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Article

Experimental Study on the Scouring Rate of Cohesive Soil in the Lower Yellow River

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Abstract: The different soil anti scourability in the lower reaches of the Yellow River leads to different scouring and retreating speeds, which has a great influence on river regime evolution. Through the incipient motion scouring test of cemented cohesive soil in the lower reaches of the Yellow River, the physical phenomena of the incipient motion of cohesive soil were expounded, the scouring rate of cohesive soil was calculated, and the relationship between the scouring rate and its influencing factors was established. The results show that when the moisture content of cohesive soil is 43%~61%, the scouring rate is about 0.001~0.03 kg/(m^2·s). The scouring rate of cohesive soil with the same particle size varies with the flow shear stress under different deposition duration conditions. Under the same flow rate, the scouring rate of cohesive soil increases with the increase of water content, showing an exponential relationship of increment. Under the same shear stress condition, the scouring rate decreases with the increase of dry density, while the exponential relationship between dry density and scouring rate is not clear when the shear stress is small. With the increase of shear stress, there is an obvious exponential relationship between dry density and scouring rate. Finally, the relationship between the scouring rate and relative residual shear stress was established, and the scouring rate formula suitable for cohesive extremely fine sediment was fitted. The formula can better estimate the scouring rate of the riverbank composed of very fine cohesive sediment and provide support for predicting the scouring and retreating rate of riverbanks in natural rivers.

Keywords: cemented cohesive soil; soil physical index; scouring rate; incipient motion scouring test; lower reaches of the Yellow River

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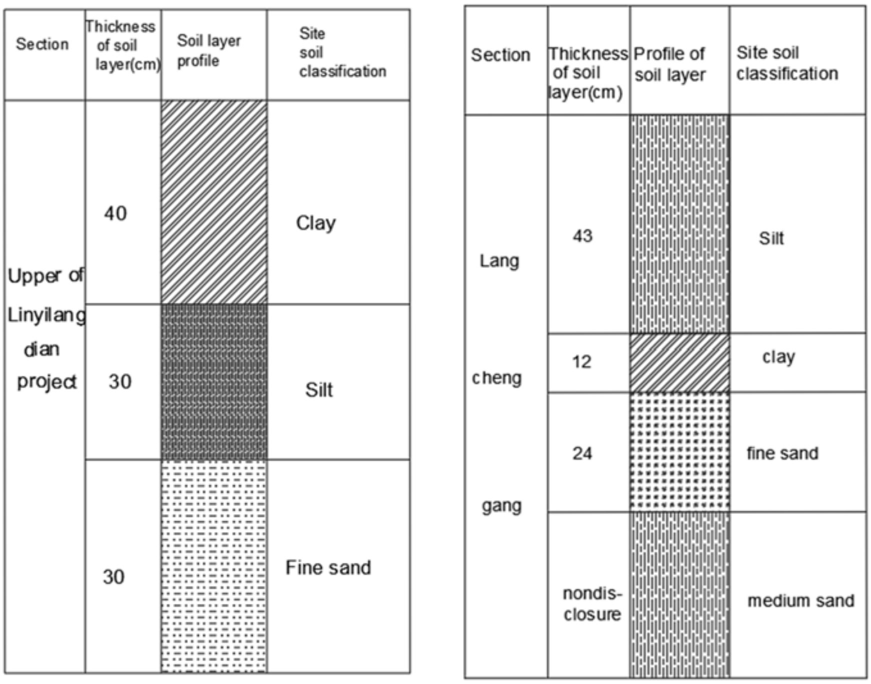
1. Introduction

There are obvious layered structures in the lower Yellow River (Figure 1). During the geological exploration of the Yellow River riverbed in the 1950s and different periods after that, it was found that the riverbed in the lower Yellow River showed a typical layered siltation structure. Water conservancy workers measured the riverbed sedimentation in the wandering section of the Xiaobei main stream of the Yellow River by means of manual excavation and found that the sediment presents the characteristics of layered distribution, with different distributions and thicknesses of coarse sand, silt, and clay layers (Figure 2a). This stratification phenomenon also exists in the lower Yellow River; Figure 2b show the stratification of the riverbed near the Langchenggang section in the lower Yellow River [1].

Figure 1. Typical layered structure in the lower Yellow River.



(**a**) (**b**)

Figure 2. Stratification of riverbed in typical wandering reach of the Yellow River: (**a**) Xiaobei main stream reach; (**b**) Downstream Langchenggang section.

This leads to different anti scourability in different parts of the river bed. Besides, flow scouring occurs easily in the weak anti scouring area whose upper part is prone to local collapse; therefore, the scouring and retreating speed of the riverbank is faster. Moreover, in the beach strand with strong scouring resistance, the scouring and retreating speed of the riverbank is slow, and the river regime cannot be regularized and adjusted, which results in the change of the river regime trend, easily forming abnormal bays and threatening the safety of the Yellow River embankments and nearby villages. Therefore, the study of the scouring resistance of cohesive soil provides a basis for understanding the evolution of river regimes in the lower reaches of the Yellow River.

