CHAPTER 333

Bivalve Habitat Based on Sediment-Transport Mechanics

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Abstract

After a storm, thousands of dead bivalves washed upon a beach are sometimes observed. Bivalves are important not only as the marine products but also as the index of the quality of coastal environment. Hence, the field observations of the distribution of bivalves in a coastal zone; and the laboratory experiments on the characteristics of the behavior of bivalves have been performed.

An interesting result is found by Yamashita and Matsuoka (1994) in a laboratory experiment on the burrowing process of bivalves under eroding condition due to the oscillatory flow: even when the descending velocity of a sand surface is sufficiently smaller than the burrowing velocity of bivalves, some bivalves cannot stay in the sand layer and are picked-up by oscillatory flow.

In this study, the physical background of their results are considered from a viewpoint of sediment transport mechanics. Two important aspects are investigated: the one is the stochastic aspect of the burrowing process of bivalves; and the other is the reverse grading phenomena observed in motion of mixed-size grains.

Introduction

Thousands of dead bivalves washed upon beach after a storm have been sometimes observed in the coastal region around Japan. Most of the former field observations and laboratory experiments (Watanabe, 1982; Higano and Yasunaga, 1988; Yamashita and Matsuoka, 1994; and Kuwahara and Higano, 1994) have been performed because

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of the importance of bivalves as fishery products. Bivalves, or creatures living in sandy beach, are also important as the index of coastal environment.

There are many irregular factors in a moving process of bivalves such as fluctuation of bottom velocity, descending velocity of sand surface due to scoring, size of bivalves, activity, or moving ability, of bivalves and so on. To take these irregularities into consideration, the moving process of bivalves should be treated as a stochastic process.

The other important aspect in the moving process of bivalves is the mode of sediment motion around bivalves. In general, sediment is transported in various modes; bed load, suspended load over sand ripples and sheetflow. Especially, during storm, or under the action of high-shear force, sheetflow should be a dominant transport mode. In the sediment transport in sheetflow regime, the particle/particle interaction, or the momentum transport due to interparticle collision is a mechanism governing the flow structure. To understand the behavior of bivalves in a sediment layer moving in sheetflow regime is an important subject to clarify the mechanism of bivalves-upward motion in a sand layer.

Two important aspects mentioned above are treated in this study based on the numerical model such as the stochastic model for simulating the probabilistic characteristics of bivalve's behavior and the granular material model for the simulation of sediment/sediment and sediment/bivalves interactions.

Laboratory experiment by Yamashita & Matsuoka

Yamashita and Matsuoka (1994) found out very interesting characteristics of bivalves in their laboratory experiment. They performed the experiment on the burrowing process of infant bivalves, or *Spisula sachalinensis*, maximum length of which is more than 5 mm and less than 20 mm, under the oscillatory flow generated by U-tube type oscillating water tunnel. They investigated the probability of the occurrence of the bivalves picked-out-of sand layer under the various values of the ratio of the descending velocity of sand surface, or v_e, to the burrowing velocity of bivalves, or v_s. Figure 1 shows the one of the results of their study on the relation between the probability of the occurrence of the bivalves picked-out-of sand layer and the velocity ratio v_e/v_s.

When the descending velocity of sand surface due to the erosion is larger than the one-thirds of the burrowing velocity of bivalves, namely in the region where the ratio $v_e/v_s \geq 0.3$, whole of the bivalves in a sand layer are picked-out-of sand. In their experiment, the burrowing velocity of bivalves are measured in a still sand layer. To understand the physics of this phenomena, the behavior of bivalves in a streamwise-moving sand layer should be investigated.

In the region $0.1 \leq v_e/v_s \leq 0.3$, some bivalves are picked-out and others are staying

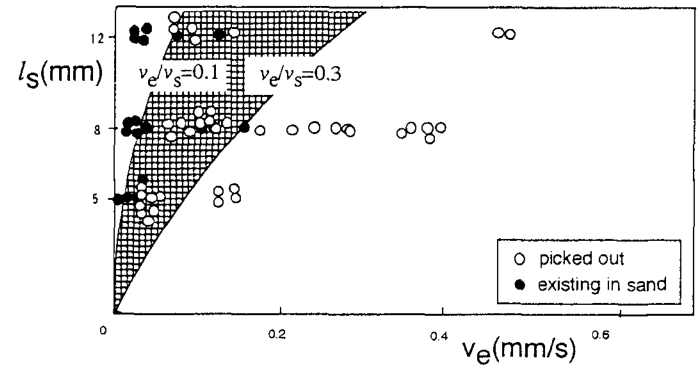

Figure 1. Occurrence of the bivalves picked-out
(Data from Yamashita and Matsuoka, 1994)

in a sand. This means the importance of stochastic consideration of the motion of bivalves to express the probabilistic aspects of the moving process of bivalves.

