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EFFECT OF BEDLOAD TRANSPORT ON EROSION RATE OF COHESIVE SEDIMENT

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The purpose of this paper is to study the effect of bedload transport on the erosion rate characteristics of cohesive sediment. The results of flume experiment and the dynamic shear stress on the bed are discussed. The sediment feeding of the bedload transport rate is varied from 0 to 150% of the equilibrium sediment transport rate. Two kinds of sand, which have fine and coarse sediment size, are used to produce the bedload transport. The results show that the erosion rate of cohesive sediment will increase when the volume of the sediment feeding increase under the small rate conditions. However, after achieving a certain volume of the sediment feeding, the erosion rate of cohesive sediment will decrease. This tendency indicates that the relation between the volume of bedload transport and erosion rate of cohesive sediment is non-linear function.

Key Words **:** *Cohesive sediment, erosion rate, bedload transport rate, dynamic shear stress, non-cohesive sediment*

1. INTRODUCTION

Erosion or re-suspension is one of the important processes in the cohesive sediment transport system[1)]. Erosion is also one of the most studied aspects of cohesive sediment transport, including theoretical approaches and field observations. There is general agreement that the bottom shear stresses exerted by flow and the physicochemical characteristics control the erosion rate of cohesive sediment[2)]. A large number of studies have described the effect of physicochemical characteristics on erosion rate of cohesive sediment. For example, the erosion resistance increases with increasing salinity and decreases with increasing water content[3)]. The erosion rate is also strongly influenced by the water content[4)]. The increase in bulk density also can decrease the erosion rate[5)]. However, most of the researchers study on erosion of cohesive sediment only flowing by clear water.

The flows in natural rivers consist of sediment transport, which consumes a portion of energy in the flow, and cause an increase or decrease the flow velocity[6)]. Therefore, the presence of sediment transport, especially bedload transport influences the shear stress magnitude. The influence of coarse material sediment on erosion of cohesive sediment is presented in Kamphuis, 1990[7)]. The results indicate that the presence of granular material on the erosion process of cohesive sediment is very important. Erosion was most rapid when the sand moving by saltation and decrease if the sand either moved as pure bedload, which covered the bed at certain times. From these results give knowledge that the size and volume of bedload transport are important matters for erosion process of cohesive sediment. However, this research still not clearly explains the effect of volume and size of bedload transport on the erosion rate of cohesive sediment.

The objective of this paper is to investigate the effect of volume of bedload transport on erosion rate characteristics of cohesive sediment. Flume test are performed under various sediment supply conditions. Furthermore, the dynamic shear stress on bed is calculated considering the vertical distribution of longitudinal velocity and sediment concentration and discussed the erosion rate of the cohesive material by both water and non-cohesive material.

2. METHODS

(1) Experimental setup

Experiments were conducted in a tilting flume with 800 cm long as shown in **Fig. 1.** The channel has rectangular cross section with 15 cm wide and 25 cm deep.

(2) Cohesive sediment sample

Cohesive sediment in this study was prepared from dry kaolinite powder. **Fig. 2a** shows the grain size distribution of dry kaolinite powder. The grain size distribution of kaolinite material is between 0.328 μm and 68.973 μm. The mean diameter is around 4.616 μm. Two types of cohesive sediment are used in the experiment. Type A is the cohesive sediment which is composed of 100% kaolinite. Type B is the cohesive sediment which is composed of 50% kaolinite and 50% coarse sand. To prepare the cohesive sediment Type A, the dry kaolinite powder and water with 1:1 volume ratio, are put into a bucket and mixed until the sample become mud, which has homogeneous condition. On preparing cohesive sediment Type B, the volume ratio is 1 water : 1 kaolinite : 1 sand size 2. The 1:1 and 1:1:1 volume ratio are designed to achieve the water content of the cohesive sediment are around 50% (in Type A) and 30% (in Type B). Therefore, the mud sample is put in the flume experiment and pooled by water slowly. The mud sample has been kept in the pooled channel for one day in order to allow for settling and consolidation naturally. During settling and consolidation process, the flume is kept in flat condition. The surface elevation of cohesive sediment was monitored by ruler, which put on the wall to check the bed level. The cohesive sediment was designed on 5 cm of thickness uniformly from upstream until downstream end.

(3) Sediment feeding

Total of 18 cases experiment are reported in this paper, as shown **Table 1**. The sediment feeding location is shown in **Fig. 1e**. Two kinds of sand, sand size 1 and sand size 2, which have difference size are used to produce the bedload transport. The sand size 1 is much finer than the sand size 2. The size distribution of sand size 1 and sand size 2 are shown in **Fig. 2b** and **Fig. 2c**.

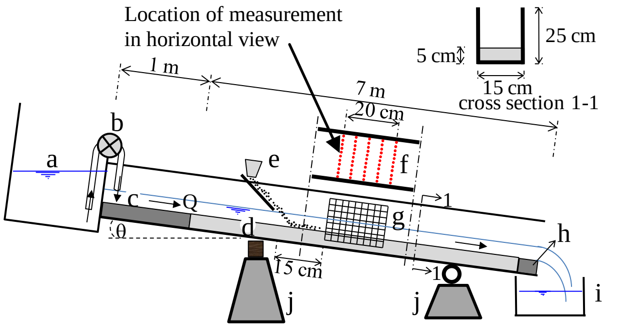

Fig.1 The experiment setup, where a) water tank, b) pump, c) rigid bed, d) cohesive sediment, e) sediment feeding location, f) horizontal view of cross sections, g) screen grid, h) downstream weir, i) downstream tank, and j) tilting machine)

Table 1 Summary of hydraulics condition and sediment feeding for each case

Expt. no.	Case	Average discharge (l/s)	Slope (m/m)	d_{50} of sediment feeding (mm)	Sediment feeding (g/10s)	Percent of bedload transport to *qb* (%)
1	Case 1	1.45	0.004	-	0	0
2	Case 2	1.45	0.004	0.324	15.96	15
3	Case 3	1.45	0.004	0.324	26.59	25
4	Case 4	1.45	0.004	0.324	37.23	35
5	Case 5	1.45	0.004	0.324	53.19	50
6	Case 6	1.45	0.004	0.324	106.37	100
7	Case 7	1.45	0.004	0.324	159.56	150
8	Case 8	1.45	0.004	0.88	0.65	15
9	Case 9	1.45	0.004	0.88	1.09	25
10	Case 10	1.45	0.004	0.88	1.53	35
11	Case 11	1.45	0.004	0.88	2.18	50
12	Case 12	1.45	0.004	0.88	4.36	100
13	Case 13	1.45	0.004	0.88	6.54	150
14	Case 1a	1.45	0.004	-	0	0
15	Case 2a	1.45	0.004	0.88	1.09	25
16	Case 3a	1.45	0.004	0.88	2.18	50
17	Case 4a	1.45	0.004	0.88	4.36	100
18	Case 5a	1.45	0.004	0.88	6.54	150

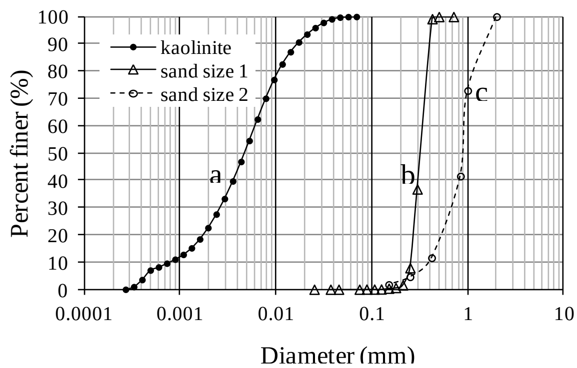

Fig.2 Grain size distribution, a) kaolinite, b) sand size 1, and c) sand size 2

The mean diameter of sand size 1 and sand size 2 are 0.324 mm and 0.88 mm, respectively. The specific gravity of both sands is 2.65. Supplied sediment discharge is widely distributed from 0 to

1.5 times as equilibrium sediment transport rate, q_b, (0% q_b – 150% q_b). Where, q_b is the potential bedload transport rate in equilibrium condition[8]. So, on 0% q_b means that the flow has no bedload transport rate or clear water. The 100% q_b is the flow consists of bedload transport with same volume to q_b. The volumes of all sediment feedings rate are shown in **Table 1**. The duration for each experiment is 6 minutes and during 6 minutes sediments are supplied. The method of sediment feeding is spread a certain volume of sediment by hand. The interval of spread time of the sediment is 10 second.

(4) Experiment condition

The hydraulic condition selected for the experiment was determined by the necessity of producing flow conditions capable of transporting bedload material. The water depth was design at around 2.5 cm. The summary of the hydraulic conditions for all cases are shown in **Table 1**. Due to the effect of temperature and water content on erosion rate of cohesive sediment[4], therefore those parameters were controlled in same condition for all experiments. The water temperature during experiment is around 30 degrees centigrade. The high temperature is caused the experiments were done during summer season. The water content of cohesive sediment in each experiment is designed on 50% (Type A) and 30% (Type B). The water content also measured for each experiment.

(5) Measurement method

In order to evaluate erosion rate, the bed elevation on the initial condition and the final condition were measured. The location of observation area is set at the middle of the flume, which has 20 cm long as shown in **Fig. 1f**. The distance between observation area and the location of sediment feeding is around 15 cm. 15 cm is enough long to get the spatially equilibrium erosion speed. Bed elevations were measured at 11 points in a cross section and 5 cross sections are measured. The longitudinal intervals between the cross sections are 5 cm. So, for each experiment around 55 points are measured in the initial and the end of experiment. The bed elevations were measured with a point gauge, which has precision 0.1 mm. Bed elevation change and water surface are also monitored during experiments by a digital high speed camera from the side wall of the flume. Video camera was shot on acrylic wall, which has grids on it as shown in **Fig. 1g.**

3. DYNAMIC SHEAR STRESS

In order to discuss the erosion rate of cohesive material by both sediment and water, sediment is transported under non-equilibrium conditions. Hence, the vertical distribution of both water and sediment velocity must be reproduced to obtain the dynamic shear stress on the surface of cohesive material. Hence, The two layer flows concept[9] is applied here. Water flow where Reynolds stress is dominant is assumed in the upper flow layer. Laminar flow that consists of the bedload and water is assumed in the lower flow layer. The constitutive equations proposed by Egashira et al. (1997) [9] are often used for debris flow. However, these constitutive equations can be also applied for bed load transport or lower flow layer. Shear stress τ and pressure p in the upper flow layer ($h_s \le z \le h_t$) are as follows:

$$\tau = \int_{h_s}^{h_t} \rho g \sin\theta dz \tag{1}$$

$$p = \int_{h_s}^{h_t} \rho g \cos\theta dz \tag{2}$$

Where, z is the vertical axis, h_t is the total flow depth, h_s is the flow depth of the lower layer, ρ is the density of water, g is the gravity acceleration, θ is the channel slope. Shear stress τ and pressure p in the lower flow layer ($0 \le z \le h_s$) are as follows[10]:

$$\tau = \tau_s + \tau_d + \tau_f = \int_0^{hs} \rho_m g \sin\theta dz \tag{3}$$

$$p = p_s + p_d + p_f = \int_0^{hs} \rho_m g \cos\theta dz \tag{4}$$

Here, the pressure and shear stress in the upper layer is the same as those in the lower layer at the boundary. τ_s and p_s are the shear stress and the pressure due to the static intergranular contact, respectively, τ_d and p_d are the shear stress and the pressure due to interparticle collisions, respectively, and τ_f and p_f are the shear stress and the pressure supported by the interstitial liquid phase, ρ_m is the density of mixed material of sediment and water. The constitutive equations proposed by Egashira et al. (1997) [9] are as follows:

$$\tau_s = p_s \tan\phi_s \tag{5}$$

$$\tau_d = k_d \left(1 - e^2\right) \sigma d^2 c^{1/3} \left(\frac{\partial u}{\partial z}\right)^2 \tag{6}$$

$$\tau_f = \rho k_f d^2 \frac{(1-c)^{5/3}}{c^{2/3}} \left(\frac{\partial u}{\partial z}\right)^2 \tag{7}$$

$$p_s = \left(\frac{c}{c_*}\right)^{1/5} \left(p_s + p_d\right) \tag{8}$$

$$p_d = k_d \sigma e^2 d^2 c^{1/3} \left(\frac{\partial u}{\partial z}\right)^2 \tag{9}$$

Where, ϕ_s is the friction angle, e is the restitution coefficient, c is the volumetric sediment concentration and c_* is the volumetric sediment concentration in stationary state, σ is the density of sediment, u is the longitudinal flow velocity, k_d (=0.0828) and k_f (=0.16) are the empirical constants.

Equations (5) to (9) are substituted to equations (3) and (4) and following velocity and sediment concentration profiles are obtained.

$$(h_t - z)\frac{\partial F}{\partial z} = F - c \tag{10}$$

$$\frac{\partial u}{\partial z} = \frac{1}{d}\sqrt{\frac{g(G-Y)}{f_d + f_f}} \tag{11}$$

Where, d is the mean diameter of sediment. F, G, Y, f_d and f_f are as follows.

$$F = \frac{f_{pd}\tan\theta}{(\sigma/\rho - 1)(F_1 - F_2)} \tag{12}$$

$$G = \sin\theta\int_z^{h_s}(\sigma/\rho - 1)c\,dz + \sin\theta\int_z^1 dz \tag{13}$$

$$Y = \left(\frac{c}{c_*}\right)^{1/5}\cos\theta\tan\phi\int_z^{h_s}(\sigma/\rho - 1)c\,dz \tag{14}$$

$$f_d = k_d(1-e^2)(\sigma/\rho)c^{1/3} \tag{15}$$

$$f_f = k_f(1-c)^{5/3}/c^{2/3} \tag{16}$$

$$f_{pd} = k_d e^2(\sigma/\rho)c^{1/3} \tag{17}$$

$$F_1 = f_f + f_d - f_{pd}\tan\theta \tag{18}$$

$$F_2 = \left(\frac{c}{c_*}\right)^{1/5}\left(f_f + f_d - f_{pd}\tan\phi_s\right) \tag{19}$$

Logarithmic velocity profile is applied to the upper flow layer as follows:

$$\frac{u}{u_*} = \frac{u_i}{u_*} + \frac{1}{\kappa}\ln\left(\frac{z - h_s + \eta_0}{\eta_0}\right) \tag{20}$$

Where, $u_* = \sqrt{gh_w\sin\theta}$, u_i is the velocity at the interface, κ is the Karman constant, h_w is the depth of the upper flow layer. η_0 is the particle interstitial scale and estimated as follows:

$$\eta_0 = a\sqrt{k_f}\left(\frac{1-c}{c}\right)^{1/3} d \quad (a \cong 1.0) \tag{21}$$

The height at c=0.05 is assumed for the interface height between the upper flow and the lower flow. Water velocity between the upper flow layer and the lower flow layer is connected at the interface.

The dynamic shear stress, τ_{dy}, in the lower flow layer is calculated to discuss the effect of the volume or concentration of bedload transport rate on the erosion rate of cohesive material bed. The dynamic shear stress, does not consider energy dissipation by the collision between the bed and the sediment in the vertical movement. Hence, here, we discuss the phenomena focusing on the erosion process by the shear in longitudinal direction. So, the dynamic shear stress is calculated by use of the following equation.

$$\tau_{dy} = \tau - \tau_s \tag{22}$$

Here, there is no sediment for the upper layer. Hence, τ_s is equal to 0, The dynamic shear stress can be obtained for both layers.

The experimental sediment transport condition in the paper is non-equilibrium condition. These equations are made to reproduce equilibrium and non-equilibrium sediment transport phenomena and can be applied to non-equilibrium sediment transport [9].

4. RESULTS AND DISCUSSIONS

(1) Erosion rate on cohesive sediment Type A

Fig. 3 show the cross section profiles of the bed at the initial and final conditions. **Fig. 3** (a) is the bed elevation profile on experiment, which flowing by water only. **Fig. 3** (b) and (c) are the results from Case 3 and Case 4, which the experiments use fine sediment (sand size 1) to produce bedload transport. Effect of the sediment supply is compared among the experimental cases by use of the cross section profiles. **Fig. 3** (b) shows that the bed degradation depth with sediment supply (25% q_b) is more than that without sediment supply. This result shows that the bed composed of the cohesive sediment will be eroded more by the addition of the non-uniform sediment in the flow under some hydraulic conditions. **Fig. 3** (c) shows that the erosion process of cohesive sediment is already stopped and the aggradation process occur. This results show that supplied sediment was trapped much by the cohesive material when the velocity of the sediment transport is small. The water discharge is constant under all experiments. Hence, the velocity of the sediment transport near the bed decreases with increase in the bedload transport rate. When sediment supply is exceed 35% q_b, the velocity of the sediment transport becomes enough small to be trapped.

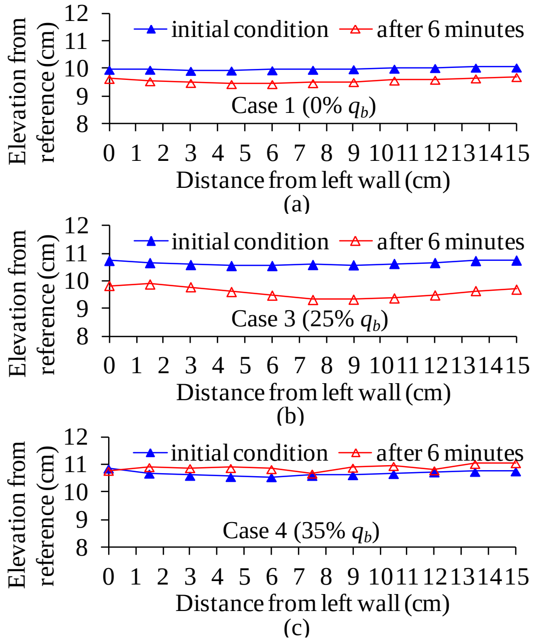

Fig.3 The cross section profiles for Case 1, 3 and 4

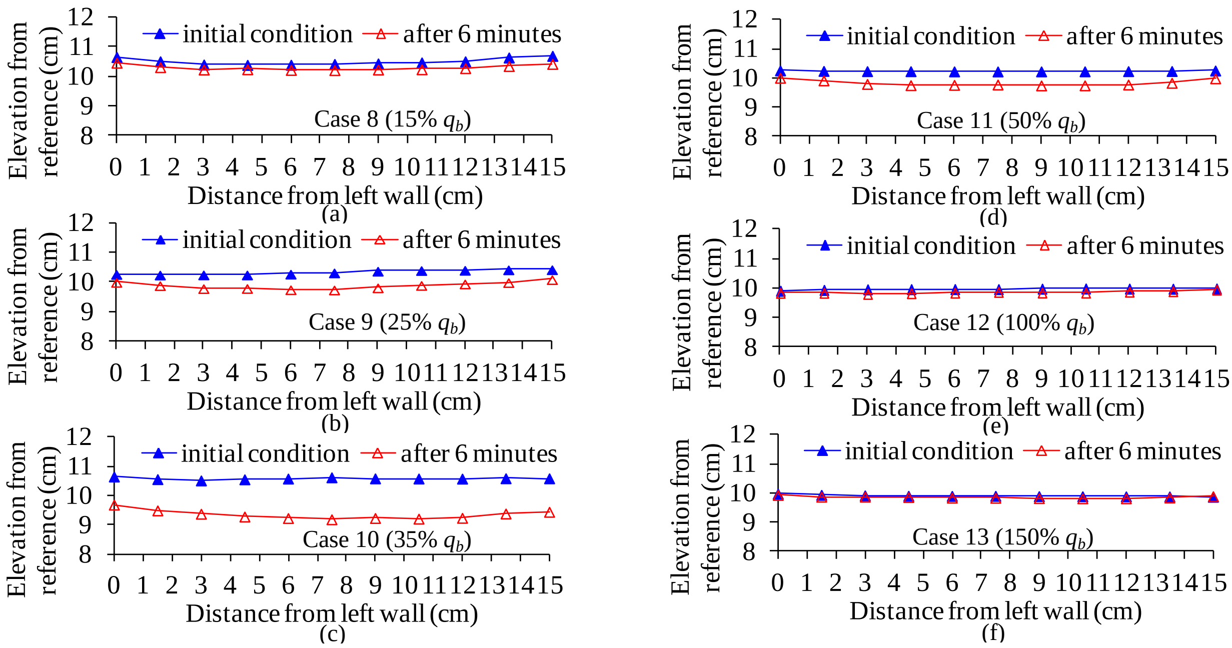

Fig.4 The cross section profiles for Case 8 until Case 13 (on cohesive sediment Type A)

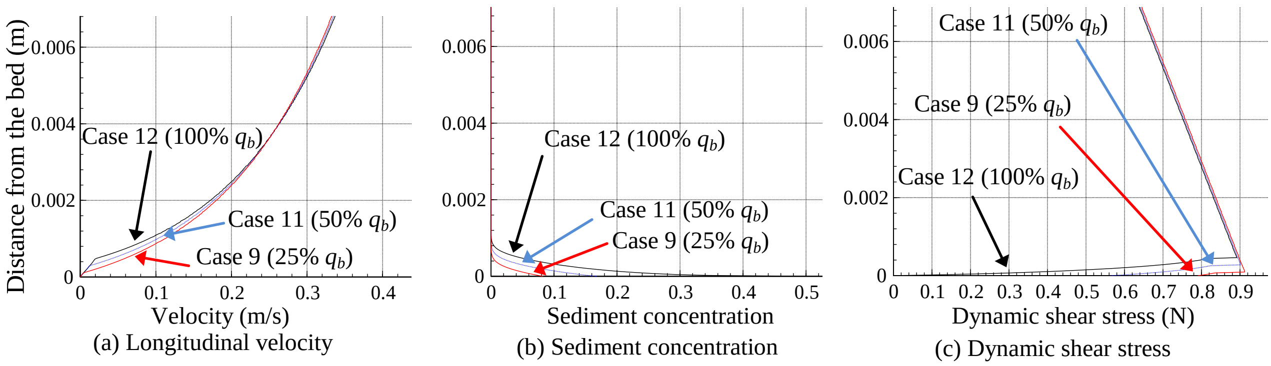

Fig.5 The vertical distribution of longitudinal velocity, sediment concentration and dynamic shear stress

Fig. 4 (a)-(f) are the results from Case 8 to Case 13, which the experiments use coarse sediment (sand size 2) to produce bedload transport. From **Fig. 4** (b) and (c), the bed degradation with sediment supply is more than without sediment supply. But the degradation decrease with adding the sediment supply as shown in **Fig. 4** (d) and (e). Effect of the sediment size is clearly observed, when the sediment supply is large. For fine material (sediment size 1), bed is aggradated when sediment supply is large, because the supplied sediment is trapped by cohesive material. However, for coarse material (sediment size 2), bed is not aggradated when sediment supply is large, because the supplied sediment is not trapped so much by cohesive material. This is one of the reason why the erosion rate of the cohesive material by coarse material is larger than that by fine material. But between coarse material and fine material have similar phenomena on erosion rate. All results show that the erosion rate will increase when the volume of the sediment feeding increase under the small rate condition. However, after achieving a certain volume of the sediment, the erosion rate of cohesive sediment will decrease. This phenomena will be discussed by use of the analysis in **Chapter 3**. In the analysis, the sediment concentrations are varied among Case 9, Case 11 and Case 12. Three cases are chose (Case 9, 11 and 12) that show increasing and continue by decreasing on erosion rate. The amount of sediment feeding in Case 9, Case 11 and Case 12 are 25% q_b, 50% q_b and 100% q_b, respectively. **Fig. 5** shows the vertical distribution of the longitudinal velocity, the sediment concentration and the dynamic shear stress in Cases 9, Case 11 and Case 12. When sediment feeding rate is 100% q_b, the thickness of the bed load layer becomes maximum and velocity near bed is smaller than in Case 9 and Case 11. The dynamic shear stress on the bed is equal to zero. Hence, the erosion rate of the cohesive material is equal to zero in the calculation. On the other hand, when sediment feeding rate is equal to 25% q_b, the thickness of the bed load layer becomes thin and velocity near bed is larger than other two cases. The dynamic shear stress on the bed is also larger than the other two cases. Hence, it is considered that the erosion rate of the cohesive material becomes largest among the three cases. However, after achieves on a certain volume of the bedload transport, the erosion rate will decrease during increasing of bedload transport, as shown in **Fig. 6**, because of the small dynamic shear stress.

(2) Erosion rate on cohesive sediment Type B

Fig. 7 is the results of erosion rate on cohesive sediment Type B. The erosion rate in Case 1a is the maximum among the 5 cases. Sediment supply due to the bed erosion between the upstream end and the observation place affects on the result. In Case 1a, coarse material is only supplied from the bed and the effect of the erosion by non-cohesive material is introduced in Case 1a. However, the non-equilibrium characteristics of coarse material in cohesive material are strong[9]. The distance from the upstream end of cohesive material layer and the measurement location, which is 4 m, is not enough to get the equilibrium sediment transport rate. As a result, the erosion rate of cohesive sediment decreases with increase in the sediment supply.

5. CONCLUSIONS

The effect of volume of bedload transport on erosion rate characteristics of cohesive sediment is studied. Obtained results are summarized as follows.

(1) In cohesive sediment composed of 100% kaolinite, the erosion rate will increase when the volume of the bedload transport increase under small sediment supply conditions. However, after achieves on a certain volume of the bedload transport, the erosion rate will decrease during increasing of bedload transport because of the decreasing in the dynamic shear stress.

(2) The supplied fine non-cohesive sediment is trapped much by the cohesive material when the sediment supply is large and the velocity of the sediment transport near bed is small.

(3) For fine non-cohesive material, bed is aggradated when sediment supply is large, because the supplied sediment is trapped by cohesive material. However, for coarse non-cohesive material, bed is not aggradated when sediment supply is large, because the supplied sediment is not trapped so much by cohesive material. This is one of the reason why the erosion rate of the cohesive material by coarse material is larger than that by fine material.

(4) In cohesive sediment composed of 50% kaolinite and 50% coarse sand, the erosion rate of cohesive sediment decreases with increase in the sediment supply.

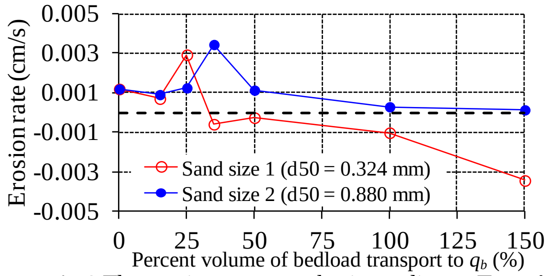

Fig.6 The erosion rate on cohesive sediment Type A

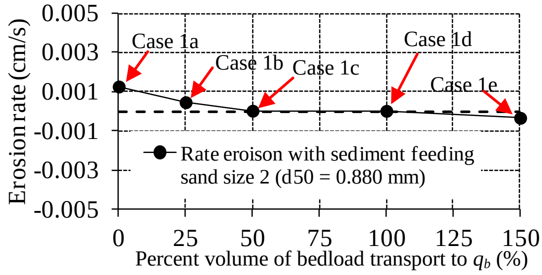

Fig.7 The erosion rate on cohesive sediment Type B

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