The scouring resistance of cohesive sediment is mainly related to the incipient motion conditions and scouring rate. At present, scholars at home and abroad mainly study the incipient motion conditions of cohesive sediment on the bed from the point of view of the force exerted on the cohesive soil particles. Based on the experimental results of the contact area of quartz fiber, Lu [2] analyzed the initial movement of sediment. Specifically, Li [3] established an adaptive criterion curve of initial sediment motion under wave and current conditions. Dou [4] summarized the results of sediment incipient motion research over 40 years and obtained the formula of incipient velocity or shear stress of coarse and fine sediment. Considering the cohesive force between particles, Zhang [5] obtained a unified incipient velocity formula for both granular and cohesive fine-grained sediments. Tang [6] deduced the incipient motion conditions of coarse and fine sediment considering the gravity of sediment particles, positive thrust, uplift force, and cohesive force between particles. Based on the measured cohesive soil scouring velocity data of the Yangtze River and the laboratory test data, Lu [7] obtained the incipient motion velocity formula of fine cohesive sediment. Starting from the mechanism of flow fluctuation, Hua [8] established the unified dynamic shear stress formula for cohesive soil and cohesive soil with sediment. All the above studies are mainly based on the incipient motion law of sediment particles on the bed, taking into account the various forces acting on the incipient motion of soil particles. With this support, a unified incipient velocity formula can be established.

Scholars also carried out a lot of research on the scouring rate of soil. With the aid of soil scouring experiments, Gao [9] verified the rationality and accuracy of the model of scouring viscosity. Xu [10] analyzed influential factors for clay soil initiation and put forward the empirical model of initiation. Liu [11] evaluated the influential factors on scouring velocity and established a mathematic model. Cao [12] carried out experiments of cohesive sediment deposition and scouring in a circular rotating flume of the Institute of Sediment, IWHR, and obtained the scouring rate formula. Li [13] carried out a sludge incipient scouring test in a sloping glass flume and determined the incipient velocity. Wu [14,15] tested the scouring rate of fine-grained cohesive undisturbed sediment in Weitou Bay of Jinjiang River, Fujian Province, using a closed rectangular plexiglass flume to analyze the influence of the content of cohesive particles and the median particle size on the scouring coefficient of various sediments under different water pressures and starting conditions. Wang [16] made use of six different kinds of cohesive sediment to carry out incipient scouring tests under different deposition duration conditions and pointed out that the scouring rate increased with the increase of flow intensity. Lv [17] used the method of factor analysis to analyze the relationship between the scouring rate, flow shear stress, and physical indexes of sediment. Krone [18] divided the influence of siltation consolidation on the scouring rate into two different stages and pointed out that under the same flow condition, the influence of dry density of silt in different stages on scouring rate is obviously different; based on this, the scouring rate formula was established. Based on a large number of scouring test data, Robert [19] obtained the scouring rate formula of cohesive fine sediment under siltation consolidation conditions with both particle size and dry density taken into account. Sanford [20] proposed a formula for calculating the scouring rate of different scouring processes, considering that the scouring rate varies with the scouring time and depth.

In addition, some scholars carried out relevant research on the stability of riverbank soil. Yang [21] discussed the mechanism of the bank collapse process of curved channels composed of different bank materials in the Heihe River Basin and the main stream of the Tahe River in the Ruoergai Basin and studied the influence of riverside vegetation on bank slope stability in the middle and lower reaches of the Tarim River. Wang [22] proposed that the value of soil safety factor in the case of dry wet alternation is mainly affected by the value of soil cohesion and pointed out that the cohesion, internal friction angle, and safety factor of soil are linear. Liu [23] analyzed the impact of the change of soil moisture content on the stability of the riverbank and pointed out that the stability of the riverbank is high in the dry season and poor in the flood season and recession period. Xia [24] put forward the quantitative calculation method of riverbed lateral swing and put forward the key water and sediment factors affecting the drastic adjustment of riverbed shape in the wandering section of the lower Yellow River. The author [25] also established a one-dimensional coupling mathematical model to simulate the erosion and deposition of the alluvial channel bed and bank collapse in the lower reaches of the dam and simulated the main bank collapse area, and bank collapse width in the Jingjiang section of the middle reaches of the Yangtze River. Chen [26] carried out the erosion test of the sandy area and studied the relationship between the starting velocity and erosion rate of sandy soil and the physical and mechanical properties of soil.

At present, research on the incipient scouring of cohesive sediment focuses on the conditions of the incipient scouring of cohesive sediment and the formula of the scouring rate; scouring research on sandy soil is also carried out, but less on the physical and mechanical properties of soil itself. However, this study is very important for understanding the anti scourability of cohesive soil. In view of the above problems, in this study, (1) the cohesive soils with strong scouring resistance in the lower Yellow River were sampled; (2) the scouring rate of cohesive soils was calculated through the incipient motion scouring test; (3) by measuring the physical properties of cohesive soil such as sedimentation time, water content, and dry density, the relationship between the scouring rate and a series of soil physical parameters, such as shear stress, water content, and dry density was established; (4) the influence of relative residual shear stress on the scouring rate was discussed, and the scouring rate formula suitable for cohesive extremely fine sediment was established.

2. Incipient Motion Scouring Test of Cohesive Soil

2.1. Testing Device

2.1.1. Test Soil Samples

The cohesive soil of a beach near Huayuankou in the lower Yellow River during the dry season was selected as the test soil sample. Two kinds of cohesive soils were selected in this test. The particle size distribution curves of each cohesive soil are shown in Figure 3. The median particle size D_{50} and the cohesive particle content are shown in Table 1. According to the literature [27], when the particle size is greater than 2 mm, the capillary force will not be formed between soil particles, and the particles are discontinuous; when the particle size is 0.05~2 mm, there is capillary force between particles, but there is no adhesion; when the particle size is 0.05~0.005 mm, the particles have adhesion when they contain water; when the particle size is less than 0.005 mm, the particles not only have adhesion when water is contained but also the adhesion increases after water loss.