Stochastic consideration of burrowing process of bivalves

procedures of stochastic calculation

The following assumptions, some of which are based on the previous experiments conducted by Higano, Kimoto and Yasunaga (1993) and Yamashita and Matsuoka (1994), are introduced in this calculation.

(1) The shell length of bivalve l_s=8 mm. (2) The bivalve burrows in a sand layer keeping shell-length axis parallel to the vertical direction. (3) Initially, the top edge of bivalve coincide with the surface of sand layer, as schematically shown in Fig. 2.

(4) Bivalve begins to burrow in a sand layer when its top is exposed due to the scouring. The threshold of exposed length at the beginning of bivalve's burrowing is treated as the probabilistic variables based on the experiment by Higano et al (1993). (5) Bivalve rests in sand layer when the clearance between its top edge and the surface of a sand layer is equal to the half of shell length as shown in Fig. 2. The burrowing and the resting are iterated alternately. (6) Bivalve is defined to be picked out of sand layer when the 80% of the shell length are exposed in water as shown in Fig. 2. (7) The cycle of calculation begins at the moment when the condition (5) is satisfied. If the condition (6) has not been satisfied for 2200 s from the beginning, the calculation is terminated. This situation is defined as the survival of bivalves. (8) As it is mentioned above, bivalve is repeating the burrowing process and resting process, the average of the repeating period of which is equal to 2.2 s, according to Yamashita and

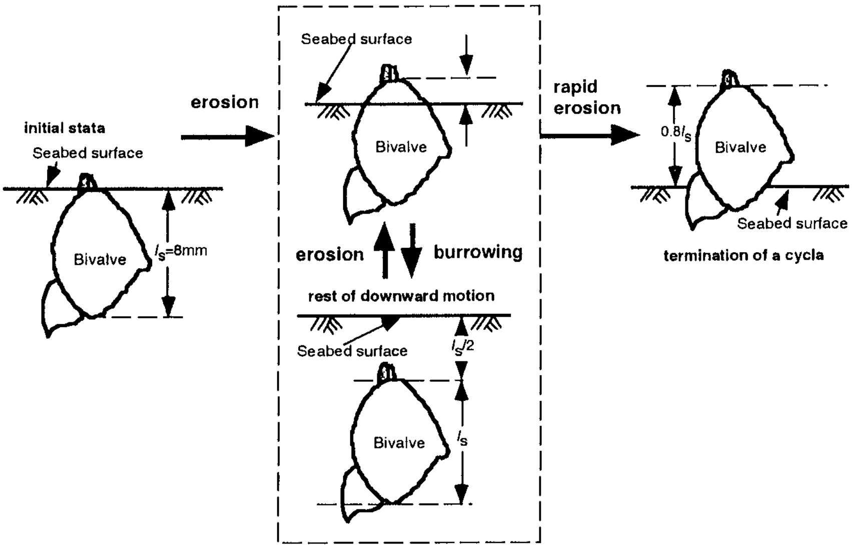

Figure 2. Definition of parameters in bivalves

Matsuoka (1994). They also investigated the distribution of burrowing velocity of bivalves. In this calculation, the burrowing velocity of bivalves changes at every 2.2 s based on the Monte Calro Method, namely by generating the random numbers following the distribution of the burrowing velocity experimentally investigated. (9) The descending velocity of the surface of sand layer is treated as a probabilistic variables following the normal distribution, the standard deviation of which is equal to one-third of averaged descending velocity, or $\sigma = v_e/3$.

