(\sum_{k=1}^{nk} q_{bk}\right) = 0 \quad (5)$$

where z_b is the bed elevation and λ is porosity of bed material.

(2) The Bed Layer Model

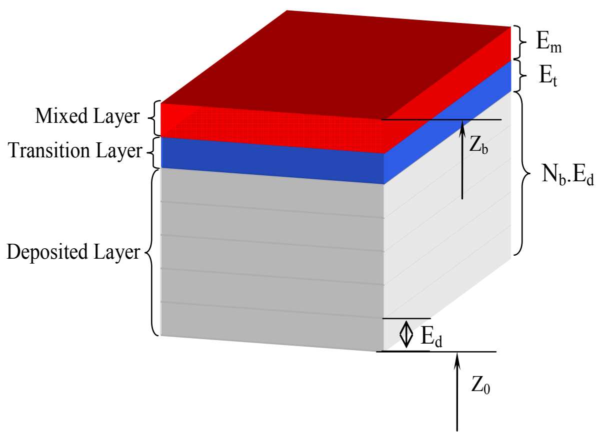

Fig.1 The bed layer model

The bed layer model proposed by Ashida et al.[7] is employed for the grain sorting simulation of non-uniform sediment in our numerical model. In the bed layer model, bed material is divided into sublayers as shown in Figure 1.

The mixed layer represents the exchange layer or top layer containing the bed materials which is active to the transport process. The mixed layer thickness is assumed to be constant and equivalent to the size d_{90} of initial bed material distribution[9]. The transition layer acts as a buffer layer between the mixed layer and the deposited layer. The thickness of transition layer is a function of time and streamwise direction and is restricted between $0 < E_t \leq E_d$, where E_t is thickness of transition layer and E_d is thickness of multiple layers. The deposited layer is divided into N_b layers in which thickness of sublayers is equal to E_d. Therefore, thickness of the deposition layer is equal to the multiplication of N_b and E_d.

With the initial non-uniform bed material in Figure 1, the bed elevation is calculated by

$$z_b = E_m + E_t + N_b.E_d + z_0 \quad (6)$$

where z_b is the bed elevation, E_m is thickness of mixed layer, N_b is total number of sub-layers in the deposited layer, and z_0 is the datum elevation.

In our calculation codes, the non-uniform sediment transport model is employed to calculate sediment pickup rate, sediment deposition rate and bed deformation in each calculated cell. Then, the concentration of sediment size fractions can be calculated from the bed layer model. Details of size fraction concentration calculation can be expressed in four cases as shown in Table 1.

Table 1 Cases and conditions for sediment size fraction concentration calculation

Cases	Bed deformation (Δz_b)	Conditions
A	aggradation	$E_t^n+\Delta z_b \leq E_d$
B	aggradation	$E_t^n+z_b>E_d$
C	degradation	$E_t^n+\Delta z_b>0$
D	degradation	$E_t^n+\Delta z_b \leq 0$

3. HYDRODYNAMIC MODEL

The governing equations for unsteady two-dimension flow in the Cartesian coordinate system (x,y,t) is transformed to the moving boundary fitted coordinate system (ξ, η, τ)[14]. The transformed equations are solved by splitting into a non-advection and a pure advection term. The non-advection term is solved by using central

Table 2 Experimental cases and conditions
(the superscript * denotes the study by Hagiwara, and + denotes the study by Miwa and Daido[1])

Run no.	q_w (cm^2/s)	Sediment mean diameter (cm)	Standard deviation	I_e ($x10^{-3}$)	u_* (cm/s)	L (cm)	Δ (cm)
Run-1*	300	0.040	2.74	3.00	4.21	23.20	1.20
Run-2*	800	0.065	2.12	4.00	6.66	78.13	1.25
Run-3+	350	0.070	1.70	350	3.31	30.70	0.67
Run-4+	400	0.070	1.70	400	3.69	54.00	1.16

