HIDING EFFECT AMONG SEDIMENT PARTICLES EXPOSED ON SURFACE OF RIVERBED WITH AN EXTREMELY WIDE RANGE OF SEDIMENT GRAIN SIZES

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ABSTRACT

The objective of this study is to clarify sediment transport phenomena on riverbed composed of materials with extremely wide range of sediment grain sizes. The riverbed materials are generally classified into the following three grain size groups: (a) larger particles which cannot move at all, (b) medium particles which can move as bedload, and (c) smaller particles which can move as suspended load. In the first stage of this study, the experiments were conducted in which each grain size group was represented by one grain size. The vertical structure of the riverbed was measured in the state after attaining the static equilibrium. As a result, it was found that a layer consisting of only medium particles was formed on the riverbed surface. In such a field, the hiding effect of larger particles needs to be fully considered. This hiding relationship was proposed based on our experimental results. The experiment in the second stage was conducted as follows. Since the materials of the actual river have continuous grain size distribution, we also investigated the vertical structure under the condition of riverbed with medium grain size group composed of several grain sizes. Based on the experimental results, it was found that a layer consisting of only medium particles was also formed in the static equilibrium state. In this layer, the bottom elevation of each size of medium particles was at the uniform level on averaged.

Keywords: cobbles, hiding effect, bedload, suspended load, vertical structure of riverbed

1. INTRODUCTION

In this study, the experimental investigation was conducted on the sediment transport on riverbed composed of materials with extremely wide range of sediment grain sizes. Such phenomena are seen in river reach just downstream of a dam in Japan. When a dam is constructed, the sediment supply to downstream is extremely reduced. This has caused issues such as the riverbed degradation and armoring. As a result, boulders or cobbles that cannot move at all by the action of running water are exposed on the riverbed surface.

In order to analyze the riverbed deformation process of such phenomena, it is necessary to fully evaluate the hiding effect of cobbles on gravels and sand. The hiding effect means that the tractive force acting on sand decreases as the exposure degree of cobbles increases. In most of the sediment transport formulas, such as Meyer-Peter and Muller's formula (1948), sediment transport discharge is proportional to the power of $(\tau^* - \tau^*{}_c)$. Therefore, when considering the hiding effect of cobbles, there are three type ways: (a) τ^* takes common value independent of grain size, and only $\tau_c{}^*$ takes different value from that in case of uniform bed, (b) τ^* takes different value due to the effect of hiding, and $\tau_c{}^*$ is same as the value on uniform bed, and (c) both of them were changed. Many previous studies, (for example, Egiazaroff, 1965; Miwa and Parker, 2017), were based on way (a). In this paper, we investigated the hiding effect based on way (b). This is because it is difficult to summarize the results based on considering that both τ and τ_c change. It is necessary to conduct further investigation on whether τ_c changes, such as by measuring the water flow near cobbles in detail. Ashida and Fujita (1986) investigated the hiding effect of gravels and proposed a formula to evaluate the sediment discharge of fine sand suspended from the void among gravels. There are some studies which examined how sand fills the void space among gravels (Blaschke and Schmalfuss et al., 2003; Gibson and Abraham et al., 2009).

The riverbed materials are classified into three grain size groups of sediment: L-, M-, and S-particles. L-particles are cobbles that cannot move at all. M-particles are gravels that can move as bedload. S-particles are fine sand or silt that can move as suspended load. We have conducted fundamental experiments on movable bed under the condition that each grain size group is represented by only one grain size (Sekine and Hiramatsu, 2017). However, since the grain size distribution is continuous in actual rivers, the experiments in this study were conducted on riverbed with M-particles consisting of several grain sizes. In the static equilibrium, the vertical structure of the riverbed was examined. Based on these results, we investigated whether the results obtained in authors' previous experiments are general.

2. SUMMARY OF EXPERIMENTS

The following materials were used for the experiments in this study. Alumina balls with diameter of D_L = 50 (mm) were used for L-particles (specific gravity is 3.98). Glass beads with grain sizes of 5, 4, 3, 2, and 1 mm were used for M-particles (specific gravity is 2.5). These are called M_a-, M_b-, M_c-, M_d-, and M_e-particles in order of decreasing grain size. These were painted black, yellow, green, red, and blue, respectively. The critical tractive force of M-particles increases as the grain size increases, and the dimensionless critical tractive force (critical Shields number) divided by each grain size are 0.041, 0.046, 0.041, 0.042, 0.066. Silica sand with grain size of 0.21 mm was used for S-particles (specific gravity is 2.65). The settling velocity of S-particles w_{oS} is 0.025 (m/s).