<u>results of the stochastic calculation</u>

Figure 3 shows one of the calculated results of the one-cycle of the burrowing process of bivalves under the condition of $v_e/v_S=1.0$. In this figure, the time series of the existing height of bivalves, elevation of sand-layer surface and the thickness of sand layer above the top of bivalves, or δ, are shown. In this case, the thickness δ is decreasing rapidly during $0.0 \leq tv_S/l_S \leq 1.0$, and on the verge of the picking-out of bivalves. After $tv_S/l_S=1.0$, the thickness δ increases again. In this case, the bivalve survives through one cycle of calculation. If the decreasing velocity of the thickness δ during $0.0 \leq tv_S/l_S \leq 1.0$ is a little more rapidly, this bivalve is picked-out-of sand layer. The survival of bivalve is strongly depends on the accidental-drastic change of the surface elevation of sand layer.

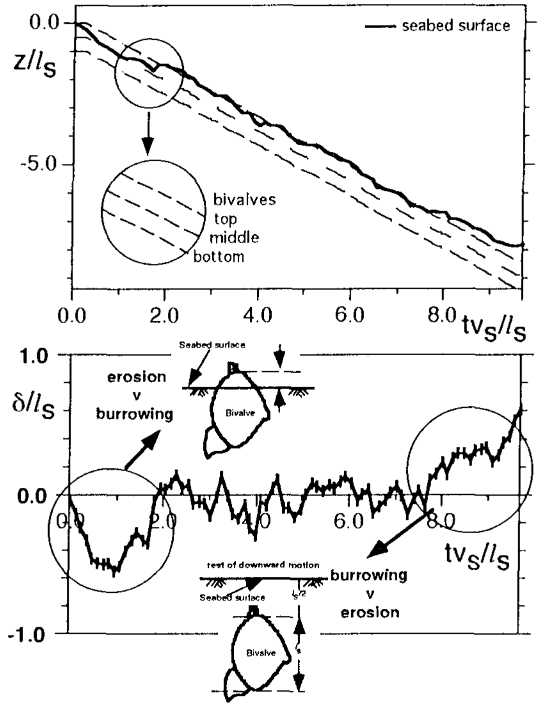

Figure 3. Burrowing process of bivalve

The probability of the survival of bivalves, or P_m, is calculated by continuing the cycle of calculation for m-times with assessing the occurrence of the bivalves picked-out-of a sand layer. Fig. 4 shows the existing probability of bivalves after 100 cycle of calculation, or P_{100}, against the ratio of the descending velocity of sand-bed surface to the burrowing velocity of bivalve, $v_e/v_s(=\alpha)$. Two cases of the calculation are shown in this figure. The one is the calculation in which the probabilistic characteristics of bivalves are only considered; and the other is the calculation in which both of the probabilistic characteristics of bivalves and that of sand-bed surface are considered. The transition range of the probability of the survival of bivalves experimentally investigated by Yamashita and Matsuoka is also shown in this figure.

The transition range of the experiment is $0.1 \leq \alpha \leq 0.3$, while the calculation, in which the probabilistic characteristics of bivalves is only considered, shows the drastic transition around $\alpha=0.9$. The calculation, in which both of the behavior of bivalves and the motion of sand-bed surface are treated as the probabilistic variables, predicts the transition range in $0.6 \leq \alpha \leq 0.75$. But even if the probabilistic characteristics of

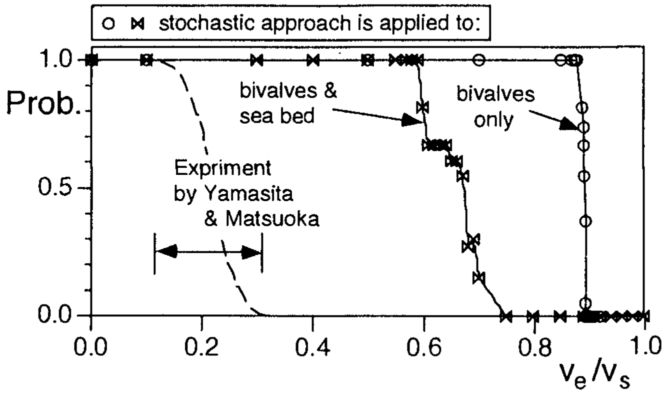

Figure 4. Survival probability of bivalve

sand-bed-surface elevation is considered, the threshold of the emergence of bivalves picked-out-of sand layer are overestimated.

