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EROSION PROCESS OF COHESIVE SEDIMENT AND EROSION RATE FORMULA

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SYNOPSIS

The erosion process of soft cohesive sediments, which were deposited naturally on a river bed, is investigated in this study. Extensive series of experiments, conditions of which were set systematically, were conducted to evaluate the erosion rates by running water in a closed conduit. Test samples consisted of a mixture of silica sand, clay and water, the composition of which was set to be a variable. The main factors which govern this process were found to be the clay content ratio (the weight ratio of clay to the total sediment), the water content ratio (the weight ratio of water to the clay), a frictional velocity of flow, a water temperature, and the size of silica sand. The effects of these parameters on the erosion rate were evaluated quantitatively. Soil mechanical tests were also conducted to investigate the correlation between erosion rates and the cohesive strength of the sediments. The erosion rate formula was also derived on the basis of experimental results. Also, the mechanism of this process was examined and made clear to a certain extent.

INTRODUCTION

In this past half century, a considerable number of studies on sediment transport have been conducted to clarify the transport mechanism and to evaluate the transport rate quantitatively. In case of cohesionless sediments such as sand or gravel, a knowledge of them has been almost established, though several problems still have not been solved. Focusing on the cohesive sediments such as clay, on the other hand, there were a limited number of studies which were made before 1980 by Partheniades (1), Ashida and Tanaka (2), Murray (3), Ariathurai and Arulanandan (4) and others in the literature except for the study by Ohtsubo and Muraoka (5). Ohtsubo and Muraoka (5) have made the significant contributions to this research field. But no systematic study has been conducted since then. Therefore, the erosion mechanism of cohesive sediments has not been fully understood yet. The reason for this is the complicated way in which the cohesive force is exerted on the surface of clay particles to combine each other. From an engineering point of view, a knowledge of how much deposited cohesive sediment can be removed under the force of given shear stress is necessary before river structures such as sluice gates can be planned and constructed effectively in the reach of tidal river. Such information is also important to understand the geometry of stable channels with cohesive sediment.

Considering such a background, the authors have continued conducting the experimental studies on the erosion process of soft cohesive sediments which deposits on the channel bed (6, 7, 8, 9). A great number of erosion experiments were performed in a closed conduit with test samples of clay-sand mixture under the conditions arranged systematically. A series of studies revealed that the important parameters which affect the erosion rate of cohesive sediment were the shear stress τ_0 exerted on the surface of the sediment, the clay content ratio R_{cc}, the water content ratio R_{wc}, the water temperature and so on. The

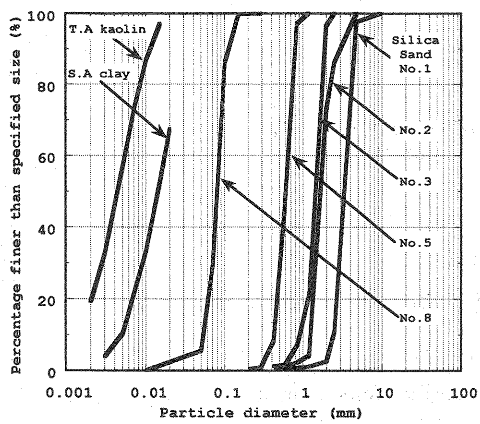

Fig. 1 Sediment size distribution

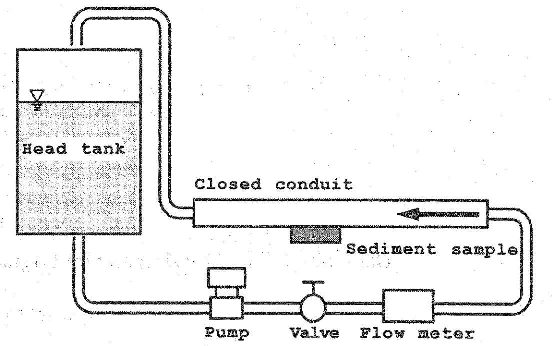

Fig. 2 Experimental apparatus of sediment erosion

definition of R_{cc} and R_{wc} will be explained later. One of the purposes of the present paper is to derive the erosion rate formula and to verify its validity on the basis of experimental data. The erosion process was also closely examined to explore its mechanism and an analysis of video image and photograph were carried out. It was found that the sediment waves appeared to form in the entire area of the sediment surface, and they were forced to deform due to the surface erosion of the sediment itself. A detailed analysis of the erosion process will also be made in the next section.