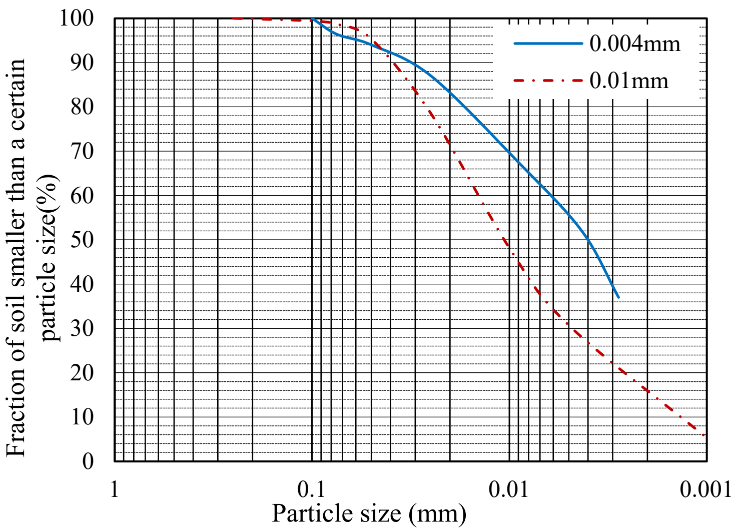


Figure 3. Particle size distribution of test soil samples.

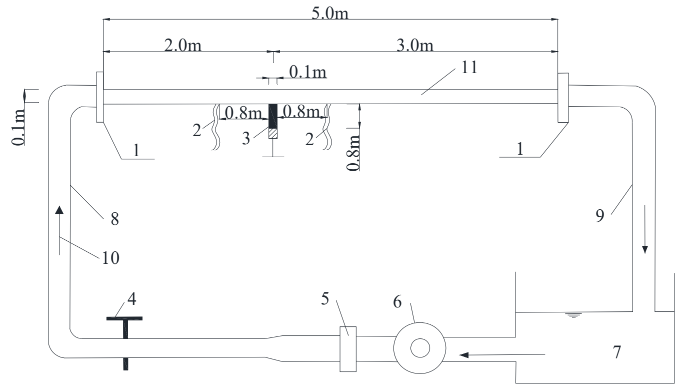
Table 1. Characteristic values of test soil samples.

S/N	Median Size (mm)	Cohesive Particle Content (%)	Silt Particle Content (%)	Liquid Limit	Plastic Limit
Sample 1	0.004	54.0	42.4	58.39	30.56
Sample 2	0.010	30.7	68.0	46.19	24.79

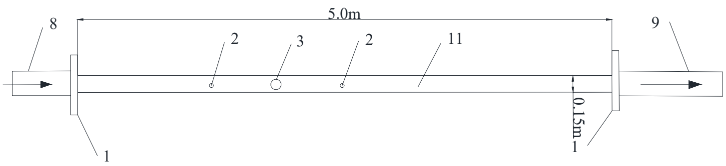
According to the literature [28], the content of cohesive particles refers to the percentage of cohesive particles with a diameter less than 0.005 mm. In order to study the cohesive force of soil, combined with the description of literature [27], the two soil samples in this study are treated as cohesive soil.

2.1.2. Flume

Considering that the incipient velocity of cohesive sediment is relatively high, it is difficult for ordinary open channel flume to meet. Therefore, a closed rectangular transparent glass flume is adopted in this test with the length, width, and height of 5.0 m × 0.15 m × 0.1 m, respectively. A cylindrical soil sample slot is set 2 m from the water inlet of the flume for placing deposited cohesive soil. The inner diameter of the slot is 0.1 m, and the height is 0.2 m. Flow is controlled by an electromagnetic flowmeter (DN-150). The experimental flume device is shown in Figure 4.



(**a**)



(**b**)

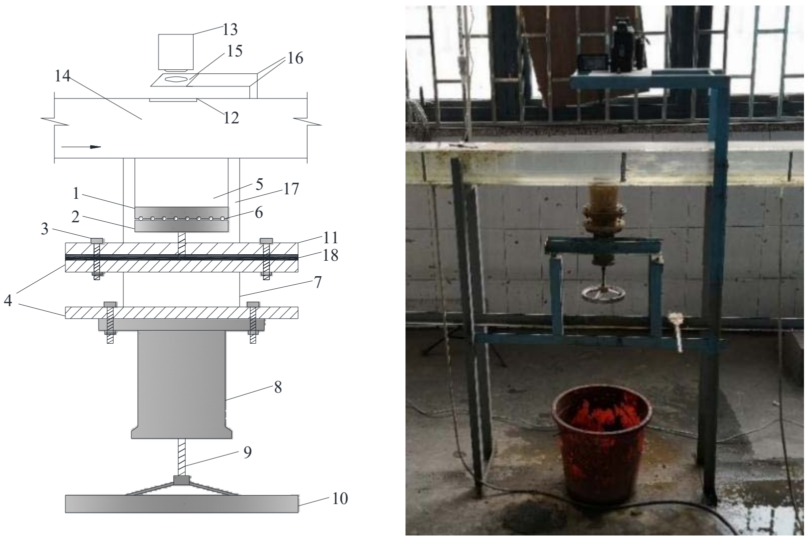
(**c**)

Figure 4. The overall structure of the flume: 1—flange; 2—piezometer; 3—top soil device; 4—valve; 5—electromagnetic flowmeter; 6—water pump; 7—reservoir; 8—water inlet; 9—water outlet; 10—water flow direction; 11—flume. (**a**) Elevation, (**b**) Plan, (**c**) Flume.