Although the stochastic calculation reproduces the existence of the transition region in the probability of the bivalve's survival against the change of velocity ratio v_e/v_s, the threshold of the bivalve's survival is not reproduced well at least quantitatively. This fact suggests the existence of other mechanism, which promotes the picking-out-of bivalves.

Behavior of bivalves in sheetflow layer

reverse grading as the mechanism of upward vertical motion of bivalves

Boulders are frequently observed to be concentrated at the near-surface region of the front part of debris flow. This phenomenon, namely the existence of the boulders above other grains and gravel, is called reverse grading.

Interparticle collision is the governing mechanism both of debris flow and sediment transport in sheetflow regime. Therefore the same kind of phenomena as the reverse grading of debris flow can be thought to be a mechanism to promote the bivalves to be picked-out-of sand layer. In this study, the behavior of bivalves is traced numerically in the moving sediment particles in sheetflow regime by the distinct element method (=DEM).

distinct element method

Sakai and Gotoh (1995) performed the numerical simulation of the motion of sheared sediment-particle layer based on the distinct element method. In this study, their simulation is applied to simulate the interactive behavior between bivalve and sediment particles around bivalve by regarding the bivalve as a large and light particle.

governing equations of sediment particles

Sediment particles are modeled by the rigid cylinders with uniform diameter d; and the bivalve is modeled by the rigid cylinder with diameter D. At inter-cylinder and cylinder-bivalve contacting point, the spring and dashpot systems are introduced, and the equations of motion of cylinder and bivalve are solved by an explicit method.

Equations of motion of the i-th particle or bivalve in the vertically two-dimensional coordinate are as follows:

$$\frac{\pi\sigma_i d_i^2}{4}\frac{d^2 x_i}{dt^2} = \sum_j \left\{-f_n(t)\cos\alpha_{ij} + f_s(t)\sin\alpha_{ij}\right\}_j + F_{0i} \tag{1}$$

$$\frac{\pi\sigma_i d_i^2}{4}\frac{d^2 y_i}{dt^2} = \sum_j \left\{-f_n(t)\sin\alpha_{ij} + f_s(t)\cos\alpha_{ij}\right\}_j - \frac{\pi(\sigma_i - \rho)d_i^2 g}{4} \tag{2}$$

$$\frac{\pi\sigma_i d_i^3}{16}\frac{d^2 \phi_i}{dt^2} = \sum_j f_s(t)_j \tag{3}$$

in which f_n, f_s=the forces acting between the i-th and j-th particles; α_{ij}=contacting angle between the i-th and j-th particles; F_{0i}=shear force acting on the i-th particle; σ_i=density of particle; and d_i=diameter of particle; and g=graviational acceleration. The subscript "n","s" mean normal and tangential components, respectively.

calculation of interparticle-acting force

Figure 5 shows the schematics of the interaction between two contacting particles. Between two contacting particles, springs and dashpots are introduced to describe the dynamic interparticle relation. The acting force between the i-th and j-th particles in normal and tangential direction, f_n and f_s, can be written as follows:

$$f_n(t) = e_n(t) + d_n(t) \quad ; \quad f_s(t) = e_s(t) + d_s(t) \tag{4}$$

$$e_n(t) = \min\left\{e_n(t-\Delta t) + k_n \cdot \Delta\xi_n,\ e_{n\max}\right\} \quad ; \quad d_n(t) = \eta_n \cdot \frac{d\Delta\xi_n}{dt} \tag{5}$$

$$e_s(t) = \min\left\{e_s(t-\Delta t) + k_s \cdot \Delta\xi_s,\ e_{s\max}\right\} \quad ; \quad d_s(t) = \eta_s \cdot \frac{d\Delta\xi_s}{dt} \tag{6}$$

in which e_n, e_s=forces working on springs; d_n, d_s=forces working on dashpots; $\Delta\xi_n$, $\Delta\xi_s$=displacement of particle during the time Δt (Δt=time step of the calculation); k_n, k_s=spring constants; and η_n, η_s=damping coefficients. In this simulation, particles

