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Segregation of water and gravel using large ball mill device laid roughness bed

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Abstract. This paper presents an experimental approach to study the phenomena of segregating water and gravel using a large ball mill device that reproduces segregation phenomena under debris flow. First, the experiment was conducted in a ball mill device under various conditions: water and gravel mixing, bed velocity, and laid roughness. The occurrence conditions of the segregation phenomena of water and gravel mixing are categorized and compared with each other with and/or without roughness on the bed. Furthermore, the movements after water and gravel mixing in the ball mill device are observed to investigate the segregation mechanism.

1 Introduction

In recent years, heavy rains and large typhoons have often caused natural disasters in Japan, resulting in sediment flow that exceeds the capture effect and capacity of dams. Therefore, it is necessary to install a Sabo dam. The open Sabo dam, a countermeasure structure, is designed based on the premise of the segregation phenomenon in which gravel or boulder concentrates on the front debris flow. However, there are many unclear points in the design information, such as the fact that there are cases where debris flow is flowing down without being classified.

The authors [1] of conducted experiments on straight canals. Therefore, the classification may not be accurate because of the limitation of the channel length, depending on how the bottom surface roughness is considered. It is difficult to observe the classification phenomenon occurring at the front of a debris flow in detail.

Therefore, research has been conducted to contain an infinite length using a ball mill device to observe the phenomena occurring in the water channel at a fixed point under a steady state. Further, the authors [2,3] have conducted research using a ball mill device that observes the phenomena occurring in channels at fixed points. We attempted to segregate the occurrence of the phenomena for two particle sizes by organizing the concentration mechanism of large particles in a mixed sphere. Subsequently, after confirming that the front of the driftwood rises like a surge [4], a characteristic of debris flow, in the ball mill device containing only water, the movement form of the driftwood in the mixed state of water and driftwood was summarized. However, it was considered that the classification phenomenon of driftwood occurs owing to the circulation of water in the state where a surge was generated. However, the surge formation conditions, motion morphology, and classification mechanism in a mixed experiment of water and gravel in a ball mill device have not been clarified.

Therefore, this study elucidates the classification phenomenon that occurs when gravel and stone flow down. The surge formation condition, behavior, and occurrence condition of the classification phenomenon are described using a mixed fluid of water and gravel using a ball mill device. We mainly examined the effect of bottom roughness on surge and classification.

2 Outline of experiment

2.1 Ball mill device, bed roughness, gravel model

Fig.1 shows the equipment used in the experiment. The experimental device is a rotated channel with a diameter, depth, and width of 235, 30, and 30 cm, respectively. The device is rotated clockwise using an electric motor. The bottom and side surfaces are made of stainless steel glass, respectively, and the internal behavior can be confirmed from the outside through the glass on the side surface. The ball mill device has no limitation on the flow path length, and the observation position is almost fixed. Therefore, if these conditions are met, an equilibrium state can be created and maintained for a long time.

The roughness of the bottom is such that the roughness height (k) is "3 × 3 mm acrylic square pillar", and spacing (b) is attached to the bottom of the rotated channel at intervals of 26 mm.

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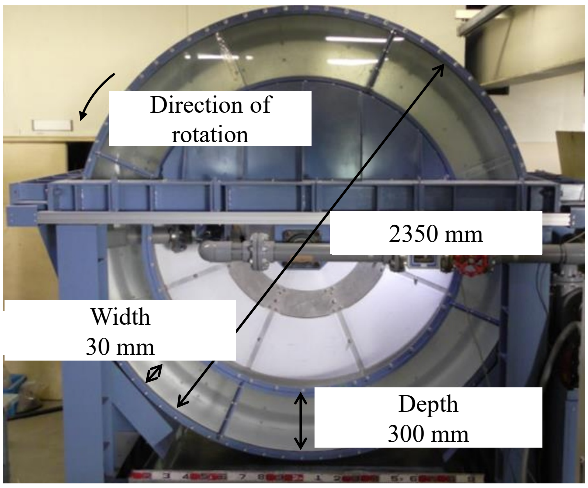


Fig. 1. Ball mill device

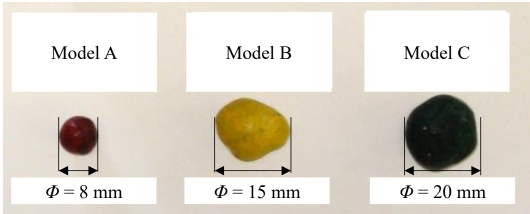
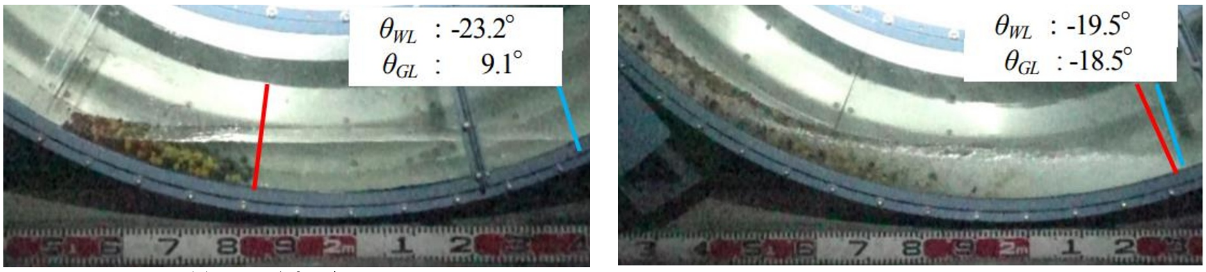


Fig. 2. Gravel model

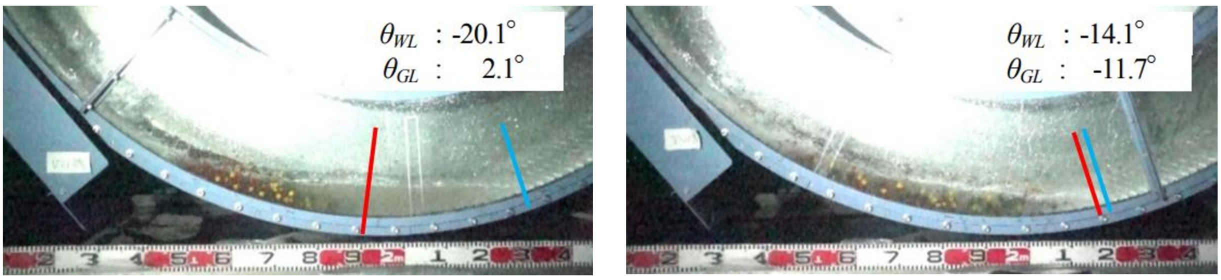
Table 1. Experimental case

Bottom rough	Water	Gravel	Bottom velocity
No	18.5 L	Mix(A,B,C) 1.5 L	0.0 m/s 1.0 m/s 2.0 m/s 3.0 m/s 4.0 m/s 5.0 m/s
With			

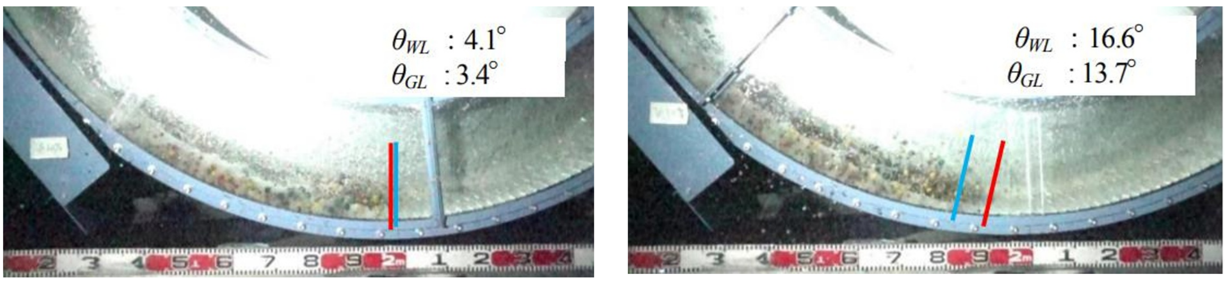


(a) v = 1.0 m/s **(b)** v = 5.0 m/s

Fig. 3. Movement form in the mixture between water and gravel (no roughness)



(a) v = 1.0 m/s **(b)** v = 2.0 m/s



(c) v = 3.0 m/s **(d)** v = 4.0 m/s

Fig. 4. Movement form in the mixture between water and gravel (with roughness)

Fig.2 shows three types of gravel models (hereafter referred to as models A–C). These materials are solidified coal ash, and the average particle sizes of A, B, and C are 8, 15, and 20 mm, respectively.

2.2 Experimental procedure

In the mixed experiment of water and gravel, the bottom speed was set between 1.0 and 5.0 m/s and increased in increments of 1.0 m/s. In addition, we compared two cases: one with and one without bottom roughness. Subsequently, the presence or absence of a surge was determined, and the motion form was observed.

In the water and gravel mixing experiment, the volume of water and gravel was 18.5 and 1.5 L, respectively.

