Journal of Environmental & Earth Sciences
https://journals.bilpubgroup.com/index.php/jees

ARTICLE

Effects of Different Cations on the Flocculation and Sedimentation of Static Fine-Grained Sediments

***Xiaomin Liu*[1,2]*, Yaotian Yang*[2,3*]*, Rui Wang*[4]*, Wenjuan Wang*[2,3]*, Qiang Luo*[5]**

[1] *College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot, Inner Mongolia, 010018, China*

[2] *Collaborative Innovation Center for Integrated Management of Water Resources and Water Environment in the Inner Mongolia Reaches of the Yellow River, Hohhot, Inner Mongolia, 010018, China*

[3] *Inner Mongolia JinHua Yuan Environmental Resource Engineering Consulting Co., ltd, Hohhot, Inner Mongolia, 010020, China*

[4] *Wuhai Wuda District Agriculture of Animal Husbandry and Water Affairs Bureau, Wuhai, Inner Mongolia, 016000, China*

[5] *Yellow River Hai Bo-Wan Water Conservancy Project Development Center, Wuhai, Inner Mongolia, 016000, China*

ABSTRACT

Natural water bodies mostly contain cations, and the type and content of these cations are the main factors affecting the flocculation of fine-grained cohesive sediments and the floc sedimentation rate at the interface between clear and turbid water. From the microscopic aspect, this study examined the changing patterns of porosity and the fractal dimension of the flocs of fine-grained cohesive sediments. Sedimentation experiments under different sediment contents and electrolyte conditions were conducted, and microscopic images of the flocs were analysed using Image-Pro Plus (IPP) and MATLAB based on the fractal theory. From the macroscopic aspect, this study experimentally investigated the flocculation and sedimentation of fine-grained cohesive sediments and proposed a sedimentation rate equation by introducing an ion concentration-related parameter into an existing sedimentation rate equation (stagnation zone) based on the adsorption isotherm equation. The equation proposed in this study was validated with measured data. The calculated values were in good agreement with the measured values, with a relative error of 16%. The findings of this study provide a reference for further research on the flocculation and sedimentation of fine-grained cohesive sediments in different water bodies.

Keywords: Flocs; Electrolyte; Fractal dimension; Porosity; Sedimentation rate

*CORRESPONDING AUTHOR:
Yaotian Yang, Collaborative Innovation Center for Integrated Management of Water Resources and Water Environment in the Inner Mongolia Reaches of the Yellow River, Hohhot, Inner Mongolia, 010018, China; Inner Mongolia JinHua Yuan Environmental Resource Engineering Consulting Co., ltd, Hohhot, Inner Mongolia, 010020, China; Email: 645347148@qq.com

ARTICLE INFO
Received: 29 May 2023 | Revised: 15 July 2023 | Accepted: 19 July 2023 | Published Online: 9 August 2023
DOI: https://doi.org/10.30564/jees.v5i2.5747

CITATION
Liu, X.M., Yang, Y.T., Wang, R., et al., 2023. Effects of Different Cations on the Flocculation and Sedimentation of Static Fine-Grained Sediments. Journal of Environmental & Earth Sciences. 5(2): 1-14. DOI: https://doi.org/10.30564/jees.v5i2.5747

1. Introduction

The Yellow River carries a higher proportion of sediment than water. Due to the mismatch between water and sediment fluxes, the Yellow River is famous for its high proneness to siltation, levee breaches, and channel migration. Water and sediment changes have always been a focus and challenge of fluvial research. Sediment-laden rivers often carry a certain proportion of cohesive sediment. Compared with noncohesive sediments, fine-grained cohesive sediments has special electrochemical properties and are thus highly prone to form flocs in water [1]. Sediment flocculation and sedimentation have important effects on sediment transport, lake water quality, siltation in reservoirs and canals, and migrations of channels and estuaries of the Yellow River [2]. Therefore, research on the flocculation of cohesive fine-grained sediment is of great importance for analysing changes in riverbed erosion and siltation and improving the ecological environment of water bodies.

According to the basic principle of flocculation, small particle size is the basic condition for sediments to form flocs, cations are the fundamental driver for floc formation, and the ion concentration also determines the degree of flocculation and floc size [3]. Some studies have investigated the effects of different cation types and concentrations on sediment flocculation and sedimentation. For example, Wang et al. [4-11] have experimentally demonstrated that flocculation is more likely to occur in an ion-rich environment than in a freshwater environment and that the ions with higher valence are more likely to cause flocculation. Qiao [12], Zhang [13], and Lee et al. [14] introduced the Extended Derjaguin-Landau-Verwey-Overbeek (XDLVO) theory in colloidal chemistry into the 3D lattice Boltzmann model of particle sedimentation and used numerical simulation to analyse the effect of salt ion concentration on the sedimentation of fine-grained cohesive sediments. These studies have found that increasing salinity in freshwater environments is more likely to produce flocculation and that as the salt ion concentration increases, salt ions initially appear to promote the flocculation of sediments and the formation of larger flocs. However, when the salt ion concentration exceeds a certain value, a counter-ion layer is formed on the outer surface of fine-grained sediment, thus inhibiting sediment flocculation [15], and consequently, the fine-grained sediment tends to be stable and deposits only due to its own weight. Through MATLAB programming, Chai et al. [16] reconstructed the 3D images of the fine-grained sediment flocs with the grey values of the SEM images using MATLAB's surf function (with the pixel positions in planar images as X and Y axes and the grey values of images as Z axis), calculated the 3D fractal dimension of the flocs using the box-counting method through MATLAB programming, and deduced an equation for the floc sedimentation rate of the fine-grained sediment at the interface between turbid and clear water during hydrostatic sedimentation based on the calculated 3D fractal dimension of the without incorporating an ion concentration-related parameter.

In summary, many studies have investigated the effect of cation concentration on sediment flocculation and sedimentation. However, only a few studies have analysed the structural characteristics of flocs, and most of these studies segmented the images of flocs through the single-threshold method [17], which resulted in a certain subjectivity. In addition, there are relatively few studies on the flocculation and sedimentation of fine-grained sediment from the perspectives of floc porosity and fractal dimension. To this end, this study used Image-Pro Plus (IPP), which is an image processing software that can directly import the floc images obtained by microscopy to extract the floc features, use the scales in the microscopic images for spatial scale calibration, and automatically track and measure object properties, thus reducing the influence of human error during image processing and improving the accuracy of the results. Furthermore, this study used MATLAB to analyse the effects of different cation concentrations, sediment concentrations, and electrolyte strength on the flocculation and sedimentation of cohesive sediments based on the fractal theory and then established a sedimentation rate equation for cohesive sediments incorporating an electrolyte concentration-related parameter based on the analysis results.

