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EXPERIMENTAL STUDY OF SCOUR RATE IN CONSOLIDATED COHESIVE SEDIMENT*

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Abstract: The erosion process of a cohesive sediment after consolidation was studied experimentally in a closed conduit system. The test samples investigated in this study are mixtures of sand and clay with variable compositions and different consolidation times. The main concern of this study is the effects of the dry density of the consolidated sediment on scour rate. A scour rate formula is derived and further interpreted based on the experimental results.

Key words: cohesive sediment, consolidation, dry density, scour rate, scour rate formula

1. Introduction

The scour process in cohesive, fine grained soil is different from that in non-cohesive, coarse grained soils and is not well studied, possibly because the cohesive behavior is complicated. The fine sediment particles are connected with each other as a result of strong influences of the electrochemical reaction on the surface of particles in water[1]. The finer the sediment particles, the more important the electrochemical effects are. Such effects are favorable for the sediment particles to become more stable against erosion. However, due to the complexity of the electrochemical effects, widely varied parameters have been used to describe the cohesive sediment behavior, such as Bingham shear stress, plasticity index, bulk density[2,3]. In order to predict the cohesive sediment behavior from one or a few easily measurable parameters, one has to study in more detail the effects of these varied parameters[4].

In the course of consolidation of fine sediment particles, the texture of deposits changes progressively into a denser state under the action of its own weight or other external forces, and the deposits acquire a stronger cohesion. The consolidated sediments are usually represented by a number of layers with specific thickness and bulk density. The resistance against erosion increases with consolidation time, with bulk density as an indicator to represent the erosion resistance of the consolidated sediment[5]. Zreik[6] believed that thixotropy leads to a structural change of the sediment and is the cause of the above phenomenon. Ray[7] also showed the importance of including effects of the bed structure in interpreting experiments on erosion of cohesive sediment beds. However, the sediments they tested are the deposits

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consolidated mostly for only several days. The difference in consolidation characteristics cannot be effectively explained. This article studies the effects of consolidation time and sediment composition on the scour rate of the cohesive sediment.

In experimental studies of the cohesive sediment, a sediment bed is mostly created by premixed soils, and then tested under controllable parameters (e.g., flow rate, sediment concentration and salinity). Experimental facilities include rotating cylinder[8], straight flume[9], and annular flume[10]. To choose an appropriate experimental method in this article, the following considerations are given: (1) the test can be carried out on various sediment beds, (2) the flow rate can be high enough to scour the sediment bed consolidated for quite a long time, (3) the flow conditions remain stable as erosion develops, and the surface of sediment bed is to be scoured uniformly.

2. Experimental study on scour rate

Scour rates are defined as the total mass of sediment transport per unit time period and unit area, as in the following form[8]:

$$SR = \frac{W_s}{At} \tag{1}$$

where SR is the scour rate, W_s is the total mass of the scoured sediment, A is the scour area of bed and t is the scour time period. If the scour is uniform, the scour rate can be determind as follows:

$$SR = \gamma \frac{H}{t} \tag{2}$$

where γ is the density of the sediment and H is the scoured thickness.

The dominant factors that influence the scour process are: the force of flow exerted on the riverbed, the resistance of the bed, the sediment-carrying capacity of flow and the sediment concentration of the flow. The former two factors are the main concern in this study.

The effects of flow conditions on the scour process can be determined from experiments with the same sample under adjustable flow conditions. In order to investigate the effect of the cohesion resistance on the scour process, a series of experiments were conducted with sediment of different compositions and with the same composition but different consolidation times.

2.1 *Experimental setup*

The cohesive sediment after consolidation is often scoured at a high flow rate, as rarely observed in open laboratory channels. As long as the scour develops, the bed deformation is bound to occur, which, in turn, will alter the flow condition.

To maintain a high flow rate and a flat river bed, experiments were conducted in a closed conduit system shown in Fig.1. The cross section of the rectangular pipe is 0.03 m×0.12 m. The test sample is placed in a bottom inset 1.2 m from the inlet. A valve is used to regulate the flow and a flow meter to measure the flow rate. The maximum mean velocity is 3 m/s.

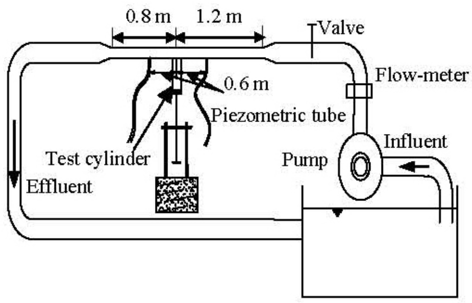


Fig.1 Sketch of experimental setup

Table 1 Detailed description of samples

Group	Description	Mean diameter (mm)	Clay content ratio (%)
A	Fine sediment from Yangtze River with the diameter less than 0.064 mm	0.046	1.66
B	Deposits from Huayuankou, Yellow River	0.008	33
C	Mixture of A and B with 5:1 mass ratio of A to B	0.042	6.9
D	Mixture of A and B with 2:1 mass ratio of A to B	0.038	12.11

Note: Cohesive content refers to the particles finer than 0.004 mm.