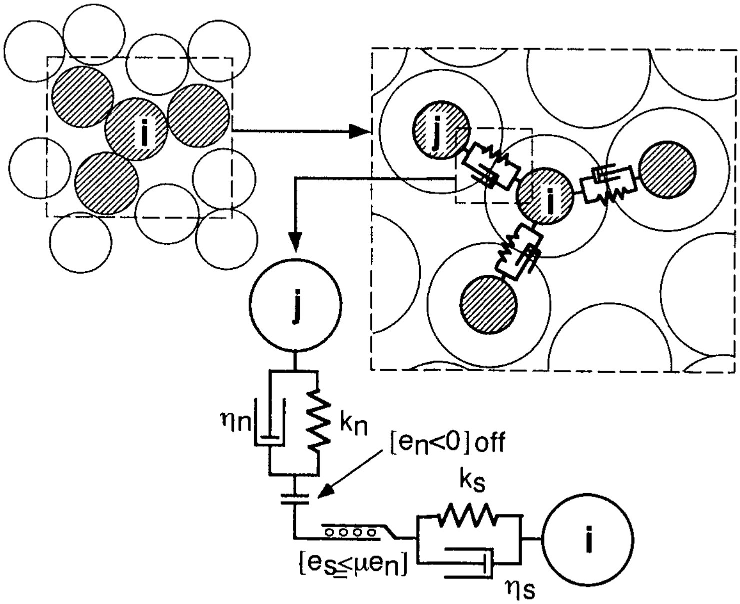

Figure 5. Schematics of the interaction between two contacting particles

are non-cohesive, hence the tensile force does not act between two contacting particles. To describe this characteristics, the joint, which no resistance to the tensile force, is assumed to exist in the normal direction. While, in the tangential direction, the friction force works. To describe this characteristics, the joint, which slips at the limit of the shear stress, is assumed to exist in the tangential direction.

initial conditions and boundary conditions

Figure 6 shows the schematic expression of the calculating domain. In this simulation, streamwise uniform condition is treated, therefore, the both sides of the calculating domain are the periodic boundaries. The bottom boundary is the fixed rough bed constituted by the particles with the same diameter as the moving particles. Before the beginning of the main calculation, the packing to determine the stable initial location of the particles is executed.

The shear stress is distributed to the particles in the neighborhood of the surface of sand layer in a following procedure. Procedure are, firstly, to set the threshold y_{th} (see Fig. 7); secondarily to calculate the area of the particles above the threshold, or

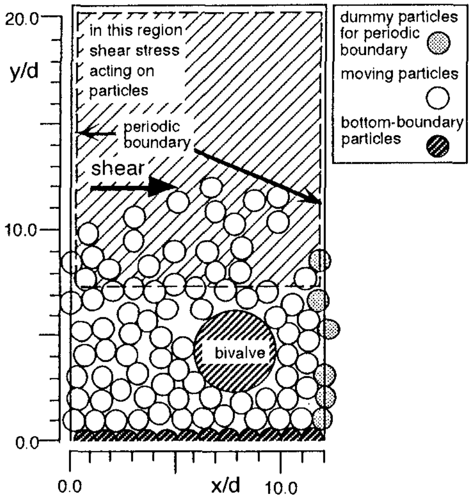

Figure 6. Schematics of calculating domain

the shaded area in Fig. 7, for the particles existing on and above the threshold; and finally to distribute the shear force to the particles existing on and above the threshold with calculating the area of particles above the threshold $S(\theta_i)$ as follows:

$$S(\theta_i)=\begin{cases}\dfrac{r^2}{4}\left(\pi-\theta_i+\dfrac{1}{2}\sin 2\theta_i\right) & ; \quad y_i \geq y_{th} \\ \dfrac{r^2}{4}\left(\theta_i-\dfrac{1}{2}\sin 2\theta_i\right) & ; \quad y_{th}-\dfrac{r}{2}<y_i<y_{th}\end{cases} \quad ; \quad \theta_i=\cos^{-1}\left(\frac{y_i-y_{th}}{r}\right) \tag{7}$$

Distributed shear force to the i-th particle is written as

$$F_{0i}=Lw_i\tau_0 \quad ; \quad w_i=S(\theta_i)\Big/\sum_{j=1}^{N}S(\theta_i) \tag{8}$$

in which L=length of the calculating domain in horizontal direction; τ_0=bottom shear stress par unit area. The test particle is 0.5 cm in diameter and 2.65 in specific gravity; and the model of bivalve is 2.0 cm in diameter and 1.30 in specific gravity (see Higano et al., 1993). In the calculating domain, 91 particles and 1 bivalve are traced. The model constants are shown in Table 1.