2. Materials and methods

2.1 Experimental equipment

The main equipment used in this experiment included an AE200 electronic balance, a graduated cylinder (1000 mL), a beaker, a syringe, a pipette, and a dropper. A Winner-2008A fully automatic wet laser particle size analyser was used for sediment sample grading, and an Olympus BX51 fluorescence microscope was used to capture the floc images. The images were then analysed and measured with IPP, which is an imaging software that can automatically track and measure the properties of imported objects, thus improving the image processing accuracy compared with the currently used image processing methods and reducing subjective human errors, allowing the internal structures of flocs to be better analysed and processed.

2.2 Experimental materials

The cohesive fine-grained sediment samples used in this experiment were sampled from the surface silt (0-20 cm) of the Haibowan reservoir during the implementation of the Reservoir Ecological Management Pilot Project of the Haibowan Conservancy Hub over the Yellow River in April 2020. Litter impurities and coarse grains were removed from the cooled and air-dried sediment. Before the experiment, a 0.074-mm standard sieve was used to remove large sediment particles and impurities, and then the sedimentation method was used for further sorting and sampling. The grading curves of the sediment samples were measured using a HELOS/OASIS intelligent, fully automatic, full-range dry laser particle size analyser, and the median particle sizes of the sediment samples were 0.01 and 0.02 mm, as shown in **Figure 1**.

2.3 Experimental methods

Hydrostatic sedimentation experiment

The experiment was carried out in a graduated cylinder with a height of 30 cm, a diameter of 6 cm, and a volume of 1000 mL. Before the experiment, a scale ruler was attached to the outer wall of the graduated cylinder to record the position of the interface during the sedimentation, and then deionized (DI) water, quantitative cation concentration electrolytes (Na^+, Ca^{2+}, Al^{3+}), and quantitative sediment sample concentrations (50 kg/m^3, 70 kg/m^3, 100 kg/m^3, 150 kg/m^3) were added. The solution was fully stirred with a stirrer for approximately 1 min to evenly distribute the sediment. The distance and time of the uniform sedimentation section at the interface of clear and turbid water were recorded, the uniform sedimentation rate of the floc was calculated, and the changing pattern of the sedimentation rate was analysed. The specific experimental process is shown in **Figure 2**.

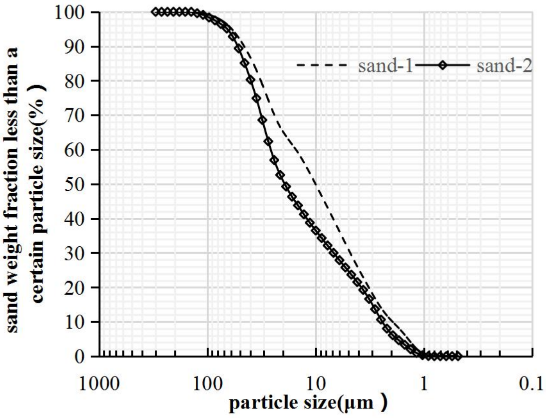


Figure 1. Experimental sand grading curve.

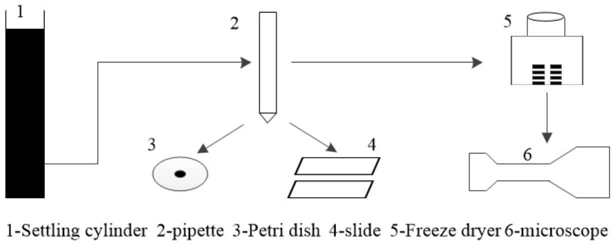


Figure 2. Experimental instrument and workflow diagram.

Collection of floc samples

When collecting floc samples, to completely obtain the floc structure that is easily broken, a pipette with a larger inner diameter was used to gently transfer the flocs from the graduated cylinder to the glass slide. Subsequently, the slides were placed into a freezer for 8 hours and then freeze-dried, and the dried floc samples were used for follow-up research.

The sampling temperature was controlled at 15 ± 1 °C to reduce the effect of temperature on sedimentation, and each test was repeated three times.

Image data extraction and analysis

In image data extraction and analysis, the single-threshold method is commonly used to segment the floc image [17]. In this paper, a BX51+DP70 microscope was used to scan and observe the floc samples, and the microscopic images of flocs at different magnifications (10, 20, and 40 times) were compared and analysed. Finally, the microscopic images at a magnification of 20 times were used for subsequent studies (**Figure 3**). First, IPP software was used to adjust the image to greyscale, adjust the brightness and contrast of the image, weaken the image background, and strengthen the floc boundary (**Figure 4**), and then the image processing function in the software was used to analyse the floc diameter, area, and perimeter and the pore diameter, area, and perimeter of the floc to calculate the floc porosity (**Figure 5**). The 2D digital images of the flocs formed under different conditions were analysed with the box-counting method through MATLAB to calculate the fractal dimensions and to analyse the changing pattern of the fractal dimensions of the flocs.

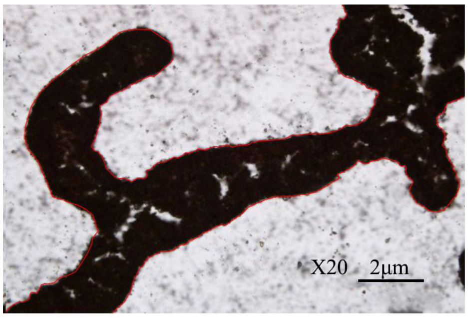


Figure 3. SEM image of the flocs (20x).