EXPERIMENTAL SETUP AND PROCEDURE

Sample preparation

Each test sample is a mixture of silica sand and two kind of clay, named 'S.A clay' or 'T.A kaolin', the size distributions of which are seen in Fig. 1. Silica sand No.3 was used in most of the experiments, but the others were used for comparison so as to investigate the effect of grain size of cohesionless sediment. These sediments were purchased from Kanto Bentonite Co., and the specific gravity of the clay is 2.7, and that of the silica sand is 2.65. Important parameters which characterize this cohesive sediment are as follows: (a) the weight ratio of clay to the total sediment, which is defined as the 'clay content ratio R_{cc}', (b) the weight ratio of water to the clay, which is defined as the 'water content ratio R_{wc}', and (c) the grain size of the cohesionless sediment. In the present study, R_{cc} was set between 0.1 and 1.0 for S.A clay and between 0.6 and 1.0 for T.A kaolin, and the water content ratio R_{wc} between 0.3 and 0.6 for S.A clay and between 0.6 and 1.0 for T.A kaolin. In the preparation for test sample, the sand, clay and water were put together in a ball mill under the specified ratio, and were mixed mechanically until the sample became uniform. After completing this procedure, the sample was set in the bottom trench of the conduit without being disturbed, and was left there under a still water for one day in order to allow for consolidation.

Measurement of sediment erosion

Experiments were conducted in a circulating closed conduit system with a square cross-section. The conduit is 500 cm long, 10 cm wide and 10 cm deep, and is made of acrylic board, so that the surface state of the sample and the phenomena which occur in the conduit can be observed. The test sample was placed in the bottom trench which was located 250 to 300 cm from the inlet of the conduit. The size of the sample is 50 cm long, 10 cm wide and 5 cm deep. On the ceiling and the bottom of the rest of the conduit, a rubber board with dense pyramid-like roughness elements, the height of which are 3 mm, is attached so as to make the boundary layer fully developed before the flow reaches the test sample. The hydraulic conditions of the flow in this conduit are controlled only by operating the flow valve. The outline of the apparatus is shown in Fig. 2 schematically. For reference, turbulent measurement by Laser-Doppler anemometer (Dantech) was conducted, and the frictional resistance coefficient f of the flow was found to be almost 0.011. Therefore, the averaged shear stress τ_0 exerted on the surface of test sample could be evaluated approximately by the relation $\tau_0 = \rho f U^2$, where U is the average flow velocity in the experimental conduit.

After finishing the preparation described above, water flow was introduced over the test sample.

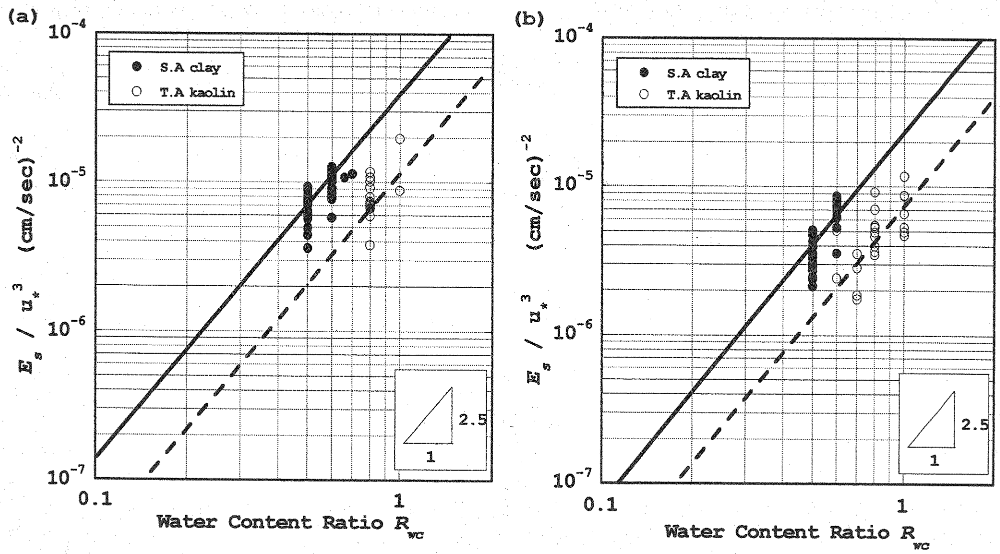

Fig. 3 Relation between erosion rate and water content ratio : (a)High Temp. , (b)Low Temp.