Initially the bivalve is contacting to the bottom constituting particles. The time step of the calculation is 2.0×10^{-5} s and the totally 80,000 cycles of calculation is executed, hence the motion of sediment particles and bivalve for 1.6 s is traced.

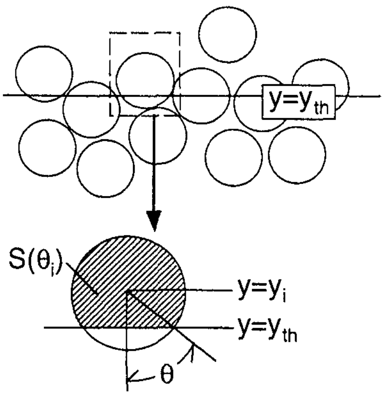

Figure 7. Shear stress distributed to sediment particles

Table 1. Model constants

k_n	9.45×10^6 N/m
k_s	2.36×10^6 N/m
η_n	40.0 Ns/m
η_s	20.0 Ns/m
μ	0.577
e_{nmax}	2.5 N
e_{smax}	0.025 N
Δt	2.0×10^{-5} s

results of simulation

Figure 8 shows the snapshots of the sediment-and-bivalve motion with 0.2 s intervals under the action of the shear stress $\tau_*(\equiv u_*^2/\sqrt{(\sigma/\rho-1)gd})=1.5$ on the surface of sediment layer. Bivalve, which is initially contacted to the bottom constituting particles, moves upward gradually, and it is picked-out-of a sand layer 0.8 s after the initiation of the shear action. Most of the particles in lower layer has laminar motion, hence the momentum exchange in lower layer is inactive. While, in the upper layer the concentration of sediment particles is less than that in the lower layer, the vertical motion of the sediment particles is less frequently obstructed by the particles in the upper layer than in the lower layer.

To understand the physics of the upward motion of bivalve, following hypothesis is proposed. The bivalve exists in the shear layer, in which the sediment particles