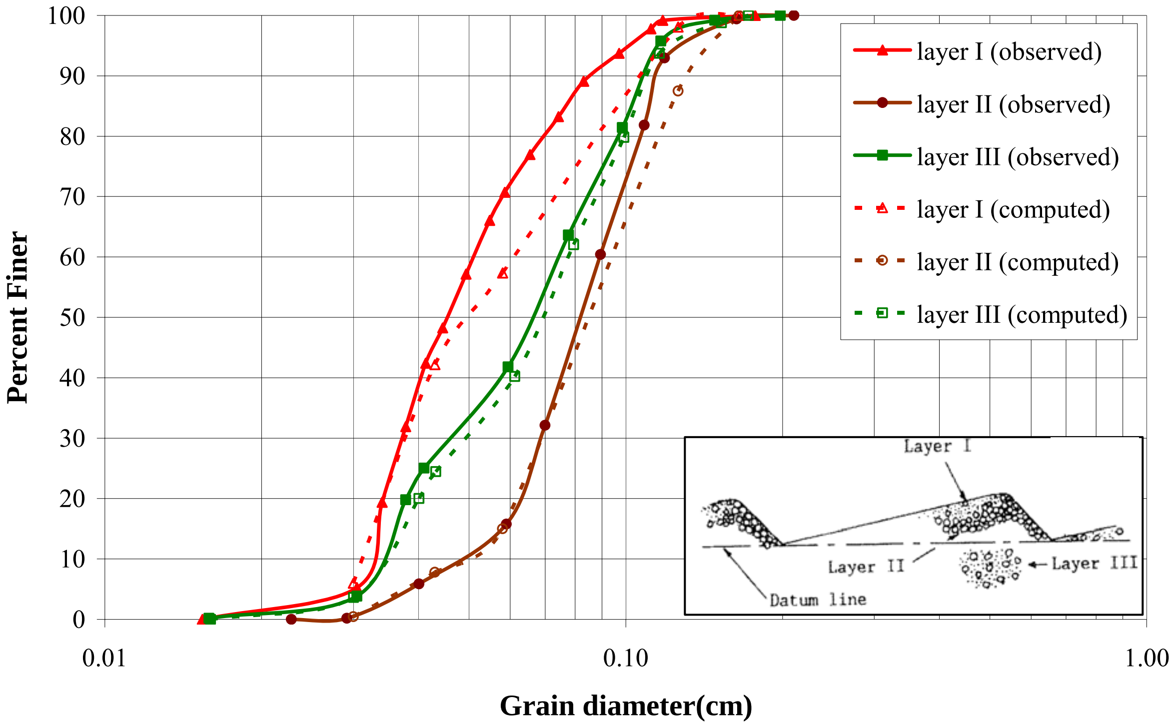

Fig.2 The comparison of grain size distributions (Run-4) where the locations of measured mixture are shown as a small figure.

difference method. The pure advection term is calculated by using a high-order Godunov scheme known as the cubic interpolated pseudoparticle (CIP) technique. The pressure term is resolved using SOR method.

In the turbulence model, a nonlinear k-ε closure is added to the standard k-ε model in order to reproduce turbulence characteristics in shear flow with separation zones. The model is also tested the performance of standard k-ε model and a zero-equation so as to assess the significance of turbulence closure in the context of morphodynamic simulation. In case of time-averaged turbulence characteristic computation, the standard k-ε and nonlinear k-ε model were employed.

The time-dependent water surface change computation is used for realistic reproduction of free surface flow over migrating bed forms. The model is able to accomplish stable and reasonable solutions with a free surface flow condition over the migrating bed forms. The kinetic condition is established along the water surface in order to compute water surface variation.

The boundary condition at the bed is no slip and a logarithmic expression for near-bed region is adopted. The periodic boundary conditions are employed in the computation domain in which output at the downstream end is set to be input at the upstream end.

4. EXPERIMENT

Table 2 shows four cases of a non-uniform sediment experimental study used to verify our numerical model for the non-uniform sediment case. Hydraulic conditions of all experiments are given in the table in which all parameters were measured after bed forms reached to their equilibrium stage. In the table, q_w is water discharge per unit width, I_e is the energy slope, u_* is the mean shear velocity, L

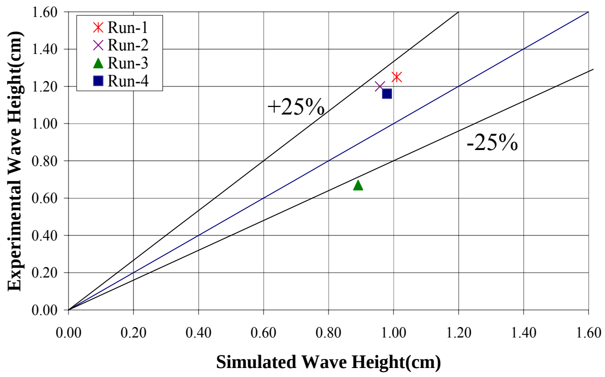

Fig.3 The comparison between the experimental results and the simulated results of the wave height of sand dunes.

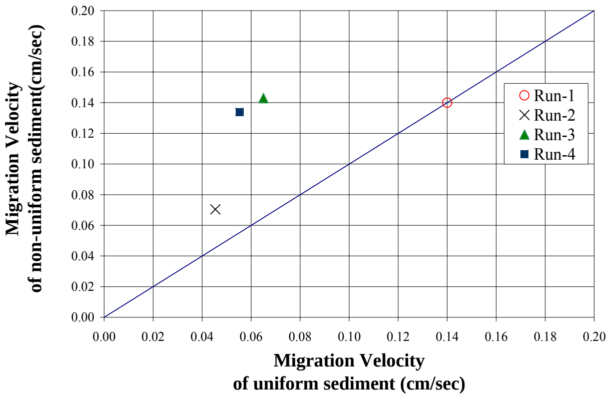

Fig.4 The comparison of migration velocity of sand dunes between the simulated uniform sediment case and the simulated non-uniform sediment case.