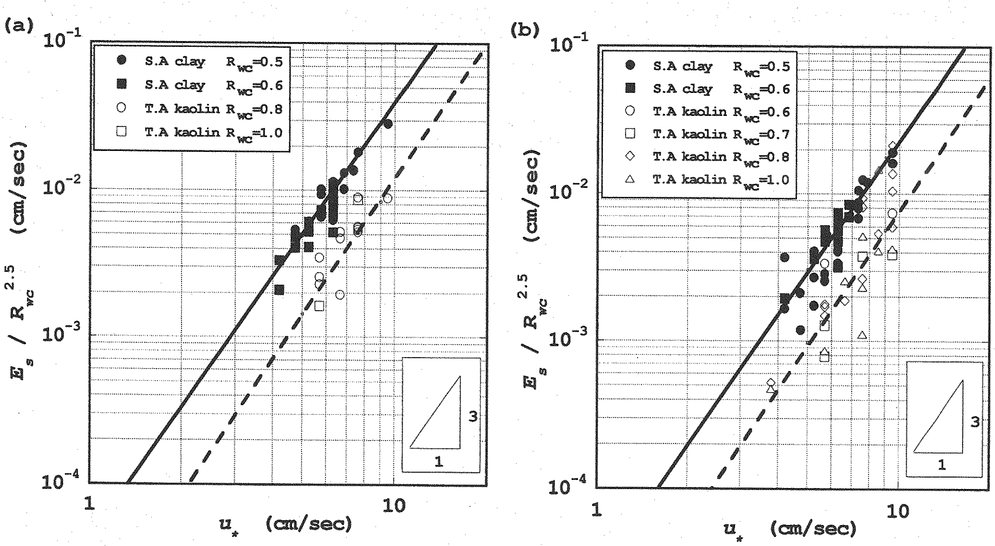

Fig.4 Relation between erosion rate and frictional velocity : (a)High Temp. , (b)Low Temp.

The surface elevation of the sample was measured directly by using a Laser Displacement Sensor (Keyence Japan). At this point, the water flow was stopped temporarily. The data were obtained along the longitudinal measuring lines on the surface which were set at equal intervals of 1 cm from the side wall of conduit, and the number of points on each line was 100. So the total number of measuring points was 900. Furthermore, the data were transferred as digital data into a computer after A to D conversion, and were processed statistically. The volume of the sample which was eroded during the given periods was evaluated by summing up the product of local erosion depth and its projected area over the surface. Erosion rate E_s is defined as the averaged value of eroded depth divided by the time. It should be noted that the side wall region where the velocity is slightly smaller than the other region is excluded from measuring points. Photographs and video images were also taken to analyze the surface state and erosion process more precisely at a later date. Several series of experiments were conducted all the year round, the data of which were processed by classifying them into the following two categories: (a) the summer season in which the water temperature was between 18 and 22 degrees centigrade ('high temperature'), and (b) the winter season in which the temperature between 9 and 12 degrees centigrade ('low temperature'), respectively.

EROSION RATE FORMULA

Erodibility of cohesive sediment

The effects of the governing parameters on the erodibility of cohesive sediment are discussed here. The following findings have been already reported in regard to the effects of the governing parameters (8, 9);

- The erosion rate E_s increases considerably as either the frictional velocity u_* or the water content ratio R_{wc} becomes larger.
- The effect of the water temperature on the erosion rate can be remarkable. The value of erosion rate in the summer season is found to be almost 50% greater than that in winter.
- Both the clay content ratio R_{cc} and the grain size of cohesionless sediments has less effect than the above three parameters, and it can be approximated that the value of E_s takes a constant value under the condition that $0.2 < R_{cc} < 0.8$, or the grain size D_s is almost greater than 1.8 mm.

Based on these findings, the authors attempted to find the functional relationship between the erosion rate and the above parameters. Figs. 3 and 4 show the results of this investigation. Fig. 3 shows the relationship between the erosion rate divided by the third power of frictional velocity E_s / u_*^3 and the water content ratio R_{wc} on a Log-Log graph. Fig.4 shows another relationship between the erosion rate divided by the 2.5 power of the water content ratio $E_s / R_{wc}^{2.5}$ and the frictional velocity u_*. As has been described above, the difference of the erosion rate between in summer and in winter season was obvious. Therefore, the data in summer season were plotted in Figs. 3(a) and 4(a), and those in winter season were in Figs. 3(b) and 4(b). In these figures, both data obtained for S.A clay and T.A kaolin were shown with paying attention to distinguish one from the other. The solid lines in Figs. 3 and 4 correspond to the approximate relation for S.A clay, and the broken line to that for T.A kaolin, and the inclinations of these lines are 2.5 in Fig. 3 and 3.0 in Fig 4, respectively. Some scattering can be seen in these figures, but no systematic trend can be detected at all between the erosion rate and some other parameters than R_{wc} and u_*. Therefore, it can be concluded that the erosion rate is proportional to the third power of frictional velocity and the 2.5 power of the water content ratio.

Derivation of erosion rate formula

Based on the above results, the erosion rate formula is derived for the cohesive sediment which consists of either S.A clay or T.A kaolin. This formula can be expressed as follows:

$$E_s = \alpha R_{wc}^{2.5} u_*^3 \tag{1}$$

in which α is the coefficient which depends on both the clay minerals and a water temperature. The values of α evaluated for S.A clay and T.A kaolin are summarized in Table 1. In the same table, the values of another coefficient β in Eq. 3 are also seen, which will be discussed in the next section. A comparison of the values in Table 1 between S.A clay and T.A kaolin reveals that the coefficient α takes a same order of magnitude even though the value for S.A clay is about three times larger than that for T.A kaolin. The dependence on water temperature is also found to be the difference in these coefficients. In Fig. 5, a direct comparison is made between the predicted value of E_s by Eq. 1 and the measured value. The solid line means a perfect agreement, and the area bordered by a couple of dotted lines corresponds to that the absolute error is less than 25 %. It can be deduced that the erosion rate formula derived here is valid to some extent for the data obtained here.

The relation between the cohesive strength of the test sample and the erosion rate is also discussed. The cohesive strength of the sediment means the resistance force against the action of surface shear force. In order to evaluate this strength, a newly invented soil mechanical test was conducted. Details of this test have been explained in the previous papers (8, 9). Fig. 6 shows one of the findings of this test for T.A kaolin, and which reveals the relationship between a normal stress σ and a surface shear strength τ. The solid lines in Fig. 6 are the best fitted line. As is seen in Fig. 6, the cohesive strength C, which is defined as the intercept of the line on the vertical axis, becomes smaller as the water content ratio increases. It was also deduced from the same kind of measurement that the clay content ratio R_{cc},on the other hand, hardly affects the cohesive strength C. The tendency of C against either R_{wc} or R_{cc} is consistent with that of E_s which was described in the previous section. Therefore, the correlation between the cohesive strength C and the water content ratio R_{wc} was thought to be a necessary matter for investigation. Fig. 7 is the result of this. Because the magnitude of this strength is smaller and this mechanical test is sensitive to the sample

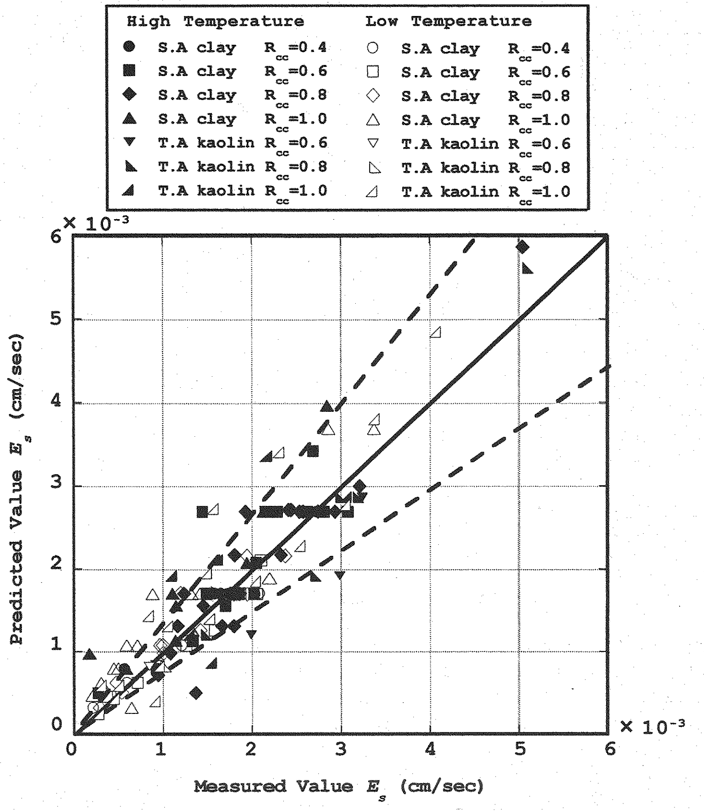

Fig. 5 Direct comparison between the predicted value by Eq. 1 and the measured one

Table 1 Coefficient in the equations

Clay		α (cm/sec)$^{-2}$	β
S.A clay	High Temp.	3.89×10^{-5}	9.35×10^{-4}
	Low Temp.	2.44×10^{-5}	5.86×10^{-4}
T.A kaolin	High Temp.	1.15×10^{-5}	2.76×10^{-4}
	Low Temp.	0.778×10^{-5}	1.87×10^{-4}

preparation, some data, which were obtained under the relatively higher water content ratio, are questionable because they contain some errors. Another problem is that the number of the measured data is still limited. The functional relationship was examined for reference, though the above disadvantages still must be overcome. The relationship between C and R_{wc} is now assumed to take the following expression:

$$C = K_c R_{wc}^{-2.5} \tag{2}$$

The solid line in Fig. 7 corresponds to this relation, and the coefficient K_c takes the constant value of 2.4 N/m^2. Substituting Eq. 2 into Eq. 1, another expression of erosion rate was derived as follows:

$$E_s / u_* = \beta (\rho u_*^2 / C) \tag{3}$$

in which β is the dimensionless coefficient ($= \alpha K_c / \rho$), which also depends on both the clay minerals and a water temperature. The value of β is also shown in Table 1. Eq. 3 is an alternative formula of erosion rate.

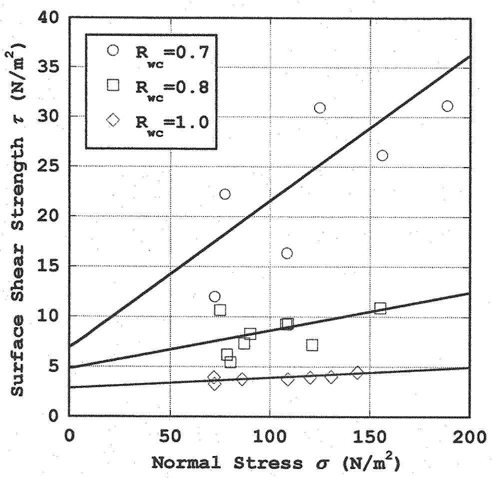

Fig.6 Results of soil mechanical test of surface shear strength

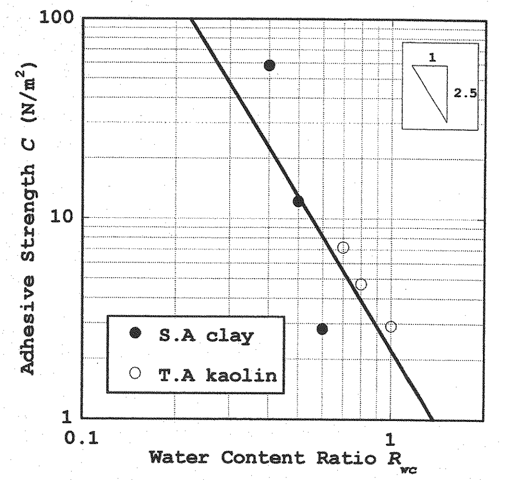

Fig. 7 Relation between adhesive strength and water content ratio

EROSION PROCESS OF COHESIVE SEDIMENT

In this chapter, the erosion mechanism of cohesive sediment is discussed. The analysis of video image and photographs, which were taken during the period of erosion, were conducted.

Before explaining the newly obtained results, some findings in the previous studies (6,7,8,9) are discussed again here. Two kinds of erosion are known to exist, and each erosion occurs mainly under the condition of shear stress exerted on the surface of sediment. Findings reveal the following facts:

- If the shear stress is less than some 'threshold value', no significant erosion occurs. But even if this condition is satisfied, erosion can still occur slightly. Therefore, this 'threshold value' has different meaning, in the strict sense, from the critical shear stress for sands and gravels.
- If the shear stress is greater than the 'critical value', a lump of sediment is successively eroded. Also the erosion rate varies considerably with the shear stress. The 'critical' shear stress takes a larger value than the above 'threshold one'. The erosion under this condition is called 'active erosion'.
- In the intermediate range of shear stress, the erosion proceeds as if the clay particle dissolves into running water. The erosion rate is restricted to keep smaller value.

Based on such information, a more detailed investigation was conducted on what occurs on the surface of the test sample in case of this 'active erosion'. In Fig. 8, the experimental results of surface elevation are shown for T.A kaolin. Fig. 8 (a) shows the temporal variation of surface configuration along the centerline of the flume. Figs. 8 (b) and (c) are the photograph and the contour map of the surface elevation 3 minutes after the beginning of the experiment, respectively. It can be seen from Fig. 8 (a) that the surface waves with almost constant wavelength cover the entire domain of sediment bed and that they migrate downstream. This significant feature was also detected under any other condition of R_{cc} and R_{wc} independent of the water temperature or the variety of clay. Existence of sediment surface wave was also reported by Ohtsubo and Muraoka (5) in their study of erosion of cohesive bottom sediment. The characteristics of this sediment wave and the interrelation between the surface deformation and the erosion itself can be summarized as follows:

- According to the statistical analysis of the measured data, the sediment waves have the mean size of 1.5-2.0 cm in wavelength and 0.2-0.6 cm in wave height. Findings indicate that the larger scale sediment waves coexist whose wavelength reaches sometimes about 10 times larger than the relatively regular waves, and the latter waves superpose on the larger waves.
- These waves migrate downstream, and their speed was found to have the same order of magnitude of erosion rate itself.
- Some wave grows in scale selectively and keeps developing toward the limited state, beyond which it can not reach. The reason for this is that the crest of the wave is eroded, or the destructive erosion occurs after the crack generation around the trough of the wave.
- If some amount of sand is contained in the test sample, the sediment waves with the larger wavelength do not form at all. In other words, the sand in the surface layer is expected to prevent the larger waves

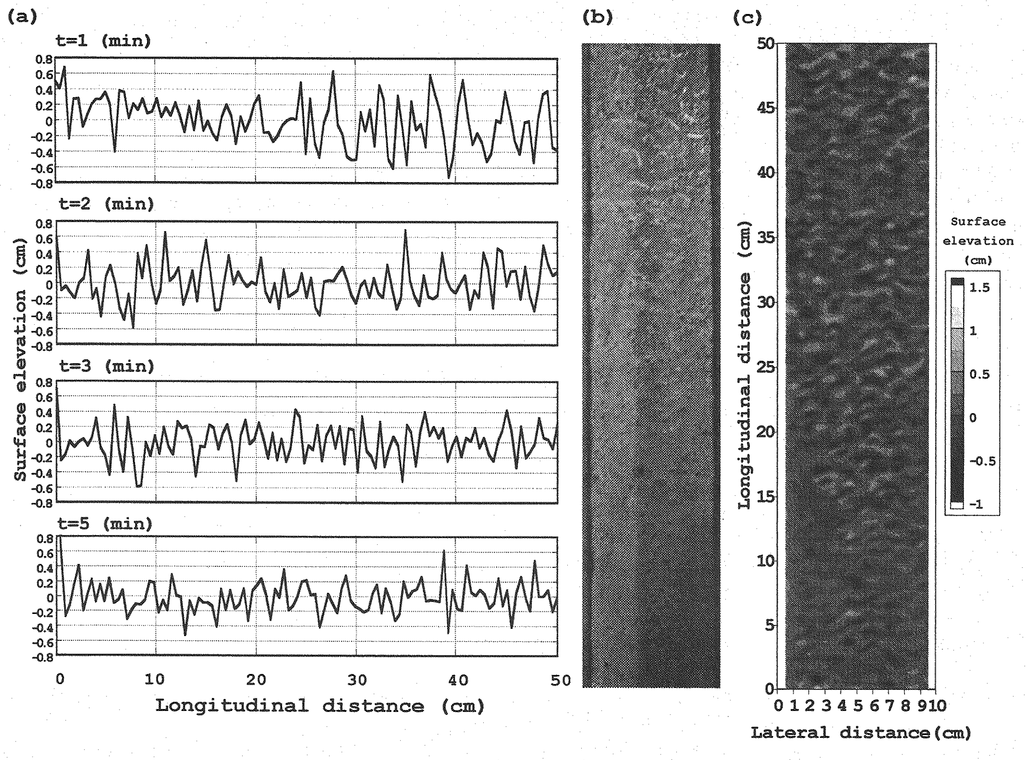

Fig. 8 Analysis of surface configuration of the test sample : T.A kaolin, R_{cc} = 0.8, R_{wc} = 0.8, u_* = 7.6 (cm/sec). (a) Temporal variation of surface configuration along the centerline, (b) Photograph of the surface at 3 min. from the begining, (c) The contour map of surface elevation at 3 min.

from generating.

After performing an analysis of the above observational findings, the following hypothesis was developed on the mechanism of this erosion process:

(a) The surface layer of the cohesive sediment is forced to deform with some thickness by the action of shear stress. In this process, some ridges are generated on the surface in the entire domain of sediment sample.

(b) The ridges develop their scale, and some sediment waves are selectively formed. During this process, erosion just like 'dissolution of clay' occurs.

(c) If the wave height becomes large enough, the crest of the wave is blown off, or the whole wave is eroded destructively as if it were torn by the action of lift force after the generation of cracks around its trough. Such kind of erosion is expected to be the 'active erosion' with a lump of sediments. The lift force exerted on the sediment surface is thought to be dominant in this sub-process.

(d) Sub-process from (a) to (c) is forced to repeat, so erosion such as 'dissolution of clay' and that of 'lump of sediment' are expected to occur as a successive phenomenon.

(e) The migrating speed of each wave increases as shear stress becomes larger. This means that erosion occurs more frequently and that the volume of eroded sediment per unit time increases.

(f) Comparing the measured data of erosion rates under the condition of R_{cc} = 1 and 0.8, the erosion rate for R_{cc} = 1 is larger than that for 0.8 by 10%. It should be noted that the existence of the larger waves affects the erosion rate very slightly.

(g) If the shear stress is less than the threshold value, no sediment wave forms. This is due to the fact that no considerable erosion is caused.

The process of how such sediment waves form regularly on the surface has not yet been understood clearly. It will be the next step to find out this erosion process and to establish the hypothesis which was proposed above.

CONCLUSION

In the present study, the sediment erodibility of cohesive clay-sand mixtures was investigated experimentally. The governing parameters were specified and the effects of each parameter on the erosion rate were evaluated. The cohesive strength of the sediments was also evaluated by means of a newly invented soil mechanical test. A correlation between the cohesive strength and erosion rate was found to exist to some extent. The erosion rate formula was derived on the basis of experimental results, and the validity of which could be verified. A detailed investigation of erosion mechanism was also attempted. A hypothesis was proposed but needs to be confirmed in further studies. Further investigations are required before the erosion mechanism is fully understood, which will enable us to obtain the universal erosion rate formula.

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APPENDIX - NOTATION

The following symbols are used in this paper:

C	= cohesive strength;
D_s	= sediment diameter;
E_s	= erosion rate;
K_c	= constant value of 2.4 N/m^2;
R_{cc}	= clay content ratio;
R_{wc}	= water content ratio;
$u*$	= frictional velocity;
α	= coeffcient in Eq.1;
β	= dimentionless coeffcient in Eq.3;
ρ	= density of water;
σ	= normal stress; and
τ	= surface shear strength.

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