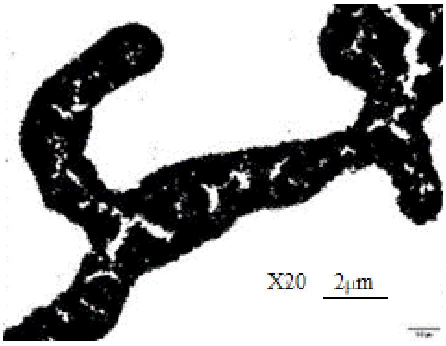
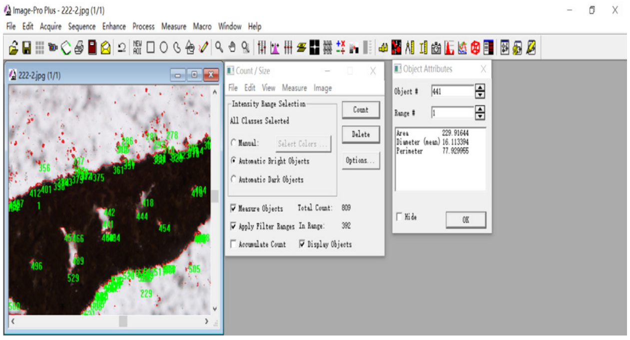


Figure 4. Floc image after IPP treatment.



Intensity Range Selection
All Classes Selected
○ Manual: Select Colors ...
● Automatic Bright Objects
○ Automatic Dark Objects
☑ Measure Objects Total Count: 809
☑ Apply Filter Ranges In Range: 392
☐ Accumulate Count ☑ Display Objects

Object # 441
Range # 1
Area 229.91644
Diameter (mean) 16.113394
Perimeter 77.929955
☐ Hide

Figure 5. Data extraction.

3. Results and analysis

3.1 Analysis of floc sedimentation rate

Analysis of the change in the sedimentation rate of flocs with different particle sizes

The physical and chemical properties of sediment particles are the decisive factors for water and sediment control in the Yellow River, and the median particle size is the most important parameter [18]. Therefore, this paper mainly studied the sedimentation of flocs formed by sediments with different particle sizes when other conditions are fixed.

According to the test results of sediment samples (1) and (2) under the same initial sediment content and electrolyte conditions, the sedimentation rate curves of flocs formed by sediments with different particle sizes were obtained, as shown in **Figure 6**.

Figure 6a indicates that when other conditions are fixed, the sedimentation curves of flocs formed by sediments with different particle sizes with the change in sediment concentration almost overlap, but as the particle size increases, flocculation decreases, and the floc sedimentation rate decreases, mainly because the finer the sediment particles are, the larger the specific surface area, and the easier the adhesion between the sediment particles.

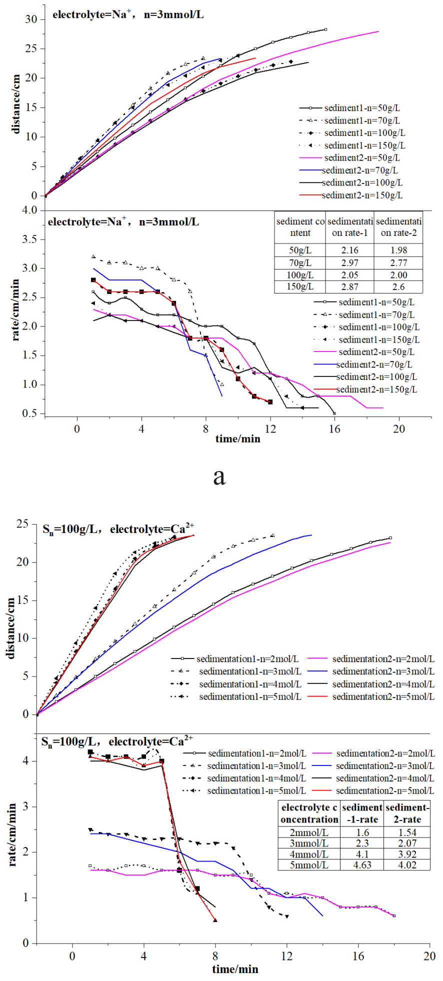
When the sediment content is 150 g/L, the fluctuation range of the sedimentation rate of flocs formed by sediments with different particle sizes is not very large. Alternatively, when the sediment concentration reaches a certain value, the change in particle size can be considered to have little effect on the floc sedimentation rate.

Figure 6b reveals that when other conditions are fixed, the sedimentation rate of flocs formed by sediments with different particle sizes increases with increasing electrolyte concentration, mainly because with increasing electrolyte concentration, the potential of sediment particles gradually decreases; that gradual decrease is conducive to mutual bonding between particles, and the change in electrolyte concentration plays a major role in the sedimentation of cohesive sediments. When the electrolyte concentration is too large, the decrease in the floc sedimentation rate of sediment sample (2) is faster than that of sediment sample (1). The preliminary analysis indicates that when the electrolyte concentration exceeds a certain value, the effect of electrolyte on flocculation decreases, and the formed flocs capture the surrounding sediment particles in the sedimentation. The smaller the particle size is, the larger the specific surface area and the stronger the adsorption effect, which supports the electrochemical properties of fine-grained sediments [19].

In summary, the effect of sediment particle size on floc sedimentation is not independent but depends on the electrolyte strength, initial sediment content, and cation valence. When the particle size of the sediment is less than 0.01 mm, the physical and chemical effects on the particle surface can produce microstructures between the particles [18]. Therefore, this paper mainly studied the change in the floc sedimentation rate of sediment sample (1) under different sediment concentrations, electrolyte concentrations, and cation valences.

Analysis of the change in the sedimentation rate of the flocs with different particle sizes

Figure 7 indicates that the sedimentation curve of flocs can be roughly divided into two stages, floc sedimentation and gel-like network sedimentation, possibly because initially, the particles collide and bond with each other to form flocs, and the sedimentation is fast, whereas in the later sedimentation, the flocs further flocculate to form a gel-like network structure, and the sedimentation is slow. When the sediment content is large enough (150 g/L), the transition from the fast stage to the slow stage is more obvious because the sedimentation rate of the floc is much larger than that of the gel-like network. When the sediment content is 50 g/L and 70 g/L, the sedimentation curves deviate significantly from those of other sediment contents, which shows that when the initial sediment content is low, the floc sedimentation is faster than when the sediment content is higher, possibly because when the number of original sediment particles is small, the average distance between particles is large; because such large distances are not conducive to the further formation of the gel-like network structure, particles sediment faster due to flocculation.