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Table 2. Stage wave formation classification, motion morphology, and classification in each experiment

Gravel model	Roughness hed	Bottom velocity v (m/s)														
		1.0			2.0			3.0			4.0			5.0		
		Surge	Movemet	Classification	Surge	Movemet	Classification	Surge	Movemet	Classification	Surge	Movemet	Classification	Surge	Movemet	Classification
Mix (A,B,C)	No	×	I	○	×	I	○	○	I	○	○	II	△	○	II	△
	with	×	I	○	○	II	○	○	III	△	○	IV	×	○	IV	×

※1 Surge
○ : Surge, × : No surge

※2 Classification
○ : Classification occurrence
△ : Difficult to distinguish
× : Vaporization

I	Water gravel separation state
II	Water gravel mixed state
III	Water gravel mixed state and tip vaporization state
IV	Vaporization state

3 Result

3.1 Movement

Fig.3 and 4 show the movement results for the cases without and with bottom roughness in the water and gravel experiment.

When v = 1.0 m/s, as shown in Fig.3(a), the gravel mass is located behind the water and becomes a gravel-separated state. At this time, the gravel moves individually in the mass, and the maximum particle size (green) is concentrated forward. At v = 5.0 m/s in Fig.4 (b)., the gravel mixes uniformly with water and becomes a gravel-mixed state.

Fig.4 (a) shows the results at v = 1.0 m/s, the same motion mode as that shown in Fig.3 (a) (water/gravel separation state). At this time, the gravel collides with the roughness of the bottom surface, and the larger the particle size, the easier it is to collect in the front. Fig.4 (b) shows the results at v = 2.0 m/s when water and gravel are mixed uniformly. Similarly, in the case of v = 3.0 m/s, as shown in Fig.4 (c), water and gravel are mixed. However, as the bottom velocity increases, the gravel at the tip strongly collides with the roughness of the bottom and evaporates as it jumps up, making the classification difficult. Fig.4 (d) shows that the bottom velocity is considerably high at v = 4.0 m/s, and the water thinly spreads as it is pulled because of the roughness of the bottom. Consequently, the gravel jumps violently and vaporizes with almost no influence of water.

3.2 Movement category and classification

Table 2 lists the wave formation and motion morphology classifications in the mixed experiment of water and gravel. First, the surge formation classification is in complete agreement with the experimental results of water, as shown in Table 2. In addition, when a surge is not formed, the water and gravel are separated and are in equilibrium, regardless of the presence or absence of bottom roughness. On the other hand, at v = 3.0 m/s with no roughness, a surge is formed, and water and gravel are in a separate equilibrium state. At $v \geqq$ 4.0 m/s with no surface roughness, a surge is formed, and the gravel is uniformly diffused into the fluid, resulting in a mixed state of water and gravel. In addition, with bottom roughness, at v = 2.0 m/s, it is in the same category as $v \geqq$ 4.0 m/s with no roughness, and it can be observed that the roughness has the same effect as no roughness at low velocity. Further, it can be observed that when $v \geqq$ 3.0 m/s, the vaporized state gradually starts from the tip, and with large particle size, the entire area vaporizes. Regarding the classification, the classification occurs at $v \leq$ 2.0 m/s, regardless of the presence or absence of bottom roughness. From $v \geqq$ 3.0 m/s, when there is no bottom roughness, water and gravel mix with each other as the bottom velocity increases, making the classification difficult. However, with the bottom surface roughness, the fluid gradually vaporizes and cannot be classified. Therefore, it can be inferred that classification is likely to occur in the low-speed region.

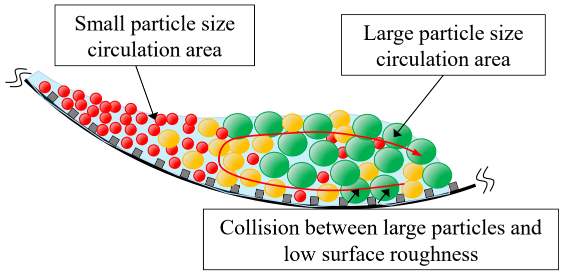

Fig. 5. Velocity distribution during flow

3.3 Classification method and bed roughness

From the above results, when the gravel classification mechanism is summarized, the same phenomenon as that pointed out in previous reports 2) and 3) on the effects of water contamination and bottom roughness is confirmed, as shown in Fig. 5.When gravel with different particle sizes is mixed, large gravel particles rise to the upper layer because of the Brazilian nut effect while climbing backward on the bottom surface. Therefore, as it travels forward along with the forward flow in the upper layer of small particles, gravel is formed forward and classified in the circulation region of large particles.

The classification associated with this circulation becomes smooth when water is mixed with gravel. In addition, when the bottom surface roughness is applicable, the collision force between the roughness and the large grain-sized gravel triggers the Brazil nut phenomenon such that the riverbed surface causes a higher degree of classification.

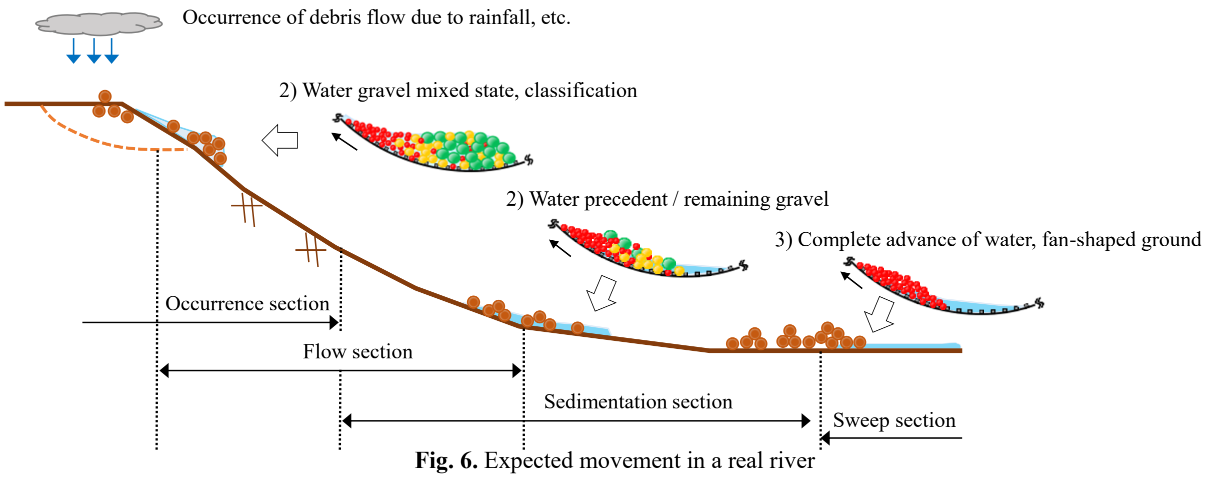

Fig. 6. Expected movement in a real river

In this experiment, the bottom surface is in continuous motion, but this is not the case in the actual river; therefore, the circulation motion in this experiment causes a flow velocity difference such that the lower and upper layer flow velocities in the actual river are lower and higher, respectively. Considering this point, Fig. 6 shows the phenomenon observed in this experiment compared to that in an actual river. That is,

1) The multiphase flow in which water, earth, and stone are mixed in the upstream area becomes a rapid flow owing to the steep slope and flows down to a state where water, sediment, and gravel are uniformly mixed, as shown in Fig.3(b). Thus, gravel with a large diameter collects at the tip owing to the mechanism shown in Fig.5.

2) When the slope becomes gentle downstream, the speed of the entire earth and stone flow decreases. In this experiment, this state corresponds to that with a low bottom surface speed, as shown in Fig.4(a). Further, as the bottom surface friction received by the earth and stone is predominant, the earth and stone begin to settle and show a tendency to remain. Even at this time, the speed difference between the upper- and lower-layers results in the collection of large gravel particles at the head.

4 Conclusions

This study experimentally investigated the surge formation conditions, motion morphology, and classification occurrence mechanism of the water and gravel mixture by using a rotating cylindrical experimental device. At this time, we considered the formation process of a surge, the morphology of motion, and the classification phenomenon owing to the influence of the presence or absence of bottom roughness. The results obtained are summarized as follows.

1) In the experiment with water and gravel mixture, there were two types of motion: water/gravel-separated state and water/gravel-mixed state, with no bottom roughness. On the other hand, with the bottom surface roughness, there were four types of motion: water/gravel separated state, water/gravel mixed state, water/gravel mixed state + tip vaporization state, and vaporization state.

2) When water and gravel were mixed, classification was observed under all conditions up to 5 m/s without bottom surface roughness; however, when bottom surface roughness was applied, the entire fluid did not vaporize at $v \leq 3.0$ m/s. The classification occurred in the range of 1–2 m/s.

In this experiment, only one case was considered for the bottom surface roughness. However, as it is necessary to examine the effect of finer bottom surface roughness, it will be addressed in future work. Furthermore, we conducted experiments on the mixing ratio of water and gravel only for the cases of 18.5 and 1.5 L. In our future work, experiments will be conducted at different concentrations.

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