2.2 *Samples preparation*

The test samples are deposits from Huayuankou, Yellow River and the fine grained sediment from Yangtze River. They are divided into 4 groups according to their compositions. The size distributions are shown in Fig.2 where PCT is the percentage of particles finer than specified diameter and the detailed properties are given in Table 1. The mean particle diameter of each group ranges from 0.008 mm to 0.046 mm, the clay content ratio from 1.66% to 33%.

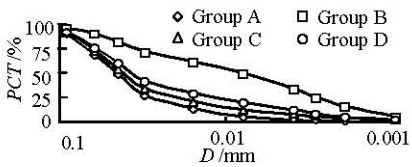


Fig.2 Size distributions of samples

2.3 *Experimental procedure*

2.3.1 Consolidation experiment

Mix each group sample with water, wait for several hours and spill the water on surface. Then put the mixture into containers, which are placed at the bottom of a small pond to simulate the consolidation process. After 1 d, 3 d, 5 d, 8 d, 13 d, 21 d, 34 d, 55 d, 89 d,144 d, 233 d, 377 d, the containers are taken out for scour experiment.

2.3.2 Scour experiment

The procedure of scour experiment is as follows:

(1) Place the sample in the bottom inlet.

(2) Push the sample up such that the surface is higher than the conduit bottom.

(3) Increase the flow rate to make sure that the conduit is full of water.

(4) Set the flow rate to a certain value.

(5) When the sample is scoured, push the sample up such that the surface of the sample is at the same level as the conduit bottom.

(6) Record the height scoured within a given time period.

Scour rate is calculated by Eq.(2) using the measurements of scoured heights and time. Repeat the above procedures with different samples.

3. Analyses of experiment results

The 117 sets of experiment data measured include samples of Groups A, B, C and D under different flow rates after consolidated for different times (Every single sample is scoured at least under 2 to 3 different flow rates). The following analyses are based on the experiment results.

3.1 *Dry density during the course of consolidation*

During the course of consolidation, deposits change progressively into a denser state, and eventually they have a relatively high dry density with a strong cohesion. Thus, it is necessary to consider the variation of the dry density at different stages of consolidation, and the dry density can be used to reflect the effect of consolidation on scour process.

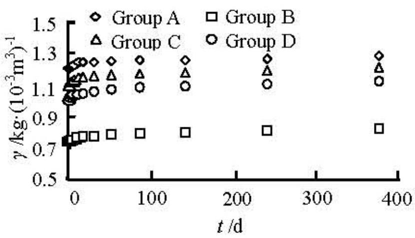


Fig.3 Dry densities versus consolidation time

After consolidated for 1 d, 3 d, 5 d, 8 d, 13 d, 21 d, 34 d, 55 d, 89 d,144 d, 233 d, 377 d, the samples are taken out and their dry densities are measured. Figure 3 is the variation of the dry density in different stages of consolidation.

Table 2 Parameters in Eq.(3)

Group	A	B	C	D
γ_0 (10^3kg/m^3)	1.2	0.74	1.09	1.0
γ_d (10^3kg/m^3)	1.2	0.822	1.21	1.124
n	0.312	0.379	0.306	0.438

It can be seen that in the early stage of consolidation, the dry density increases very fast. After several months, the dry density reaches nearly steady values. According to the measured data, every group can be considered to reach their steady state after being consolidated for 377 d. The variation of the dry density during the consolidation course can be expressed by the following formula[11]:

$$\gamma = \gamma_0 + (\gamma_d - \gamma_0)\left(\frac{t}{T_d}\right)^n \tag{3}$$

where γ_0 is the initial dry density, γ_d is the dry density after consolidated for the maximum consolidation time, t is the consolidation time, T_d is the maximum consolidation time, that is, 377 d, n is a coefficient depending on the sediment composition. The parameters in Eq.(3) are given in Table 2. The Comparson between the measured data and the calculation by Eq.(3) is shown in Fig.4

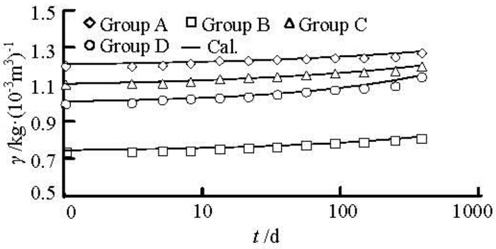


Fig.4 Comparison between the measured data and the calculation by Eq.(3)

3.2 *Effects of dry density on scour rate*

Prior to the analyses of the effects of the dry density on scour rate, the scour coefficient (or erodibility) is introduced, which is expressed as

$$E = \frac{SR}{\tau^m} \tag{4}$$

where SR is the scour rate, E is the scour coefficient, τ is the shear stress exerted on the sediment surface, m is a constant that is usually set to about 2, namely, the scour rate is proportional to square of the shear stress.

Deposits with a denser texture are more difficult to be scoured due to their higher dry density and stronger cohesion. The closer the dry density is to its steady value, the more difficult the deposits are scoured. The correlation between the dry density and the erodibility of the sediment is shown in Fig.5. It can be seen that the erodibility is negatively proportional to the dry density. By regression analyses of the experiment data, the correlation can expressed as $E = E_m - K\gamma$, or (solid lines in Fig.5).

$$E = 2.29 - 1.79\gamma = 1.79(1.28 - \gamma),$$

$$E = 0.28 - 0.35\gamma = 0.35(0.8 - \gamma),$$

$$E = 0.4135 - 0.34\gamma = 0.34(1.21 - \gamma),$$

$$E = 0.32 - 0.28\gamma = 0.28(1.14 - \gamma)$$

for Groups A, B, C, D, respectively. The terms in the parentheses are just the differences between the dry density and its maximum value. Therefore, the erodibility can be written as $E = K(\gamma_d - \gamma)$, and the scour rate can then be expressed as:

$$SR = K(\gamma_d - \gamma)\tau^2 \tag{5}$$

where γ and γ_d are the dry density and its steady value, τ is the shear stress, K is a coefficient.

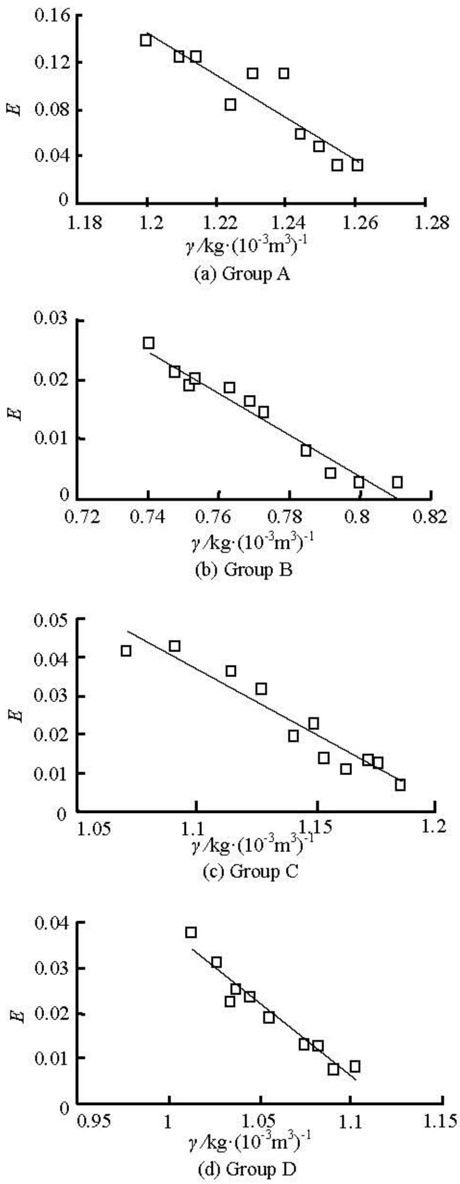


Fig.5 The relations between erodibility and dry density

Substituting Eq.(3) into Eq.(5), one can obtain the scour rate as a function of the consolidation time:

$$SR = K(\gamma_d - \gamma_0)\left[1-\left(\frac{t}{T_d}\right)^n\right]\tau^2 \tag{6}$$

3.3 *Validation of scour rate formula*

Data of Roberts[2] are used to check the relations between dry densities and scour rates as proposed in Eq.(5). For each type of sediment, an adequate value of parameter K has to be determined for Eq.(5) to represent the effect of the dry density (or bulk density) on scour rate. The parameters in Eq.(5) for different sediments are shown in Table 3. Figure 6 shows the comparison between calculation and measurement of Roberts. It can be seen from Fig.5 and Fig.6 that Eq.(5) describes very well the relations between the erodibility of the sediment and the dry density (bulk density) (especially when $E < 0.06$), which shows that the equation is applicable to the deposits consolidated to a middle dense state. With the dry density variation over the consolidation time being taken into consideration, Eq.(6) can be used to represent the relation between consolidation time and the erodibility of the sediment.

Table 3 Parameters in Eq.(5)

Dataset	Group	K	$\gamma_d{}^*$
	$d_0 = 5.7\mu\text{m}$	0.16	1.78
Robert's[2]	$d_0 = 14.8\mu\text{m}$	0.6	1.89
	$d_0 = 48\mu\text{m}$	0.75	1.92
This study	A	1.79	1.282
	B	0.35	0.822
	C	0.34	1.21
	D	0.28	1.124

*maximum bulk density (10^3 kg/m^3)

3.4 *Effect of sediment composition on erodibility*

The term in parentheses in Eq.(5) can also be interpreted as the volume of pore in deposit[7]. The closer the dry density is to its steady value, the denser the deposit is. Consequently, a smaller pore volume means that the deposit contains less water. Therefore, the effect of the bulk density on the scour rate is similar to that of the water content, that is, the increasing water content leads to the increasing scour rate, as explained by Sekine[12].

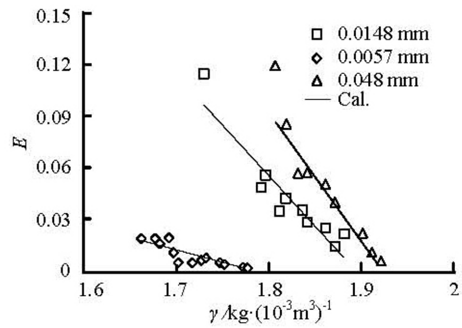
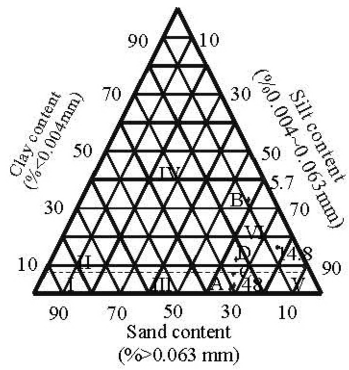


Fig.6 The relations between erodibility and dry density (Roberts's data[2])



I—Non-cohesive sand-dominated, II—Cohesive sand-dominated, III—Non-cohesive sand-mixed, IV—Cohesive clay- dominated, V—Non-cohesive silt-dominated, and VI—Cohesive silt- dominated network structure[13]

Fig.7 Sand-silt-clay triangle with transitions for cohesion and network structure

However, the dry density does not explicitly include the effect of sediment composition. The erodibility also varies with the size gradation. Apparently the cohesion is more dominant in a finer sediment structure. According to Van Ledden[13], the sediment structure can be classified into six types, as shown in Fig.7. The horizontal dashed line indicates the transition between non-cohesive and cohesive structures. The sediment considered in this study and by Jesse Roberts can then be categorized into 2 types accordingly. The sediment of Group B in this study and the sediment with mean particle diameter of 5.7 μm, 14.8 μm and 18.3 μm are similar in structure, which can be characterized as the cohesive silt-dominated network structure. The sediment of Group A and Group C and the sediment with mean particle diameter of 48 μm can be characterized as the non-cohesive silt-dominant structure.

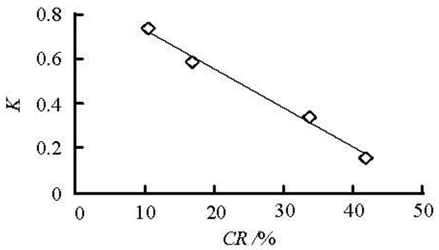


Fig.8 Relation between clay content ratio (*CR*) and parameter K in Eq.(5)

It is expected that, the erosion of sediment with different compositions and structures is dominated by different inherent factors[14]. The cohesive structure is mainly controlled by cohesion and the non-cohesive structure by particle size and density. It is reported that the capability of a cohesive soil to resist erosion increases with clay content and plasticity index[15]. It is believed in this article that, with a such classification by sediment composition, a correlation might be more convincing. It is observed in Fig.8 that K decreases when the clay content ratio decreases. Yet, the validity of such a correlation is limited by the very small number of data points. More experiments with variable clay content ratio and size distributions are required to reveal the relation between erodibility and cohesive characteristic. Furthermore, if the correlation in Fig.8 is reliable, or relation between K and common sediment properties is to be found, such a formula is useful in predicting the scour rate of the cohesive sediment.

4. Conclusions

The scour process of the cohesive sediment after consolidation is experimentally studied in this article. The following are the main conclusions:

(1) Due to the gravitational action or another external forces, the cohesive sediment becomes denser and more difficult to be scoured. By using the dry density as a function of consolidation time, the effect of consolidation on scour process can be evaluated. The closer the dry density is to its steady value, the more difficult the deposits are scoured. However, the dry density alone could not be used to predict the scour process of a cohesive sediment.

(2) A scour rate formula for the cohesive sediment after consolidation is derived as

$$SR = K(\gamma_d - \gamma_0)\left[1 - \left(\frac{t}{T_d}\right)^n\right]\tau^m$$

based on experiment results. The formula can describe the correlation between scour rate and flow condition and deposits properties after consolidation. Parameter K is expected to have some relation with the sediment composition.

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