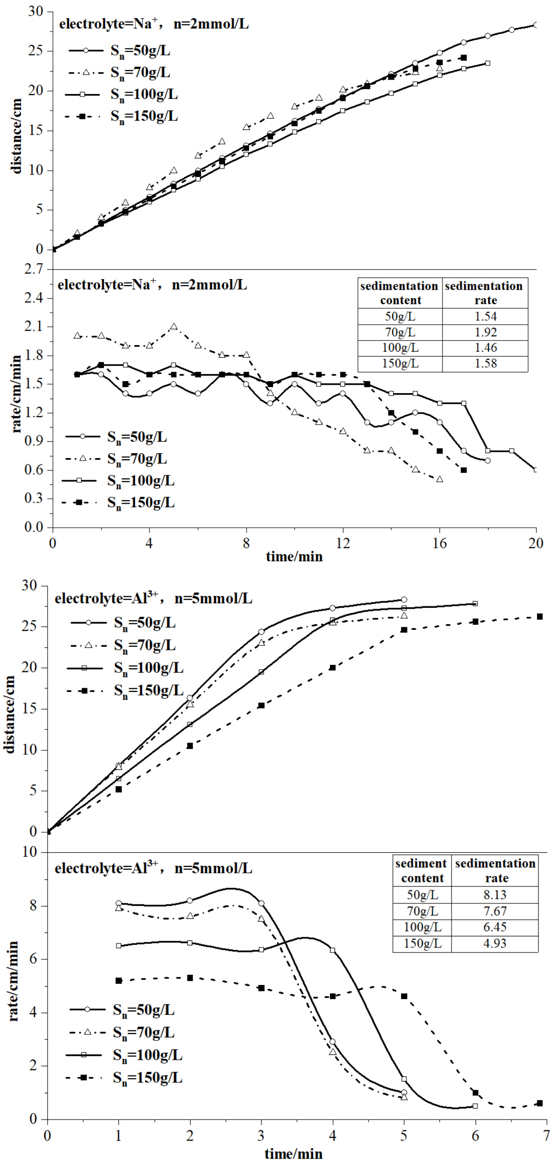
sediment content	sedimentation rate-1	sedimentation rate-2
50g/L	2.16	1.98
70g/L	2.97	2.77
100g/L	2.05	2.00
150g/L	2.87	2.6

a

electrolyte concentration	sediment-1-rate	sediment-2-rate
2mmol/L	1.6	1.54
3mmol/L	2.3	2.07
4mmol/L	4.1	3.92
5mmol/L	4.63	4.02

b

Figure 6. The curve of the floc settling process under different sediment particle sizes. (a) Sedimentation curve of the flocs (n = 3 mmol/L, z = 1). (b) Sedimentation curve of the flocs (Sn = 100 g/L, z= 2).



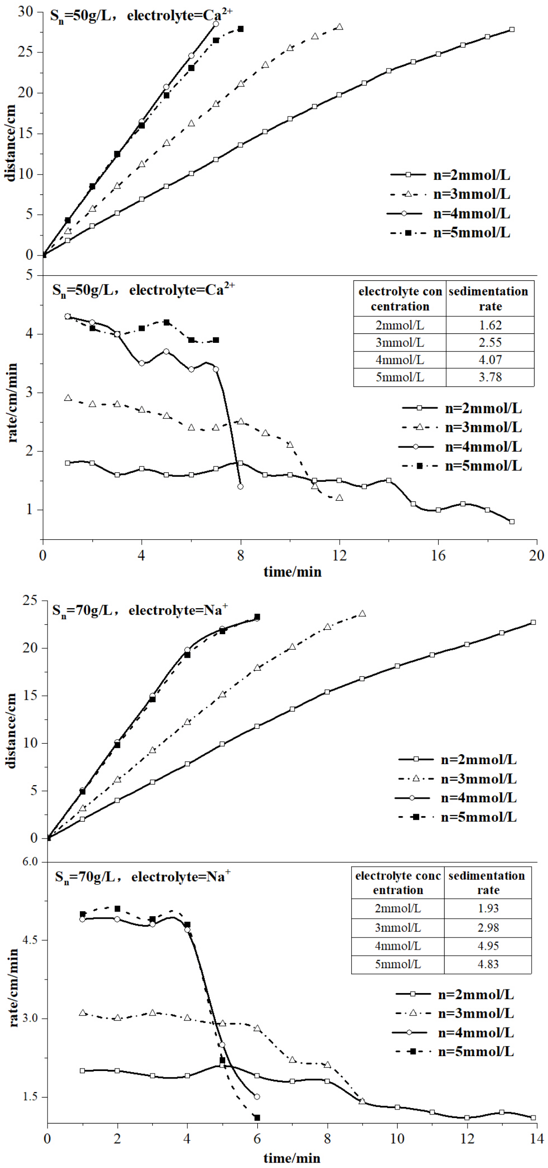
sedimentation content	sedimentation rate
50g/L	1.54
70g/L	1.92
100g/L	1.46
150g/L	1.58

sediment content	sedimentation rate
50g/L	8.13
70g/L	7.67
100g/L	6.45
150g/L	4.93

Figure 7. The curve of the floc settling process under different sediment concentrations.

Analysis of the change in floc sedimentation rate under different electrolyte concentrations

Figure 8 shows that when other influencing factors remain unchanged, with the increase in electrolyte concentration, the trends of floc sedimentation are consistent, and the changes in the rapid sedimentation stage almost overlap. When the electrolyte concentration reaches the optimum, sediment particles tend to stick to form flocs during sedimentation, the sedimentation becomes faster, and the flocculation and sedimentation curve tends to deviate from curves of other electrolyte concentrations, with the turning point occurring significantly earlier. According to the DLVO theory and the electric double-layer theory, the preliminary analysis indicates that under the comprehensive cohesive force of the fine-grained sediment particles in the suspension system, when other influencing factors are unchanged, higher cation valence and greater electrolyte strength result in a thinner electric double layer on the surfaces of the sediment particles and thus weaker interparticle repulsion but have almost no effect on the interparticle attraction. Therefore, the increase in the comprehensive force leads to flocculation between the sediment particles, which form relatively dense flocs, thereby increasing the floc sedimentation rate.



electrolyte concentration	sedimentation rate
2mmol/L	1.62
3mmol/L	2.55
4mmol/L	4.07
5mmol/L	3.78

electrolyte concentration	sedimentation rate
2mmol/L	1.93
3mmol/L	2.98
4mmol/L	4.95
5mmol/L	4.83

Figure 8. The curve of the floc settling process under different sediment concentrations.