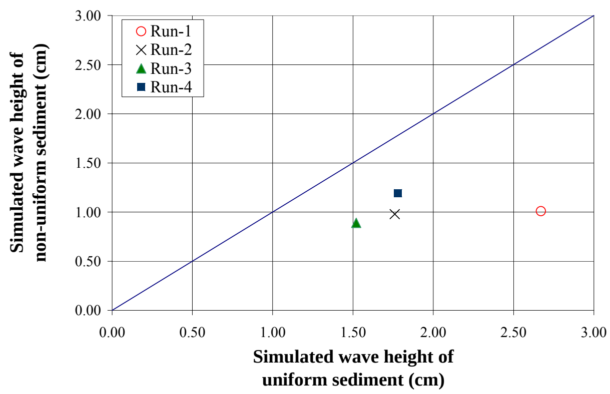

Fig.5 The comparison of wave height of sand dunes between the simulated uniform sediment case and the simulated non-uniform sediment case.

and Δ are wave length and wave height of sand dune, respectively. Run-1 and Run-2 were conducted by Hagiwara, whereas Run-3 and Run-4 were carried out by Miwa and Daido[1].

5. MODEL VERIFICATION

As described earlier, the numerical model is composed with two main models which are the hydrodynamic model and the non-uniform sediment transport model. The hydrodynamic model was employed and verified in Giri and Shimizu[8]. In this study, only the numerical simulation for the non-uniform sediment case is needed to be verified. In the numerical calculation, the computational mesh consists of 302×22 cells. The simulation period was 4800 seconds for all Runs which was more than the equilibrium time of all experiments. The time step is 7×10^{-4} seconds. The measured time for sand dune geometries and grain sorting were made after the bed forms reach to the equilibrium stage. Run-1 and Run-2 were measured after 1800 seconds and after 3600 seconds for Run-3 and Run-4.

(1) Grain sorting at various locations in sand dunes

Among four experiments, Run-4 is the only one that the grain size distributions of bed material at various locations were measured. Figure 2 shows the comparison between the experimental results and our simulated results, and a small figure shows three locations of the measured mixture as Layer I, II and III. Layer I denotes the mixture on the upstream part of dune crests, Layer II denotes the mixture in the trough of dunes, and Layer III denotes the mixture in the substrate layer. From the experimental results, it was found that Layer I provides the finest mixture among three layers. Layer II which is coarser than Layer I and III because coarse grains was deposited at the lee side, whereas the grain size distribution in Layer III shows no significant change because it does not strongly participate with the sediment transport and bed evolution. Comparing with the simulated results, the grain size distribution of bed material inside the sand dunes in layer II and layer III are reproduced very well by our new numerical model. This implies that our model can imitate the mechanism of grain sorting. However, we hypothesized that the discrepancy in the result of Layer I may be due to fine sediment that it may be transported by the mode of suspended load which does not include in our present model. From this point, it can be concluded that the present numerical model shows the capability to reproduce the realistic mechanism of grain sorting inside the sand dunes.

(2) Wave height of sand dunes

Figure 3 show the comparison of the wave heights of sand dunes between the experimental results and the simulated results for Runs 1–4. It is found that the numerical model shows a satisfactory agreement with the discrepancy within ±25%.

6. EFFECTS OF NON-UNIFORM SEDIMENT

Figures 4 and 5 show the results of migration velocity and wave height of sand dunes comparing the simulated uniform sediment case and the simulated non-uniform sediment case with the use of the hydraulic conditions of Runs 1–4. The mean diameter of Runs 1–4 in Table 2 were used in the simulation of the uniform sediment case. The solid line in the figures means that the simulated uniform sediment case and the simulated non-uniform sediment case provide an identical value. If the point is beyond the line, it implies that the simulated non-uniform sediment case give a value higher than that of the uniform sediment case.

In Figure 4, it is found that the simulated migration velocities of sand dunes in the non-uniform sediment case are faster than that of the uniform sediment case for all runs. According to Miwa and Daido[1)], with the same hydraulic conditions and mean diameter, the migration velocity of the non-uniform sediment case in the experiment is faster than that of the uniform sediment case. Thus, our model shows the satisfactory agreement with the experiment.

Figure 5 shows that the wave heights in the simulated non-uniform sediment case are smaller than that in the uniform sediment case. Again, Miwa and Daido[1)] found the same trend as our model results.

7. CONCLUSION

The proposed numerical model satisfactorily predicts grain sorting at various locations of sand dunes. Among sediment layers, the upstream part of dune crests in which the sediment is finest shows some discrepancy between the experiment and the model. It is hypothesized that the mode of suspended sediment transport influences that part. The model may need to include the suspended sediment transport in order for better estimating the fine sediment transport. A good agreement in the wave height of sand dunes between the experiment and the simulation with the discrepancy within ±25% is also found. The study of the effect of non-uniform sediment shows that non-uniform sediment transport causes an increase in migration speeds and a decrease of wave height compared with the uniform sediment case.

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