The flume used for the experiments was an open channel with a rectangular cross-section with the total length of 16 m, the width of 0.2 m and the slope of 1/250. The bottom of the reach between 8.5 and 14 m from the upstream end of the channel is 0.05 m lower than that of the other reach, and this lower reach is called 'movable bed reach'. As shown in Figure 1a, L-particles were densely positioned in orthogonal lattice in this reach. The initial riverbed of Case C is shown in Figure 1b, where M- and S-particles were filled to the top of L-particles. The experiments were begun under the predetermined flow conditions and the flow of running water were stopped after judging that the riverbed attained the static equilibrium state. This static equilibrium state means the equilibrium state which is attained under the condition that sediment is not supplied from the upstream. Therefore, no sediment was fed during the experiments.

A riverbed in which the void space among L-particles is filled with only S-particles is called 'L-S bed', and that filled with only M-particles is called 'L-M bed'. The experiments on each riverbed were conducted under the conditions that tractive force τ was set to different values. In addition, the experiments were performed on 'L-M-S bed' composed of three grain-size groups of sediment. The experimental conditions in this case are summarized in Table 1. The volume of M-particles to be filled in the initial riverbed was set to be the same as that of S-particles. As can be seen from Table 1, M-particles of each grain size are mixed by the same volume. In Case A, M-particles were represented by only one grain size. In Cases B and C, on the other hand, M-particles were composed of three or five grain sizes. In each case, the average grain size of M-particles in the initial bed was equal. Moreover, the flow rate was constant at Q = 15 (L/s) in all experiments, and the friction velocity was u* = 0.058 (m/s).

After the riverbed attained the static equilibrium state, the friction velocity was calculated based on the water surface gradient. The side wall effect was eliminated by the same method as before (Sekine and Hiramatsu, 2017). In addition, the vertical structure of the riverbed was determined by measuring the height of each particles in the void space in the middle reach of the movable bed and in the center of the transverse direction.

Table 1. Experimental conditions and results: The flow rate was set to Q = 15 (L/s) in all cases. Δ_{Ma} - Δ_{Me} and Δ_S are the vertical distances from the top of L-particles to the upper surface of M- and S-particles, respectively. D_L is grain size of an L-particle.

Case	Mixed ratio of M- and S-particles						Δ_{Ma}/D_L	Δ_{Mb}/D_L	Δ_{Mc}/D_L	Δ_{Md}/D_L	Δ_{Me}/D_L	Δ_S/D_L
	M_a	M_b	M_c	M_d	M_e	S						
A	0	0	0.50	0	0	0.50	-	-	0.30	-	-	0.37
B	0	0.17	0.17	0.17	0	0.50	-	0.27	0.28	0.29	-	0.34
C	0.10	0.10	0.10	0.10	0.10	0.50	0.28	0.29	0.31	0.33	0.38	0.38

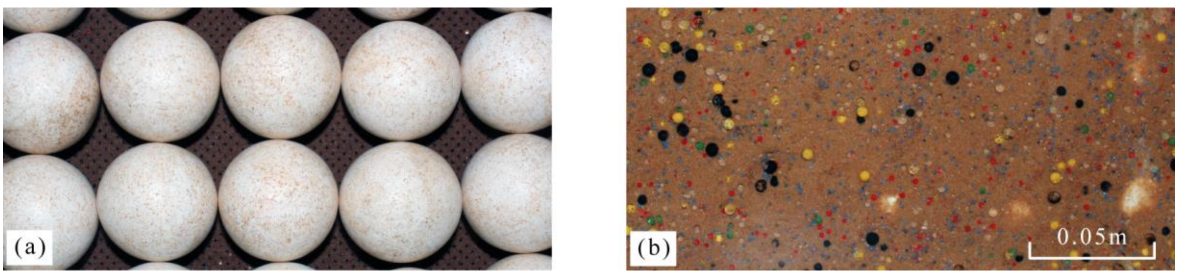

Figure 1. Photographs taken from above channel: (a) L-particles in movable bed, (b) initial riverbed in Case C.

The elevation was measured in order from the particles located above, and the measured particles were carefully removed not to move the surrounding particles. The measurements were carried out until more than half of M-particles embedded in S-particles appeared.