Analysis of the change in the floc sedimentation rate under different cation valences

Figure 9 shows that when the other influencing factors are fixed, with the increase in cation valence, the turning point of the sedimentation at the interface between clear and turbid water becomes increasingly earlier. In the system with the addition of Al^{3+} ions, the floc sedimentation is the fastest, with large fluctuations [20]. Comparing the changes in floc sedimentation rate under different electrolyte strengths reveals that the effect of cationic valence on floc sedimentation is greater.

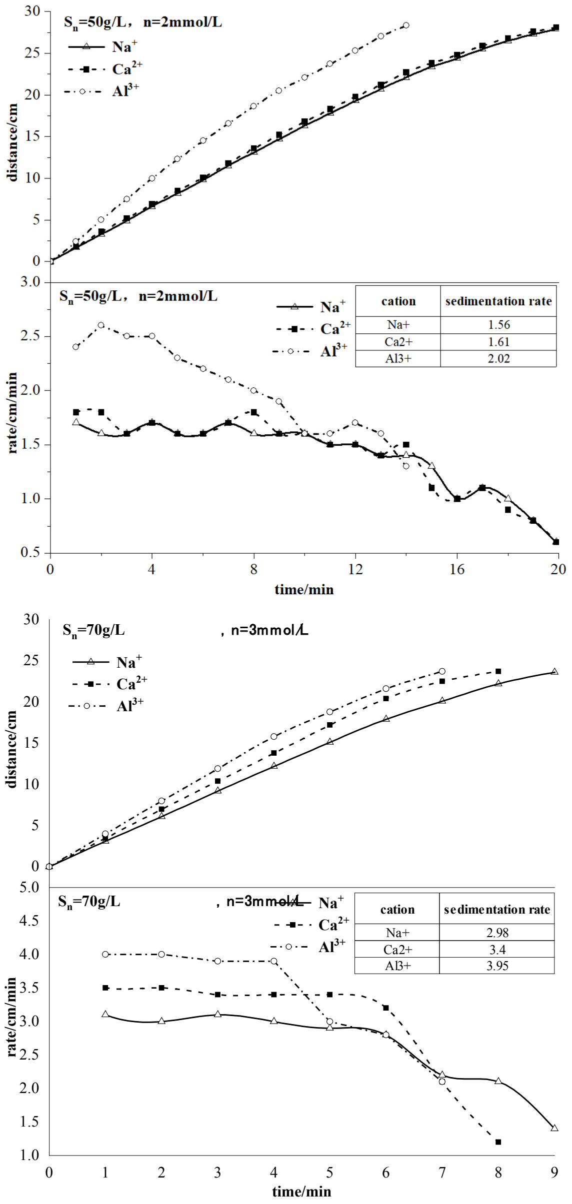


Figure 9. Floc settling process curve under different cationic valence conditions.

3.2 Analysis of the morphological characteristics of flocs

Calculation of floc pore structure parameters

Based on the images of the floc sample observed by microscope scanning, the cross-sectional area S of the floc and the pore area Sa in the floc can be obtained by using IPP image processing software. According to the definition of plane porosity, the porosity of the floc can be calculated.

$$n = \frac{S_a}{S} \times 100\% \qquad (1)$$

where n is the porosity of the sediment floc; s is the equivalent area of the polygon corresponding to the floc, μm²; and sa is the area of the equivalent polygon of pores within the floc, μm².

Figure 10 indicates that when the sediment concentration is constant, the floc porosity decreases with increasing electrolyte strength, and under the same electrolyte strength, the floc porosity decreases with increasing cation valence, which is related to the force between the cohesive sediment particles. According to the DLVO theory, with the increase in the cationic valence, the repulsive force between the sediment particles gradually decreases, which facilitates bonding between particles. As a result, flocs are formed more densely, and thus, the porosity of the flocs is reduced.

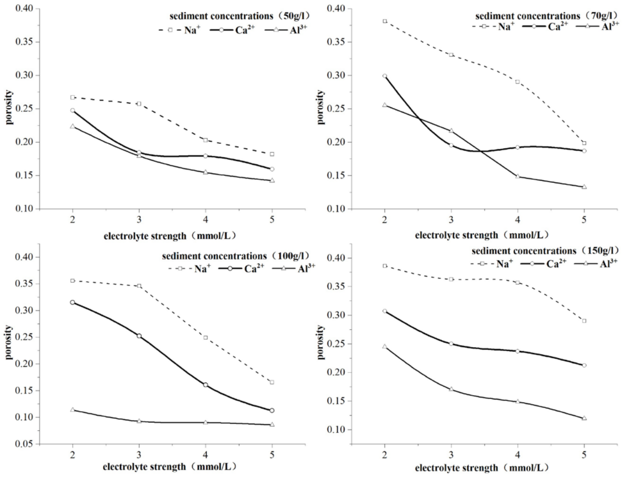


Figure 10. Variation curves of the floc porosities under different conditions.

Fractal dimension of flocs

This paper used MATLAB to find the fractal dimension of flocs. Using the box-counting method, a program was written to perform grid division and statistical analysis of the black-and-white binary image [19], and a series of data pairs of "grid size" and "number of covered grid cells" were obtained, that is, the data pairs of submatrix order and the number of submatrices containing image points (pixel is 0). Then, the data points were drawn in double logarithmic coordinates, and linear regression analysis was performed; the negative value of the slope of the line is the box-counting dimension of the image (the slope of the line is the absolute floc fractal dimension), and the results are shown in **Figure 11**. The changing pattern of the fractal dimension of flocs under different sediment contents and electrolyte conditions is shown in **Figure 12**.

The calculation principle of the box-counting dimension is to cover the fractal set with small boxes of side length ε; the total number of small boxes is N(ε), and the following relationship is obtained:

$$N(\varepsilon) \propto \varepsilon^{k} \tag{2}$$

Fitting log N(ε) vs. log ε (in double logarithmic coordinates) by least squares yields the following relationship between the box-counting dimension D and the slope of the line K:

$$D = -K \tag{3}$$

In **Figure 12**, the changing pattern of three different types of cations is similar to that of the fractal dimension of their flocs; i.e., the fractal dimension of the flocs tends to decrease with increasing cation concentration, mainly because after the addition of different types of cations, flocs are formed mainly by electrical neutralization and adsorption-induced bridging between particles. When the electrolyte strength is low, although there are cations in the aqueous solution, which can neutralize some negative charges on the surface of the particles and reduce the interparticle repulsion, the flocculation effect between the particles is weak, the shape of the flocs is irregular, and the fractal dimension of flocs is too large. With a further increase in the electrolyte strength, the optimal salinity for flocculation is reached, and the floc density is the largest; consequently, the fractal dimension gradually decreases. Continuing to increase the flocculant concentration further increases the cation concentration in the water, and when the number of cations exceeds negative charges on the surface of the particle (solid phase), the sign of the external charge of the water film with the electric double layer is reversed, and the stability of the floc in the water body is enhanced, which inhibits the further formation of flocs, causing the fractal dimension of flocs to increase slightly.

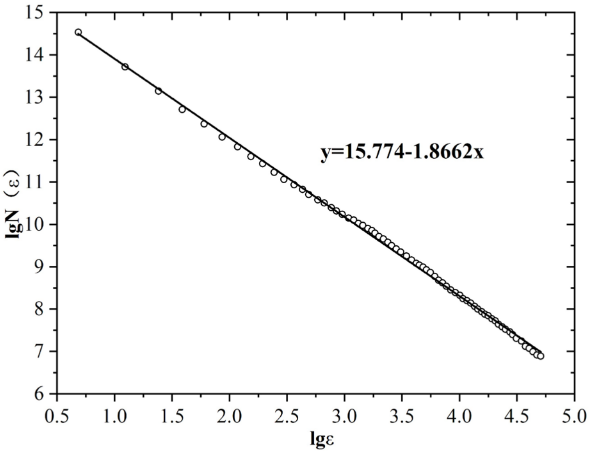


Figure 11. Double logarithmic relationship between the length of sides and number boxes.

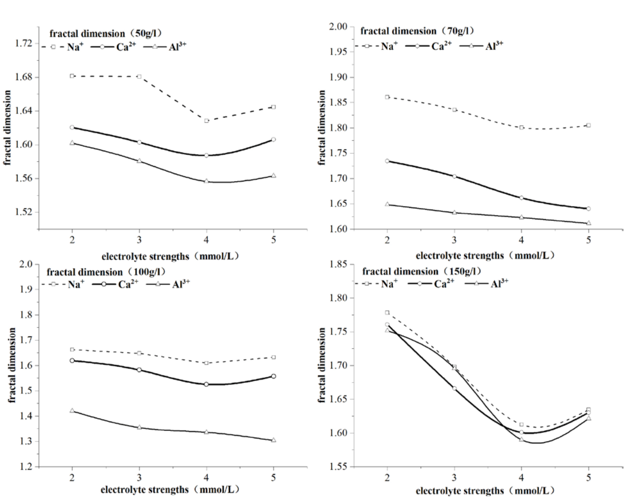


Figure 12. Graph of the fractal dimension change under different conditions.

Modification of the sediment sedimentation rate equation under the influence of different cations

For a single floc, the following relationship is satisfied between the number of sediment particles N_f that make up the floc and the floc diameter d_f:

$$N_f = \left(\frac{d_f}{d_0}\right)^{D} \tag{4}$$

where d_0 is the median particle size of the analysed sediment sample and D is the fractal dimension of the flocs.

Based on adsorption theory, Wang et al. [21] used the Langmuir adsorption isotherm equation and combined the relationship between the sedimentation rate and particle size to obtain the following:

$$k_\omega = \frac{\omega_f}{\omega_0} = \frac{1}{\lambda_1 C^2+\lambda_2 C+\lambda_3}\cdot c^2 \tag{5}$$

where k_ω is the flocculation coefficient expressed by the change in sedimentation rate, ω_f is the sedimentation rate of the floc, ω_0 is the sedimentation rate of a single sediment particle, C is the electrolyte concentration, and λ_1, λ_2, and λ_3 are the coefficients.

From Equations (2)-(5), the floc sedimentation rate ω_f incorporating the ion concentration-related parameter can be obtained:

$$\omega_f = k_\omega \cdot c^2 \cdot \omega_0 = \frac{1}{\lambda_1 C^2+\lambda_2 C+\lambda_3}\cdot c^2 \cdot \omega_0 \tag{6}$$

The meaning of the symbols in Equation (6) is the same as above. The coefficients λ_1, λ_2, and λ_3 are related to the sediment particle size, surface characteristics, and cation species, respectively, which must be determined experimentally.

Based on the above analysis, the floc porosity ε and fractal dimension D were used to analytically calculate the flocculation coefficient $k\omega$.

If the volume of a sediment particle satisfies $V_0 = \pi/6\cdot d_0^3$ and the volume of the floc satisfies $V_f = \pi/6\cdot d_f^3$, then the floc porosity ε is as follows:

$$\varepsilon = \frac{V_f - N_f V_0}{V_f} \tag{7}$$

Substituting Equation (4) into Equation (7), we can obtain Equation (8):

$$\frac{d_f}{d_0} = (1-\varepsilon)^{\frac{1}{D-3}} \tag{8}$$

If the fine sediment and the floc sedimentation are in the stagnation zone and the sediment sedimentation rate in the stagnation zone is proportional to the square of the particle size, then,

$$\frac{\omega_f}{\omega_0} = \left(\frac{d_f}{d_0}\right)^2 \tag{9}$$

According to Equations (5), (8), and (9), we can obtain Equation (10):

$$k_\omega = \frac{\omega_f}{\omega_0} = \left(\frac{d_f}{d_0}\right)^2 = \left((1-\varepsilon)^{\frac{1}{D-3}}\right)^2 = \frac{1}{\lambda_1 C^2+\lambda_2 C+\lambda_3} \tag{10}$$

Substituting the calculated fractal dimension D and floc porosity ε into Equation (10), the flocculation coefficient k_ω can be calculated, and the relationship between $1/k_\omega$ and the electrolyte concentration C was plotted, as shown in **Figure 13**, and fitted with a quadratic polynomial.

Equation (10) establishes the relationship between the floc sedimentation rate of cohesive sediments and the ion concentration in the water. It should be noted that some simplifications and assumptions have been made in the derivation of Equation (10) to facilitate the establishment of a relationship between the floc sedimentation rate of cohesive sediments and the ion concentration in the water. The coefficients λ_1, λ_2, and λ_3 in Equation (10) are correlated with many factors; that is, the coefficients λ_1, λ_2, and λ_3 change when conditions change, such as the surface properties of the sediment, the cation type, and the particle size of the sediment; therefore, coefficients λ_1, λ_2, and λ_3 should be calibrated under different conditions.

Many studies have demonstrated that there are different sedimentation resistance behaviours for different motion states. For the sedimentation rate equations proposed by Goncharov et al. [22-25], some coefficients are slightly different in various flow zones, but the structural forms of the sedimentation rate equations in the stagnation zone are essentially the same. This paper introduced the ion concentration-related parameter into an existing sedimentation rate equation and obtained the sedimentation rate equation incorporating the ion concentration-related parameter:

$$\omega_f = \frac{1}{\lambda_1 C^2+\lambda_2 C+\lambda_3}\cdot c^2\left(\frac{1}{24}\cdot\frac{\gamma_s-\gamma}{\gamma}\cdot g\cdot\frac{d^2}{\upsilon}\right) \tag{11}$$

where γ_s is the specific gravity of sediment, γ is the specific gravity of water, g is the gravity, υ is the coefficient of hydrodynamic viscosity, and d is the particle size of sediments. Other symbols have the same meanings as above.

The obtained experimental data are used to test the validity of Equation (11).

The error rate for individual tests is calculated using Equation (12):

$$\text{Error rate} = (\textit{Calculated value-Experimental value}) / \textit{Experimental value} \tag{12}$$

After substituting the relationship between cation concentration C and flocculation coefficient k_ω into Equation (11), the corrected sediment sedimentation rate can be calculated. Compared with the experimental results as shown in **Figure 14**, the average relative error is 16% (**Figure 15**), which essentially meets the computational accuracy requirements. Therefore, in this paper, based on the calculated fractal dimension and porosity of flocs, the obtained flocculation coefficient and sedimentation rate equation incorporating the ion concentration-related parameter for flocs formed by sediments with different particle sizes are essentially reasonable.

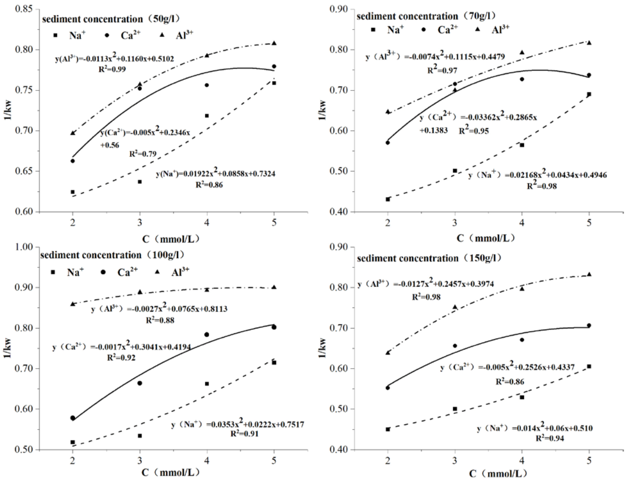


Figure 13. Relationship curves between the different cation concentrations C and 1/kw.

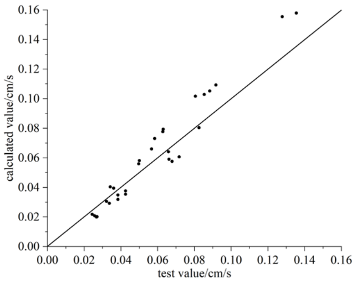


Figure 14. Comparison of the test value and the calculated value of the floc settling rate in Equation.

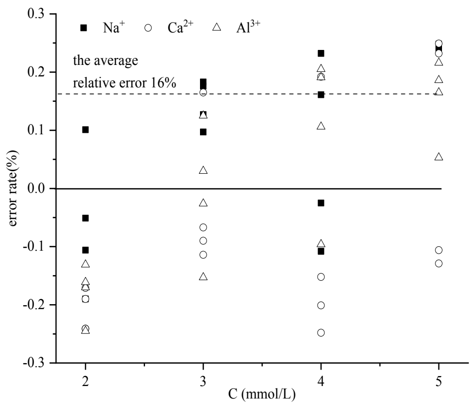


Figure 15. The error rate of settling velocity is calculated by Equation (11).

4. Discussion

(1) IPP image processing software is a relatively complete image analysis software with advanced functional modules for image processing and is widely used in fluorescence imaging, material imaging, medical research, and industrial production. In this paper, IPP image processing software was used to extract the morphological parameters of flocs, and the relationships between the porosity (a structural parameter) of flocs and the sediment and cation concentrations was analysed. The results indicated that the changing pattern of the floc structure characteristics analysed in this paper is consistent with that of Chai [17] and Chen [26], i.e., under the same electrolyte strength, the porosity of flocs decreases with increasing cation valence. The main reason for this finding is that the addition of cations in the water neutralizes some negative charges on the surface of the sediment particles, which reduces the interparticle electrostatic repulsion and increases the interparticle interaction; thus, flocculation can occur between the particles that were not prone to flocculation originally, and the interparticle bonding is enhanced such that the interparticle pores are smaller [17].

The results demonstrate that it is feasible to apply IPP software to analyse scanning electron microscope (SEM) images of flocs. However, IPP is only suitable for 2D observation. To gain a more comprehensive understanding of the complex internal structure of flocs, it is necessary to develop new software or improve observation techniques.

(2) In natural water bodies, the sedimentation rate of cohesive sediment changes due to the presence of cations. The main reason for this change is the flocculation of cohesive sediments under the action of ions. According to the existing research results, the main cations in the Yellow River are Ca^{2+}, Na^{+}, and K^{+} [27]. Therefore, this study selected the silt in the Haibowan Reservoir and mainly discusses the flocculation and sedimentation of cohesive sediments under the action of three different cations (Na^{+}, Ca^{2+}, and Al^{3+}). The results indicated that under the same sediment and cation concentrations, when the cation valence increases from +1 to +3, the floc sedimentation rate increases, which is essentially consistent with the findings of Wang [4] and Jiang [28]. The main reason for this finding is that according to the DLVO theory and the electric double-layer theory, the surface of the cohesive sediment particles is generally negatively charged; therefore, adding cations can reduce the thickness of the electric double layer on the surface of the sediment particles and the charge repulsion between the sediment particles, increase the chance of sediment particle bonding after collision, increase the formation rate of flocs by sediments, and promote flocculation and sedimentation of cohesive sediments [29]. However, the flocculation and sedimentation of fine-grained cohesive sediment are complex, and under different influencing factors, the sedimentary process and sedimentation rate of formed flocs are different. In actual water bodies, many factors act together; therefore, further research must comprehensively consider the influence of various factors to draw conclusions that are more in line with the actual situation.

5. Conclusions

(1) Under the same initial sediment concentration, the porosity and fractal dimension of flocs decrease with increasing cation concentration. After the cation concentration exceeds the optimal cation concentration for flocculation, the floc porosity and fractal dimension start to decrease more slowly or increase slightly.

(2) Cations with different valences have different effects on sediment sedimentation rates. When other influencing factors are fixed, higher-valence cations in the water have a stronger effect on sediment flocculation, and cation valence has a greater impact on the floc sedimentation rate compared with the sediment and cation concentrations. Therefore, high-valence ions are the main indicators for assessing the effect of ion concentration in water on sediment sedimentation rate.

(3) In natural water bodies, the sedimentation rate of cohesive sediment changes due to the presence of cations. The main reason for this change is the flocculation of cohesive sediments under the action of ions. In this paper, the ion concentration-related parameter was introduced into the existing sedimentation rate equation (stagnation zone) based on the changing patterns of the floc fractal dimension (D) and porosity (ε) under different influencing factors and the adsorption isotherm equation. The modified sedimentation rate equation was verified since the calculated values were essentially consistent with the measured values.

Author Contributions

L.X.M conceived and designed the manuscript; Y.Y.T processed and analysed the data and performed the proposed methods; L.X.M interpreted and discussed the results; Y.Y.T edited the manuscript; L.X.M and W.R revised the manuscript; W.W.J and L.Q handled the submission steps. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

Declaration of conflict of interest.

Funding

This research was funded by The Nature Foundation of Inner Mongolia Autonomous Region 2021MS05042. The National Natural Science Foundation of China project 51969021, 52169016. The

Major Science and Technology Projects of Inner Mongolia Autonomous Region 2021ZD0008.

References

[1] Li, X.K., Niu, W.Q., Zhang, W.Q., et al., 2019. Liu suan jia fei dui jing zhi huang he shui ni sha xu ning chen jing de ying xiang (Chinese) [Effect of potassium sulfate fertilizer on flocculation and sedimentation of static Yellow River water]. Shui Tu Bao Chi Xue Bao. 33(4), 140-146.

[2] Wang, X.J., Wang, Y.N., Zhao, J., 2022. Recent progress of the effect of suspended sediment movement on the transport of microplastics in rivers. China Environmental Science. 42(2), 863-877.

[3] Liu, J.X., Ji, Z.W., Wang, D.W., 2019. Nian xing xi ke li ni sha xu ning shi yan yan jiu zong shu (Chinese) [Review on the flocculation test of cohesive sediment]. Ni Sha Yan Jiu. 44(2), 63-68. DOI: https://doi.org/10.16239/j.cnki.0468-155x.2019.02.009

[4] Wang, J.Sh., Chen, L., Liu, L., et al., 2005. Yang li zi nong du dui ni sha chen su ying xiang shi yan yan jiu (Chinese) [Experimental study on effect of positively charged ion in river on the velocity of sediment particles]. Shui Ke Xue Jin Zhan. 16(2), 169-173.

[5] Chen, H.S., Shao, M.A., 2002. NaCl dui xi ke li ni sha jing shui xu ning chen jiang dong li xue mo shi de ying xiang (Chinese) [Effect of NaCl concentration on dynamic model of fine sediment flocculation and settling in still water]. Shui Li Xue Bao. 33(8), 63-68.

[6] Liu, Q.Zh., Li, J.F., Xu, C.H., et al., 2008. Yan du he fu zhi suan gong tong zuo yong xia de chang jiang kou ni sha xu ning guo cheng yan jiu (Chinese) [Flocculation process of fine-grained sediments by the combining effect of salinity and humus in the Changjiang Estuary in China]. Hai Yang Xue Bao. 30(3), 140-147.

[7] Liu, L., Chen, L., Wang, J.Sh., et al., 2007. Bu tong li zi nong du xia ni sha nong du dui xu ning chen jiang de ying xiang (Chinese) [Effect on the flocculation sedimentation velocity in different conditions of cation concentration by concentration of sediments particles]. Wu Han Da Xue Xue Bao (Gong Xue Ban). (1), 29-32.

[8] Yao, P., Sun, W., Guo, Q.Q., 2022. Ji pei he han yan du dui shi ying zhi fen sha de jing shui chen jiang ying xiang shi yan yan jiu (Chinese) [Experimental study on the effect of sediment composition and water salinity on settling processes of quartz silt in still water]. Ni Sha Yan Jiu. 47(5), 15-22. DOI: https://doi.org/10.16239/j.cnki.0468-155x.2022.05.003

[9] Li, W., Yu, C., Yang, S., et al., 2020. Measurements of the sediment flocculation characteristics in the Three Gorges Reservoir, Yangtze River. River Research and Applications. 36(7), 1202-1212. DOI: https://doi.org/10.1002/rra.3614

[10] Guo, L., He, Q., 2011. Freshwater flocculation of suspended sediments in the Yangtze River, China. Ocean Dynamics. 61, 371-386.

[11] Mikeš, D., Manning, A.J., 2010. Assessment of flocculation kinetics of cohesive sediments from the Seine and Gironde estuaries, France, through laboratory and field studies. Journal of Waterway, