PROCESS OF CLAY BED DEFORMATION DUE TO THE ACTION OF MOVING PARTICLES OF BEDLOAD

SEKINE MASATO
Waseda University, Tokyo, Japan, sekine@waseda.jp

SHUN ISHIHARA
Waseda University, Tokyo, Japan

NOKO FUJIURA
Waseda University, Tokyo, Japan

FUMITAKA YOSHIKAWA
Waseda University, Tokyo, Japan

ABSTRACT

The purpose of this study is to elucidate the effects of sand or gravel transported as bedload on the clay bed deformation and to understand the lateral and vertical structures of the clay bed. It has already found that the bedload plays a role of erosion promotion of clay bed and a mixed layer of deposited sand and clay is formed on the bed surface. This mixed layer prevents from more clay erosion by protecting it from the contact or collision with bedload. As a result, the mixed layer has the suppressing effect of clay erosion. In this study, a series of experiments in two different channels, one is a straight channel and the other is a uniformly curved channel in order to make these two effects clear, and the deformation process of clay bed is revealed. In considering this process, we focused on the mixed layer of sand and clay formed on a bed surface. As a result of this study, the mixed layer is formed in the initial stage around to the central portion of the bed in a straight channel. In case of bed in uniformly curved channel, the layer starts to form in the area close to the inner side wall because of the effect of centrifugal force on bedload. After the mixed layer was formed, the erosion process proceeds gradually in the transverse direction with lateral widening of the mixed layer.

Keywords: clay bed, erosion and deposition, a mixed layer, bedload

1. INTRODUCTION

Many studies had been conducted in the field of sediment transport and deformation of riverbed with non-cohesive sediment. But research on clay riverbeds was hardly conducted, and the knowledge about it was restricted. If the bed material contains about 10% clay, the mechanism and process of bed erosion will be significantly different from that of the sand bed. The authors have been conducting a systematic basic experiment on the erosion of "clay bed" generated by the effect of only water flow as the first stage of research (Nishimori and Sekine, 2009). It results in the erosion rate formula of clay, and it has already been applied by many researchers for their numerical computation. "Erosion rate" refers to the depth of erosion that occurs per unit time, which is significantly affected by the water content ratio and water temperature contained in the clay. It is proportional to the cube of the friction velocity. In actual rivers, erosion of the clay bed is caused by the flow of water, and is also affected by bedload supplied from upstream. Experimental studies on this effect have been attempted by Sekine, Oka and Nomura et al. (2013), and Sekine and Hiramatsu (2017). According to these two studies, the following remarks were found.

(1) Under conditions where sand is transported as bed load, sand enters below the surface of the clay bed, and a "mixed layer" is formed. When a large amount of sand is further supplied, a layer of only sand (sand layer) is formed on this mixed layer. This means that the mixed layer and sand layer are placed on the original clay layer.

(2) If the amount of sand equivalent to the equilibrium bedload transport is continuously supplied, the state of bed attains the quasi-equilibrium state of sand bed river, and the thickness of this mixed layer may be about 1.5 times the particle size regardless of the tractive force.

(3) Under the condition that sand or gravel is transported as bedload, there can be the characteristic relationship between the sand supply rate and the erosion rate of clay. The erosion rate increases as the sand supply rate increases, but it decreases if the sand supply rate is larger than some critical value.

(4) Sand covers the surface of the clay bed to form a mixed layer, which significantly improves the erosion resistance of the riverbed and suppresses the erosion of the clay.

Based on the above results, this study focused on the effect of sand or gravel transport as bedload to promote or suppress the clay bed erosion. Fundamental experiments were conducted on the deformation process of clay bed to sand or gravel bed. In this study, experimental study in uniformly curved channel was also conducted in order to understand the bed deformation process more deeply under the influence of centrifugal force.