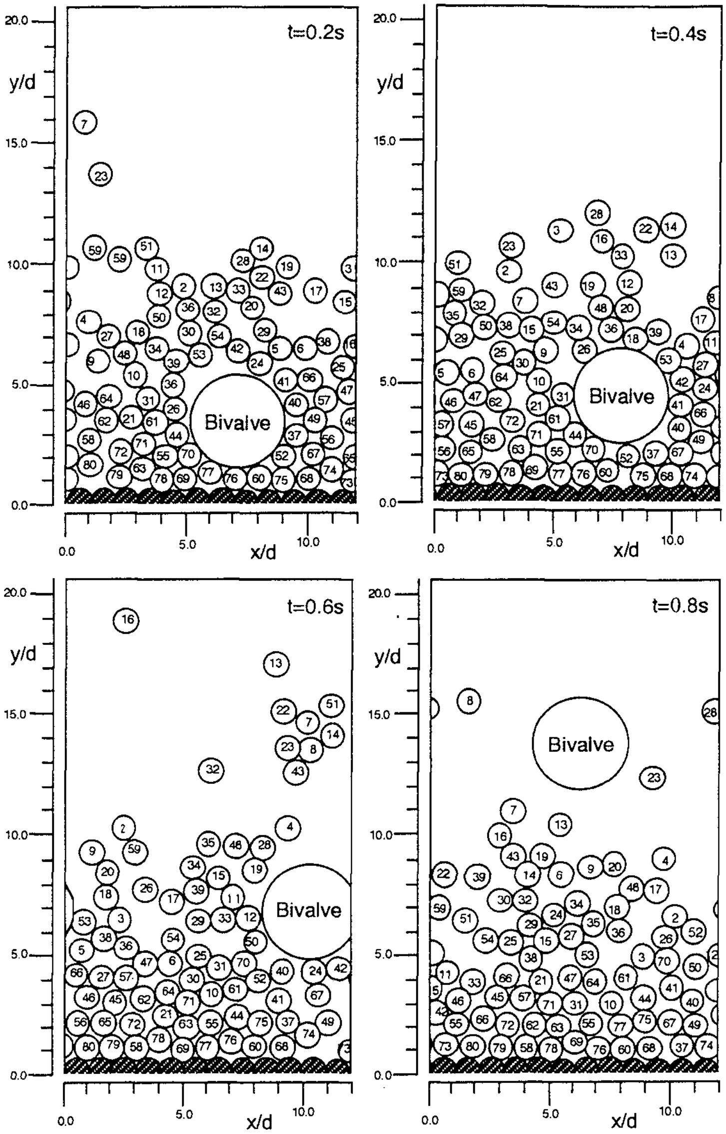

Figure 8. Snapshots of the sediment-and-bivalve motion

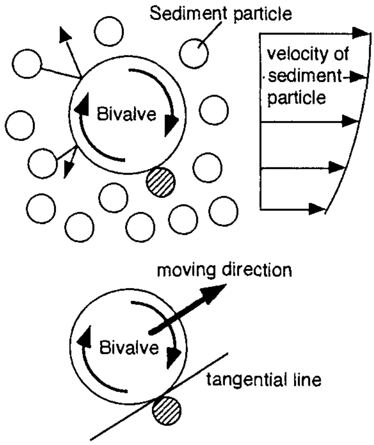

Figure 9. Upward motion of bivalve

have a vertical velocity distribution as schematically shown in Fig.9. Therefore the particle colliding at the upper part of bivalve is faster than that colliding at the lower part of bivalve. This velocity difference of the colliding sediment particles makes the bivalve to rotate in clockwise. Supposing the contacting sediment particle with just the lower part of the bivalve in the downstream section (hatched particle in Fig.9) and the hypothetical plane at the contacting point between bivalve and the particle, the behavior of the bivalve can be simplified as the clockwise rotating cylinder on the slope. And the clockwise rotation moves the cylinder to upward.

Figure 10 shows the time series of the rotating angle, the sign of which is positive in counterclockwise, and the elevation of the centroid of bivalve. The bivalve begins to move upward gradually accelerating the rotational motion. Around 0.6 s, bivalve moves in upward direction drastically, and at the same time the rotational motion is accelerated also drastically. From this fact, the rotational motion of bivalve can be regarded as the driving mechanism of the upward motion of bivalve.

Conclusion

The physical background of the behavior of bivalve in sand layer during storm are considered from a viewpoint of sediment transport mechanics. Two important aspects are investigated: the stochastic aspect of the burrowing process of bivalves and the reverse grading phenomena observed in a motion of mixed-size grains.

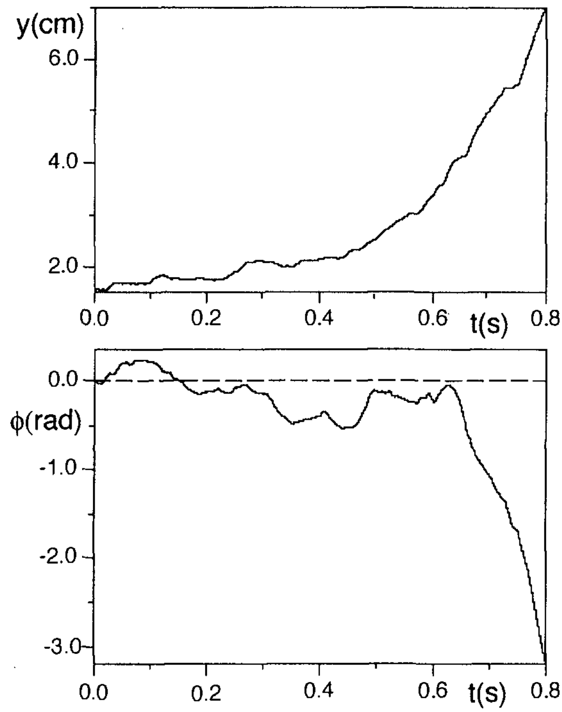

Figure 10. Rotating angle of bivalve

The stochastic model simulates the probabilistic characteristics of environment around bivalves. And the granular material model, or distinct element method, simulates the motion of bivalve in upward direction based on the sediment/sediment and sediment/bivalves interactions.

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