2.1.3. Top Soil Device

In the incipient motion scouring test of cohesive soil, it is necessary to observe the scouring of cohesive soil samples in the flume and accurately measure a series of test data. In the previous tests, there was always water leakage because of the poor connection between the device for placing cohesive soil sample and the flume, and inaccuracy of the observation or the failure of the experiment due to the failure of the incipient motion of cohesive soil scouring.

Aiming at the problem that the cohesive soil sample is not easily placed into the flume incipient motion scouring test, which affects the overall observation accuracy and progress of the test, and based on the experience of predecessors and many attempts, a scouring device for placing cohesive soil samples in a flume is developed (Figure 5). This can not only ensure that there is no water leakage at the joint of the flume and the soil sample slot but also ensure that the soil sample slot itself is water-tight and that the cohesive soil samples in the slot can be used smoothly in the test process to meet the requirements of the incipient motion scouring test of cohesive soil.



(**a**) (**b**)

Figure 5. Topsoil device and shooting device of cohesive soil samples: 1—stainless steel upper tray; 2—stainless steel lower tray; 3—screw; 4—flange; 5—cohesive soil sample; 6—steel ball; 7—transparent organic glass flume; 8—stainless steel sealed steel pipe; 9—bolt; 10—stainless steel handle; 11—flange connecting cohesive soil sample device and the flume; 12—lighting source; 13—video camera; 14—flume; 15—organic transparent glass plate for placing camera lens; 16—parallel angle steel; 17—organic transparent glass pipe fixed at the bottom of the flume and connected with a flange; 18—rubber blanket. (**a**) Schematic diagram of topsoil device and shooting device (**b**) Physical pictures of topsoil device and shooting device.

2.2. Test Scheme and Process

In this paper, the incipient motion and scouring rates of cemented cohesive soils with different particle sizes under different water content conditions are experimentally studied.

(1) Soil sample remodeling

In order to make the soil sample close to the natural siltation state of the soil in the river bed, it is necessary to consolidate the soil sample to form a cohesive soil with strong scourability. Specifically, some cohesive soil was tampered with and placed in a bucket filled with water, stirred evenly, and then left to deposit naturally for a certain time in the water. After being fully immersed, clear water from the top was removed, and it was taken out and placed in a 1 m × 0.5 m × 0.2 m soil sample box (Figure 6). The cohesive soil samples with different water content can be obtained according to the different deposition times.

Figure 6. Soil sample remodeling.

(2) Test groups

Thirty groups of scouring tests are carried out for two kinds of remolded cohesive soils with different particle gradations. The flow rate ranges from 20 to 110 m^3/h, and the water content of soil samples ranges from 43% to 61%.

(3) Scouring test

After the cohesive soil is consolidated for a period of time, water content and other indicators are tested with a ring knife at the upper and lower parts of soil samples at regular intervals, and the average value is taken as the final test result. Then, the soil samples of the same size as the soil sample slot are taken out and loaded into the soil sample slot to carry out the scouring test of cohesive soil.

The scouring test is adjusted according to the increase of 10 m^3/h flow rate for each time, and the scouring time of each group is 2 h. During the test, manual rotating bolts are used to control the rise and fall of the soil sample slot (Figure 2). The height of the soil sample in the flume is adjusted according to the scouring of the soil sample along with the flow, and the surface of the soil sample is even with the bottom of the flume. In the actual test, in order to observe the scouring of soil samples, the soil sample slot is slightly higher than the bottom of the flume (about 0.5 cm) at the beginning. In the process of scouring test, in order to ensure that the surface of the soil sample and the bottom of the flume are flat, it is necessary to adjust the soil sample upward at any time according to the scouring situation of the soil sample to ensure the smooth progress of the soil sample scouring test.

3. Analysis of Test Results

3.1. Incipient Motion Phenomenon

Under the condition of sediment consolidation, the incipient motion of cohesive sediment is essentially different from that of granular sediment. The incipient motion of granular sediment is usually a starting unit in the form of single granular sediment, while the cohesive sediment is usually motioned in the form of blocks or clusters due to the effect of intergranular cohesion. There are two methods to distinguish the incipient motion of cohesive soil at present: first, the incipient motion of cohesive soil can be divided into three criteria, i.e., individual, small, and general micro-cluster incipient motion [29]. Second, the incipient motion of cohesive soil is divided into two critical states: small motion and large motion [30,31].

According to the incipient motion state of the cohesive soil sample observed in this test, the incipient motion of the cohesive soil sample can be divided into three stages: the small incipient motion of cohesive granular aggregate, the general incipient motion of cohesive granular aggregate, and the destruction of cohesive granular aggregate.

(1) Small incipient motion of cohesive granular aggregate: When the flow velocity is close to the scouring velocity of cohesive soil, the surface of cohesive soil is coarsened, and the sheet or block cohesive particles are carried away by the flow (Figure 7). In this study,

the general incipient motion of cohesive granular aggregates was taken as the incipient motion standard of cohesive soil.

(**a**) (**b**)

Figure 7. Incipient motion of sporadic sheet or block cohesive granular aggregates. (**a**) Primitive (**b**) Denudation of sheet or block cohesive granular aggregates.

(2) General incipient motion of cohesive granular aggregate: As the shear stress of water continues to increase, more and more sheet or block cohesive granular aggregates are lifted and stripped away by water when the comprehensive force of water acting on the cohesive soil block exceeds the cohesive force of soil block. Local scouring is more and more obvious on the surface of soil samples, and scouring pits are more and more obvious (Figure 8a). Cracks appear gradually in soil samples (Figure 8b), and there are streaks of smoke near the scouring pits.

(**a**) (**b**)

Figure 8. Continually lifted soil. (**a**) The soil is continually carried away by the flow (**b**) The soil is lifted.

(3) Destruction of cohesive granular aggregates: When cracks occur in cohesive soil, large blocks are quickly lifted and destroyed, and the destruction process is completed in a very short time (Figure 9).

(**a**) (**b**) (**c**)

Figure 9. A large sample of soil is lifted in an instant, and the sample is destroyed. (**a**) The cohesive soil block is lifted momentarily (**b**) The cohesive soil block are lifted (**c**) The failure of cohesive soil block is completed.

The incipient motion phenomenon of cohesive soil shows that cohesive granular aggregates first motion near the edge of the cohesive soil block on the water-facing surface because the cohesive soil particles near the edge are loosely bound, and the water will continue to dive and scour down at the edge of the clay block after the cohesive soil particles are washed away by the water flow. The cohesive soil blocks are motioned in sheets or blocks. During the whole incipient motion process, the water body is not turbid, which is obviously different from that of granular sand.

3.2. Test Results of the Scouring Rate

The scouring rate is defined as the amount of sediment scouring per unit area in a unit time. The main factors affecting the scouring rate of the riverbed are the force of flow on bed sand, the scouring resistance of bed sand, the saturated sediment carrying capacity of flow, and the amount of sediment that can be exchanged with bed sand. In this study, the impact of water flow on the bed sand and its scouring resistance on the scouring rate were analyzed without considering the sediment carrying capacity of the flow due to scouring without sediment motion. The interaction force of flow on bed sediment is mainly expressed in the form of shear stress. The scouring resistance of cohesive sediment mainly depends on the cohesive force and dry density of cohesive sediment. The cohesive force is mainly affected by the moisture content and particle size of the cohesive sediment or the content of cohesive particles. Therefore, the influence of flow shear stress, water content, and dry density on the scouring rate was analyzed using the isolated factor method in this paper.

3.2.1. Test Data Calculation

In general, the scouring rate of the riverbed is defined as the weight of sediment carried by the flow from the riverbed per unit area in a unit time, expressed by formula as follows:

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

where, E = scouring rate, kg/(m^2·s); W_s = mass of the sediment carried by the current when it scours the riverbed, that is, the amount of scouring, kg; A = area of riverbed scour, m^2; t = scouring time, s. If it is uniform scouring, Formula (1) can be expressed as:

$$E = \rho_m \frac{H}{t} \tag{2}$$

where, ρ_m = dry density of sediment, kg/m^3; H = height of scouring, m. Since the scouring process in this test is uniform, the scouring rate of the cohesive soil samples under the siltation consolidation condition is calculated according to Formula (2). Formulas (3)~(5) can be used to calculate the shear stress of water flow [32].

$$\lambda = \frac{8\tau}{\rho U^2} \tag{3}$$

$$\lambda = \frac{0.316}{\mathrm{Re}^{1/4}} \tag{4}$$

$$\mathrm{Re} = \frac{U h_d}{\nu} \tag{5}$$

where, ρ = density of water, kg/m^3; U = mean flow velocity of rectangular flume, m/s; h_d = the characteristic length between the upper and lower pressure measuring tubes, m; ν = kinematic viscosity, it is related to the temperature of the water, when t = 20° is taken here, ν = 1.01 × 10^{-6} kPa·s.

In this paper, cohesive soil samples 1 and 2 were prepared by the natural settlement method. Incipient motion scouring tests were carried out for these two samples, respectively.

The specific results are shown in Tables 2 and 3. Tables 2 and 3 show that the moisture content of cemented cohesive soil is 43%–61%, the dry density is 1.02–1.24 kg/m^3, and the scouring rate is in the range of 0.001–0.03 kg/(m^2·s).

Table 2. Test results of the scouring rate of cohesive soil sample 1.

Moisture Content ω (%)	Group	Dry Density (g/cm^3)	Shear Stress (N/m^2)	Incipient Shear Stress (N/m^2)	Scouring Rate kg/(m^2·s)
51.20	1 2 3	1.13	3.13 3.89 4.72	2.46	0.0013 0.0057 0.0100
53.48	4 5 6	1.11	2.46 3.13 3.89	2.21	0.0007 0.0062 0.0139
54.32	7 8 9	1.10	2.46 3.13 3.89	1.85	0.0030 0.0098 0.0220
56.45	10 11 12	1.08	2.46 3.13 3.89	1.72	0.0066 0.0206 0.0283
60.76	13 14 15	1.02	1.33 1.85 2.46	1.26	0.0007 0.0094 0.0304

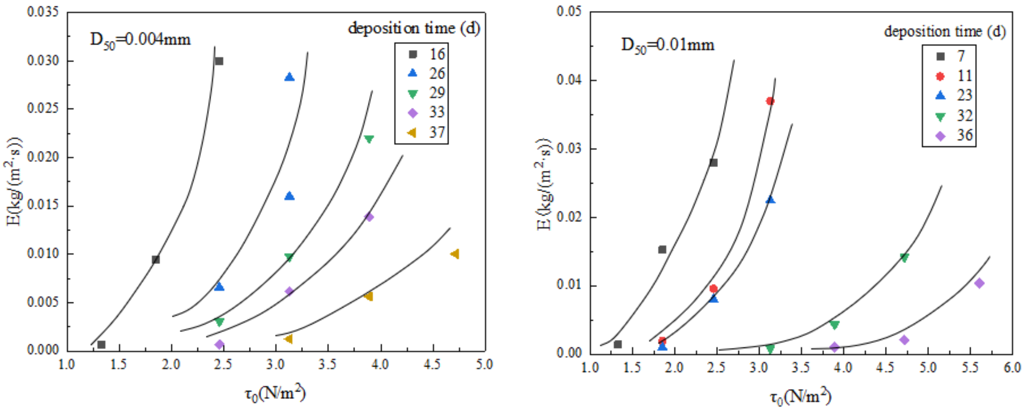
Table 3. Test results of the scouring rate of cohesive soil sample 2.

Moisture Content ω (%)	Group	Dry Density (g/cm^3)	Shear Stress (N/m^2)	Incipient Shear Stress (N/m^2)	Scouring Rate kg/(m^2·s)
43.66	1 2 3	1.24	3.89 4.72 5.60	3.13	0.0010 0.0021 0.0103
45.60	4 5 6	1.19	3.13 3.89 4.72	2.21	0.0008 0.0043 0.0142
48.09	7 8 9	1.18	1.85 2.46 3.13	1.64	0.0010 0.0090 0.0225
50.29	10 11 12	1.15	1.85 2.46 3.13	1.26	0.0019 0.0096 0.0370
51.54	13 14 15	1.12	1.33 1.85 2.46	0.98	0.0014 0.015 0.0280

3.2.2. Effect of Flow Shear Stress on the Scouring Rate

The experiment of Partheniads. E shows that the scouring of cohesive sediment is determined by the shear stress of the bottom flow, and the shear stress of the flow is the main factor affecting the motion of sediment [33–38]. Researchers at home and abroad carried out field or laboratory tests to determine the relationship between the scouring rate and flow shear stress [8,18,36,37,39–42]. They generally believe that there is a positive correlation between shear stress and the scouring rate, which is confirmed by the test data.

Figure 10 show the effect of flow shear stress on the scouring rate of two kinds of cohesive soil samples under different deposition duration and that the changing trend of the scouring rate with shear stress is different for cohesive soil samples with the same particle size under different deposition durations. When the siltation time of cohesive soil is short, the scouring rate increases with the increase of shear stress. When the siltation time of cohesive soil is longer, the scouring rate increases with the increase of shear stress, and the magnitude of increase slows down. The scouring rate is approximately exponential with the increase of shear stress. In the figure, the abscissa τ_0 is the shear stress, and the ordinate *E* is the scouring rate.

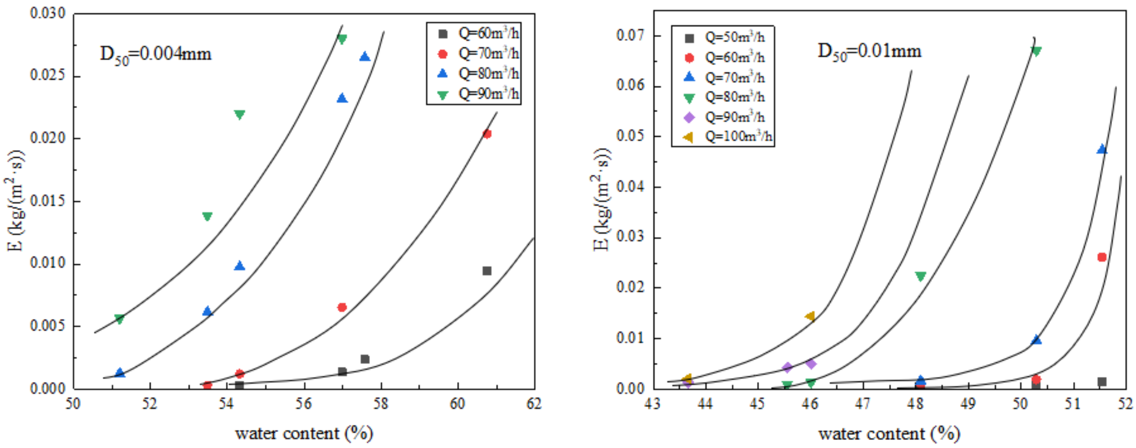


(**a**) (**b**)

Figure 10. Relationship between shear stress and scouring rate (**a**) D_{50} = 0.004 mm (**b**) D_{50} = 0.01 mm.

3.2.3. Effect of Water Content on the Scouring Rate

Figure 11 show the relationship between water content and the scouring rate and that the scouring rate of cemented cohesive soil increases with the increase of water content at the same flow rate, and the relationship between them shows an exponential increase. As shown in Figure 11, when the flow rate is low, the relationship between the scouring rate and water content is slow exponential. With the increase of flow rate, the scouring rate increases greatly, showing a steeper exponential relationship with water content, or even a nearly linear relationship (flow rate of soil sample 1 is 80 m^3/h or more, water content is 53% or more, the flow rate of soil sample 2 is 80 m^3/h or more, water content is 48% or more). For the same flow rate and water content, the coarser the particle size, the higher the scouring rate.

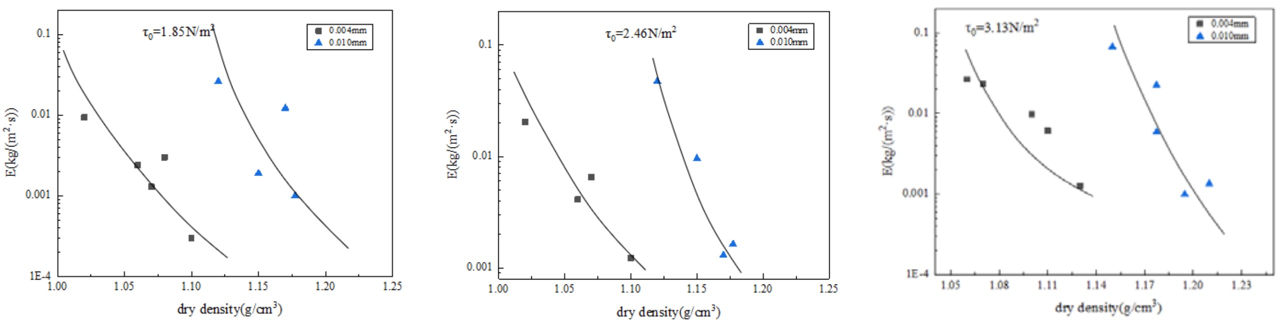


(**a**) (**b**)

Figure 11. The relationship between water content and scouring rate. (**a**) D_{50} = 0.004 mm (**b**) D_{50} = 0.01 mm.

3.2.4. Effect of Dry Density on the Scouring Rate

Figure 12 show the variation of the scouring rate with dry density under three flow shear stress conditions. For the same soil sample under the same shear stress condition, the scouring rate decreases with the increase of dry density. When the shear stress is small, the exponential relationship between dry density and scouring rate is not obvious. With the increase of shear stress, there is an obvious exponential relationship between the dry density and scouring rate. For the test soil samples with different particle sizes, the effect of dry density on the scouring rate is different. The median particle size of the two soil samples in this test is relatively fine. Figure 12 show that the dry density has a greater impact on the scouring rate regardless of the shear stress; that is, a small change in dry density can cause a significant change in the scouring rate.



(**a**) (**b**) (**c**)

Figure 12. The relationship between dry density and scouring rate. (**a**) Shear stress = 1.85 N/m^2, flow = 60 m^3/h (**b**) Shear stress = 2.46 N/m^2, flow = 70 m^3/h (**c**) Shear stress = 3.13 N/m^2, flow = 80 m^3/h.

4. Discussions

4.1. Effect of Relative Residual Shear Stress on the Scouring Rate

The factors affecting the scouring rate of sediment can be summarized as [12,43]: $E = f(J, H, D, \rho_m, \gamma_s - \gamma, \xi)$, among which the critical starting shear stress is: $\tau_c = f(D, \xi, \gamma_s - \gamma, \rho_m)$, so scouring rate E can be described as: $E = f(\tau_0, \tau_c)$. That is, $E = M(\frac{\tau_0}{\tau_c} - 1)$. In the formula, M is the scouring coefficient; N is the exponent; $\frac{\tau_0}{\tau_c} - 1$ is the dimensionless relative residual shear stress; τ_0 is the shear stress of bed form; τ_c is the critical incipient shear stress; J is the stream gradient; H is the depth of water; D is the sediment grain size; ρ_m is the dry density of sediment; γ_s is the volume–weight of sediment; γ is the volume-weight of water; ξ is the cohesive force between cohesive sediment particles. Because the incipient shear stresses of soil samples with different median sizes or similar median sizes are quite different, the corresponding bed shear stresses that make soil samples reach scouring conditions are also quite different, so the effect of the difference of incipient shear stresses can be eliminated using relative shear stress $\frac{\tau_0}{\tau_c}$.

Figure 13 show the relationship between the relative residual shear stress and scouring rate. For each soil sample, the relationship between the relative residual shear stress and scouring rate conforms to the power exponential relationship of $E = M(\frac{\tau_0}{\tau_c} - 1)^n$ above. For soil samples 1 and 2, the relationship between the scouring rate and relative residual shear stress is as follows in Formulas (6) and (7):

$$E_{0.004} = 0.021\left(\frac{\tau_0}{\tau_c} - 1\right)^{1.9176} \tag{6}$$

$$E_{0.01} = 0.0112\left(\frac{\tau_0}{\tau_c} - 1\right)^{2.1505} \tag{7}$$

The correlation coefficients R^2 are 0.9663 and 0.9055, respectively. Formulas (6) and (7) show that the relationship between the scouring rate and relative residual shear stress is approximately quadratic.

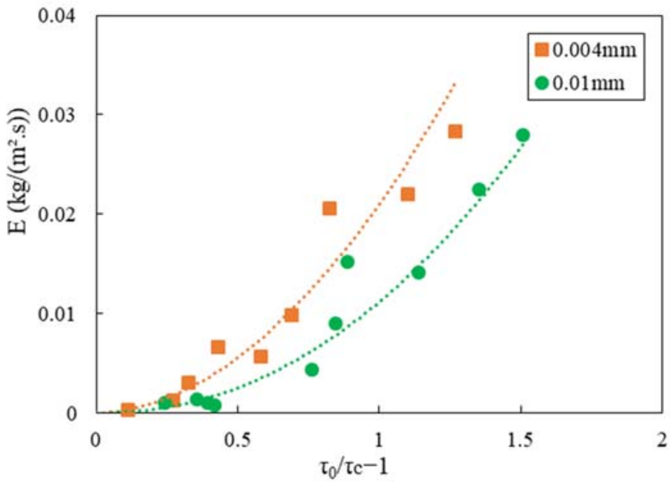


Figure 13. Relationship between relative residual shear stress and scouring rate.

4.2. Study on Formula for the Scouring Rate of Cohesive Extremely Fine Sediment

The particle size distribution of soil samples 1 and 2 is fine, which is less than 0.01 mm. Formulas (6) and (7) are fitted to Formula (8), and Formula (8) is a unified scouring rate formula to satisfy this kind of cohesive extremely fine sediment.

$$E= 0.0142(\frac{\tau_0}{\tau_c}-1)^{1.8967}\ (R^2=0.8609) \quad (8)$$

where, E = scouring rate, kg/m^2·s; τ_0 = bed shear stress, N/m^2; τ_c = incipient shear stress, N/m^2. Formula (8) is used to calculate the scouring rate which is compared with the measured data, as shown in Figure 14.

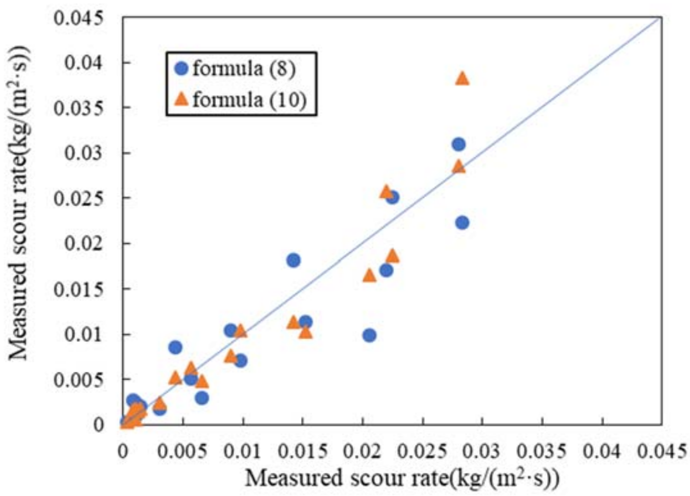


Figure 14. Comparison of measured and calculated values.

Figure 14 show that there is an error between the calculated results by Formula (8) and the measured values. This is because, according to the test results, the cohesive sediment is not only affected by the shear stress of water flow but it is also related to water content and the cohesive content of the soil sample under the condition of clear water scouring, which is not considered in Formula (8). Now, considering the factors of water content and cohesive content of cohesive sediment, the Formula (9) is:

$$E=MC^aW^b(\frac{\tau_0}{\tau_c}-1)^n \quad (9)$$

where, C = content of cohesive soil; W = water content; a, b = coefficients. The rest of the symbols are the same as above.

According to the experimental data, the coefficients M, a, b, and n in Formula (9) were analyzed by multiple linear regression. The coefficients were obtained and substituted into Formula (9) and, then Formula (10) is:

$$E = 0.2063C^{0.6036}W^{3.1056}\left(\frac{\tau_0}{\tau_c} - 1\right)^{1.9348} \quad (10)$$

In Formula (10), the effects of the content of cohesive soil (particle size), cohesive force, dry density, water content, and flow shear stress are considered. Formula (10) was used to calculate the scouring rate which was compared with the measured data, as shown in Figure 12, which shows that the calculated results by Formula (10) are in good agreement with the measured values. The individual data have errors, and the calculated results are obviously more accurate than those calculated using Formula (8).

Formula (8) can be used to estimate the scouring rate of the riverbank composed of very fine cohesive sand and to predict the scouring retreat rate of the riverbank in natural rivers so as to provide support for understanding the evolution of the river regime.

5. Conclusions

A series of relationships between the physical properties of cohesive soil and the scouring rate were established using the incipient motion scouring test on cohesive cemented soil in the lower Yellow River in this paper. The effect of relative residual shear stress on the scouring rate was discussed. A formula for the scouring rate of cohesive extremely fine sand (median particle size is less than or equal to 0.01 mm) was established. The main conclusions are as follows:

(1) The changing trend of the scouring rate with shear stress is different for cohesive soil samples with the same particle size under different deposition durations. When the siltation time of cohesive soil is short, the scouring rate increases obviously with the increase of shear stress. When the siltation time of cohesive soil is longer, the scouring rate still increases with the increase of shear stress, and the magnitude of increase slows down. The scouring rate is approximately exponential with the increase of shear stress.

(2) At the same flow rate, the scouring rate of the cohesive soil increases with the increase of water content, and the relationship between them shows an exponential increase. When the flow rate is low, the relationship between the scouring rate and water content is slower. With the increase of flow rate, the increase of the scouring rate is larger, and the exponential relationship between the scouring rate and water content is steeper, even nearly linear.

(3) For the same soil sample under the same shear stress condition, the scouring rate decreases with the increase of dry density. When the shear stress is small, the exponential relationship between the dry density and scouring rate is not obvious. With the increase of shear stress, there is an obvious exponential relationship between the dry density and scouring rate.

(4) Considering the factors affecting the scouring rate of cohesive soil (water content, cohesive content, etc.), the scouring rate formula of very fine cohesive sediment is established. The results are found better than the measured data after comparison, so it can be used to estimate the scouring rate of the riverbank composed of very fine cohesive sediment and predict the scouring retreat rate of the riverbank in natural rivers to provide support for understanding the evolution of river regimes.

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