2. SUMMARY OF EXPERIMENT

2.1 Experimental apparatus

In this study, a series of experiments were conducted in two types of channels; a straight channel and a uniformly curved channel. Schematic diagram of a straight channel is shown in Figure-1(a), which has a total length of 4.9m and a cross section of 0.1m square. The channel sections between upstream end 0 and 0.23m and between 3.7 and 4.9m from upstream end are set to be fixed bed, and a rubber sheet with pyramid like roughness was attached on the surface of the channel bottom. Section between 2.3 and 3.7m was covered with sediments explained later, which is called movable bed. In the upstream part of this movable bed section from 0 to 0.2m, the bed was composed only of sand, and a surface of the bed can be moved upward by jacking up the bottom plate in that section. By this operation, the sand can be supplied on the downstream clay bed. The rate of sand supply can be adjusted by changing the speed of jacking up, which means that sand transport rate as bedload can be controlled and set uniform over the channel cross section. Another set of experiments were conducted in uniformly curved channel shown in Figure-1(b). The radius of curvature is 1 m, and this section is a rectangle 0.2 m wide and 0.4 m high. The sections between 90 and 240 degree is set to be movable bed which composed of clay, and the other portion is fixed bed on which sand of the same particle size as bed load was attached. During this experiments, the sand was supplied uniformly over the section at 90 degree which is the boundary between fixed bed and movable bed. Supplying rate of sand is one of the most important parameter to be changed in this experiment.

2.2 Materials and Methods

TA kaolin (50% particle size: 0.005 mm, specific gravity: 2.65) was used for clay, and silica sand No.3 (60% particle size: 1.56 mm, specific gravity: 2.65) was used for sand in this experiment. In preparing the test sample as the movable bed, T.A. kaolin and water were mixed uniformly. After that, the clay sample was left in a still water for about a half day to make compaction. In this study, the height of the riverbed surface before and after the action of water flow were measured on the entire range of movable bed by a laser displacement sensor. Local erosion depth of the bed can be evaluated by the difference between two measured values of each height at the same point.

2.3 Experimental conditions

Experiment ware conducted under the different condition of flow discharge and supplying rate of sand. In a straight channel, the flow rate of water is 0.270 L/min, and the dimensionless tractive force for silica sand No.3 is $\tau^* = 0.079$. Supply rate of sand q_b was set to be larger or smaller than the equilibrium bedload transport rate q_e which was estimated by Meyer-Peter & Müller’s formula. The value of q_e can be the transport capacity of sand under the tractive force in each flow in experiment. In this paper, the results of experiment where the

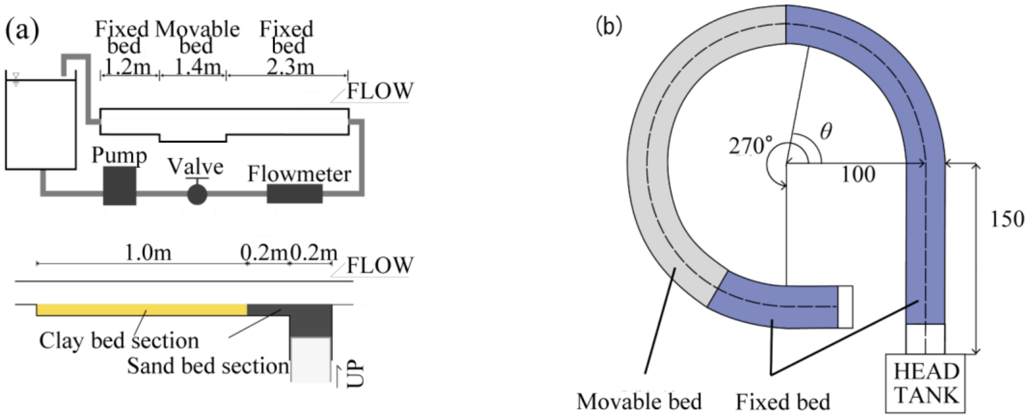


Figure-1. Experimental setup: (a) Straight channel (b) Uniformly curved channel relative sand supply rate q_b / q_e was set to be 0.25, 0.5, and 0.75 respectively were explained. In the curved channel, the flow rate of water was set to be 200 L/min, and relative sand supply rate q_b / q_e was set to be 0.2.

3. Change of clay bed in straight channel

3.1 Erosion promotion and suppression effects of bedload

In this chapter, the effect of sand transported as bedload on the deformation process of clay bed was investigated quantitatively. Figure-2 shows one of the experimental results. Relation between two important physical variables; one is the erosion rate of clay which can be evaluated by dividing the erosion depth by required time, and the other is sand coverage ratio F_{sand} which is the ratio of the area covered with sand to the entire bed area. From this figure, it can be seen that the erosion rate decreases as the coverage increases, and the relation is independent of relative sand supply rate q_b / q_e. This means that sand covered with the bed surface play a role to suppress the erosion of clay bed. In the initial stage of water flow, on the other hand, the erosion rate increases because the transported sand particles contact the clay bed surface and promote clay erosion significantly. As time goes on, erosion rate decreases and gradually approaches zero. Such effect of suppressing clay erosion is also important in deformation process of clay bed exerted by the action of bedload. As was explained above, this process is controlled by both "erosion promoting effect" and "erosion suppressing effect" on clay bed by sand or gravel transported as bedload. In addition to this, it was also found that the required time before it attains the state of same coverage ratio F_{sand} becomes larger as relative sand supply rate q_b / q_e is smaller.

3.2 Formation process of mixed layer

Figure-3 illustrates the state of the riverbed at 15, 30, 45 and 60 minutes from the beginning of this experiment. The color of supplying sand was set to vary with time. In the first 15 minutes, a brown sand was supplied, after that the color is changed to red, blue and green every 15 minutes. Left photograph in Figure-3 is the enlarged one which corresponds to the portion in yellow box in the middle photograph. Sand remaining on the riverbed surface is in the state where half of the particle is buried in clay bed and forms a layer together with clay. This layer of sand and clay is called the "mixed layer" in this paper. This photograph shows that the formation of this mixed layer starts from the central portion of the bed, and the extent of this layer expands gradually in the transverse direction. The right column of Figure-3 shows the erosion depth contour diagram. It was revealed that the clay bed erosion proceeds simultaneously with the formation of the mixed layer, and therefore the erosion depth becomes larger in the area covered with sand. Erosion occurs hardly in the white portion where clay is still exposed on the bed. As is seen from the middle photographs, the width of the portion where the sand coverage ratio became relatively higher and clay erosion occurred extended in the transverse direction. It is also seen in the same photograph that the green and blue sand which was supplied later exists around the edge of the mixed layer facing laterally on the clay bed which is not eroded yet. Figure-4 shows a cross-sectional profile of riverbed measured at each time. It is obvious that eroded channel appears on the bed and extends in transverse direction. Channel migration speed or the lateral erosion rate was found to be about 0.02 cm/s. This value is the order of magnitude 10^2 times the vertical erosion rate. The process of bed deformation can be summarized as follows; (1) a streak-like erosion occurs in the central portion due to the concentration of bedload, (2) erosion in the vertical direction proceeds but is suppressed as the coverage of sand proceeds, (3) lateral erosion occurs gradually in transverse direction, and (4) finally, the sand coverage proceeds over the wide range of bed.

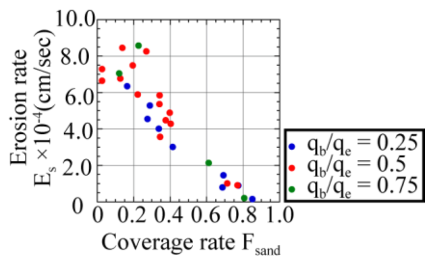
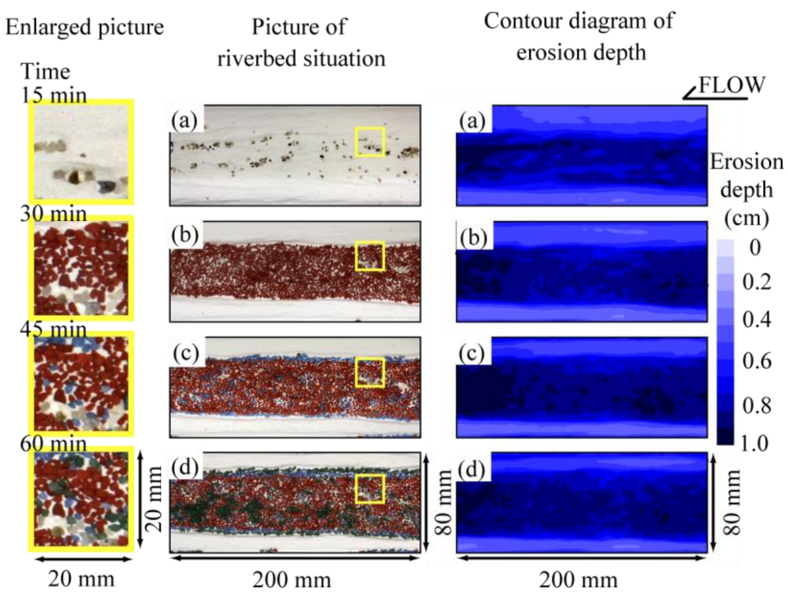


Figure-2. Relation between sand coverage ratio and erosion rate



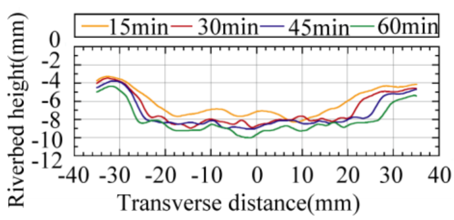
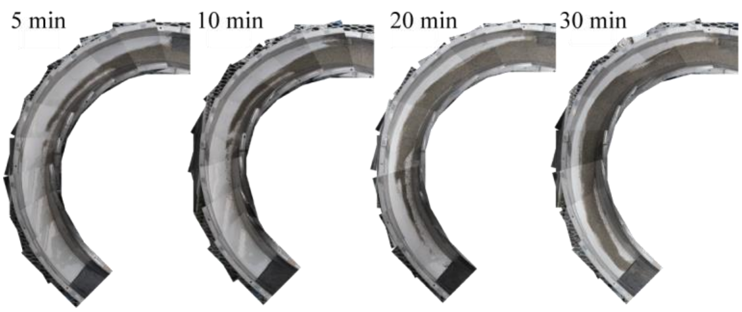


Figure-4. Cross-sectional profile of the riverbed

Figure-3. Riverbed situation and contour diagram



Photograph-1. Riverbed situation in a curved channel

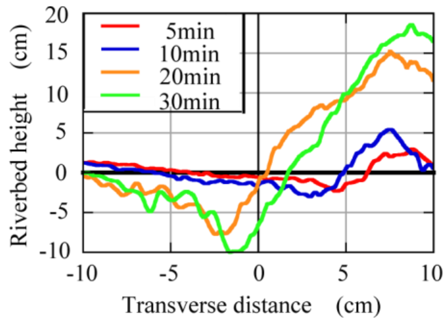


Figure-5. Cross-sectional profile of the riverbed at different times

4. Erosion phenomena of clay bed at curved river

First, the experiment was conducted under the condition that model river bed is composed of sand only in the whole reach of experimental flume. It has been confirmed that erosion occurs in the outer side of bed and deposition occurs in the inner side, as usual. This means that a well-developed secondary flow has occurred, as already explained by several previous studies. After such verification, we conducted a series of main experiments in the same channel under the condition of the clay bed. Photograph-1 (a)-(d) shows that sand is initially deposited along the inner side-wall due to the influence of the secondary current, and erosion of clay bed occurs initiates from the area there. Dark portion along the inner wall in Photograph -1 denotes such area. White portion in Photograph -1, on the other hand, is the clay bed hardly eroded yet. It can be seen from Photo-1 that the eroded area extends laterally toward outer wall gradually as time goes on. Figure-5 shows the cross-sectional profile of riverbed at each time. The left half with minus transverse distance denotes the inner half of bed, and the right is outer half. It can be seen that the remarkable erosion initiates in the inner half and the point of maximum erosion migrates toward the outer side wall as time goes on. The location where this erosion is most active is along the boundary between the area mixed layer developed and the area clay is exposed on the bed surface. In this case of uniformly curved channel, the promotion effect and the suppression effect of clay bed erosion caused by bedload, which was made clear as a results of straight channel experiment, works in a same manner. As a reference, the sand coverage ratio F_{sand} is approximately 0.8 and the clay content ratio R_{cc} is approximately 0.35 on the bed where the mixed layer is sufficiently formed in this experiment, and these two values are same as the ones in the straight channel.

5. CONCLUSIONS

In this study, we conducted an experimental study to elucidate the deformation mechanism of clay river bed under the influence of transporting sand and gravel as bedload as well as running water. It was found from a series experiments that sand and gravel moving as bedload promotes the erosion of clay bed significantly. Such effect was made clear in both the straight channel and the curved channel. In addition, the formation of the mixed layer of clay, sand and gravel on the bed surface also proceeds, which reduces clay bed erosion by being covered with deposited sand and gravel. This process initiates in the central portion of the riverbed gradually, and then the widening proceeds laterally in a straight channel. In case of uniformly curved channel, such a process is from the inner side to the outer side, the mechanism of which is expected same as the one in straight channel.

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