3. VERTICAL STRUCTURE OF RIVERBED WITH THREE GRAIN-SIZE GROUPS OF SEDIMENT

First, we explain the hiding effect of L-particles that we have already clarified. In order to investigate this effect, the static equilibrium states of L-M and L-S bed were examined. Figure 2 shows the schematic view of this static equilibrium riverbed. The following discussion focuses on L-M bed. As shown in this figure, Δ_M is defined as the vertical distance from the top of L-particles to the upper surface of M-particles. The particles on the uppermost surface in the void space among L-particles are at the critical transport. In this case, it is assumed that the tractive force acting on M-particles at Δ_M below from the top of L-particles is equal to the critical tractive force τ_{MC} on a uniform grain size riverbed. When the tractive force τ acting on the entire riverbed is set to different values, Δ_M corresponding to the critical transport changes. Therefore, the relationship between Δ_M/D_L and τ_M/τ was investigated. Based on this, the relationship of the hiding effect was formulated as follows:

$$\frac{\tau}{\tau_M} = \frac{1}{\alpha^2}\left(\frac{\Delta_M}{D_L}\right)^2 + 1 \qquad (1)$$

, in which α is proportional constant (= 0.3). In Figure 3, the horizontal axis corresponds to Δ_M/D_L (Δ_S/D_L), and the vertical axis corresponds to τ_M/τ (τ_S/τ). The black solid line in this figure shows the relationship of Eq. (1), and it can be seen from the figure that the experimental results appear on this relationship. When we see the results of L-S bed, it is found that the relationship of the hiding effect does not change from Eq. (1). This is because the degree to which the tractive force is reduced depends on the exposure degree of L-particles.

The riverbed composed of three grain-size groups of sediment is discussed, which is the main objective in this study. First, the vertical structure of riverbed in static equilibrium state is described when each grain size group is represented by only one grain size. Figure 4a shows the cross section of static equilibrium riverbed in Case A. Figure 5a is a schematic view of this cross section. The characteristics of the riverbed structure found from the experimental results are as follows. The vertical sorting occurred clearly in the void space among L-particles. A layer consisting of only M-particles was formed on the riverbed surface. This layer is called 'M-particle layer'. Below this layer, there was no change from the initial state. This means that sediment mixing was not active below M-particle layer. As shown in Figure 5a, L_M is defined as the vertical distance from the upper surface of M-particles exposed on the riverbed surface to that of S-particles. This distance corresponds to the thickness of M-particle layer. Based on the results of experiments conducted in previous authors' study, it was found that the thickness of M-particle layer was approximately 1-2 times the diameter of an M-particle D_M (Sekine and Hiramatsu, 2017).

In order to explain why M-particle layer was formed, the process of L-M-S bed attaining static equilibrium state is described. When the experiments were begun, M- and S-particles start to transport from the riverbed surface. As a result, the upper surface of the particles filled in the void space among L-particles gradually decreases. This means that L-particles are exposed on the riverbed surface. The tractive force acting on the M- and S-particles decreases because of the hiding effect. When the tractive force acting on the particles is less than the critical tractive force, the transport stops in the order of particles with the larger critical value. Therefore, even after the transport of M-particles has stopped, S-particles continue to transport so as to pass through the void space among M-particles. Then, when the upper surface elevation of S-particles is decreased and the tractive force is equal to the critical value of sediment transport, the riverbed attains a static equilibrium state because the transport of S-particles is also stopped. Since the transport of S-particles is stopped after M-particles, a layer consisting of only M-particles is formed on the riverbed surface.

Next, it is necessary to investigate how general the experimental results represented by one grain size are. The experiments were also conducted under the condition that M-particles were composed of several grain sizes.

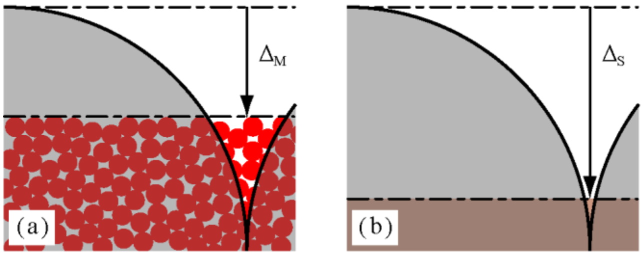

Figure 2. Vertical structure of riverbed in static equilibrium: (a)L-M bed, (b)L-S bed. Gray quadrant shows L-particle, red circles show M-particles, and brown part shows S-particle.

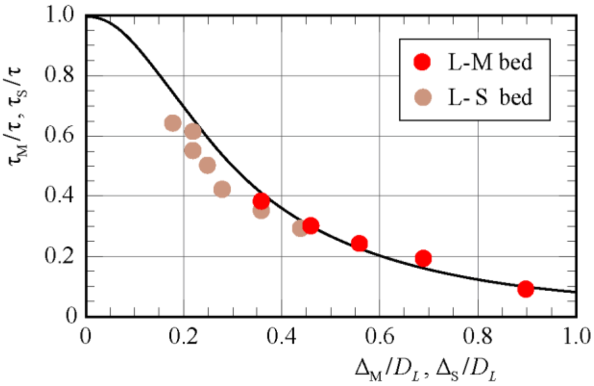

Figure 3. Hiding effect of L-particles

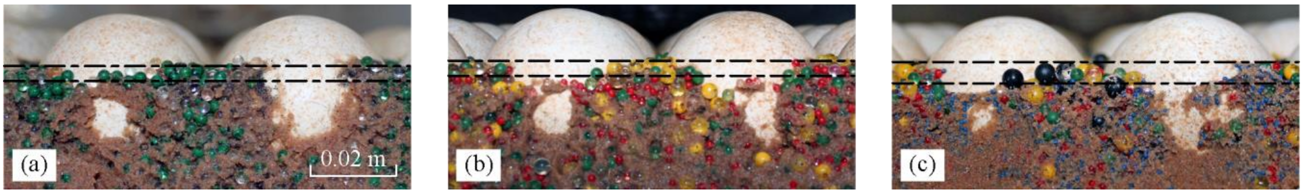

Figure 4. Cross-section of riverbed in static equilibrium: (a) Case A, (b) Case B, (c) Case C.

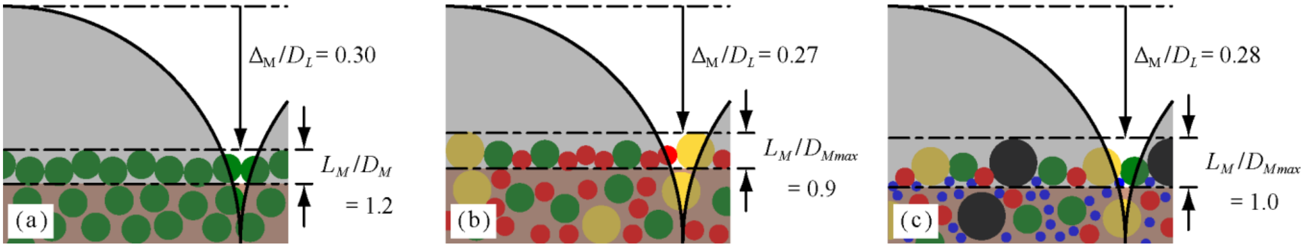

Figure 5. Schematic view of vertical structure of riverbed in static equilibrium: (a) Case A, (b) Case B, (c) Case C.

Figures 4b and 4c are photographs taken after the end of the experiments in Cases B and C. Figures 5b and 5c are schematic views of these photographs. In these cases, M-particle layer was also formed in the void space among L-particles, as in Case A. The maximum grain size of M-particles group is defined as $D_{M\,max}$. In Cases B and C, $L_M / D_{M\,max}$ were 0.9 and 1.0. In other words, the thickness of M-particle layer was approximately $D_{M\,max}$, which was found to be consistent with the previous authors' results (Sekine and Hiramatsu, 2017).

In addition, the structure in M-particle layer is discussed. Δ_{Ma} is defined as the vertical distance from the top of L-particles to the upper surface of M_a-particles, and this definition is the same from Δ_{Mb} to Δ_{Me}. Table 1 shows nondimensional values calculated by dividing these experimental results Δ_{Ma} -Δ_{Me} by D_L. As shown in Figures 5b and 5c, M-particles are hardly piled up in M-particle layer. When we see the top surface elevation of the particles for each grain size, the height appears in descending order of the sediment grain sizes. The difference in elevation among each grain size was almost the same as the difference in grain size. In other words, the bottom elevation of each size of M-particles is at the uniform level on averaged.

4. CONCLUSION

In this study, the experiments were conducted in which the riverbed framework is composed of cobbles that cannot move at all. We investigated the vertical structure of the static equilibrium state which was attained under the condition that the gravels that move as bedload consisted of several grain sizes. As a result, M-particle layer was formed in the void space among L-particles, as in the case that each grain size group was represented by only one grain size. In addition, it was found that the bottom elevation of each size of M-particles in this layer was the same level on averaged.

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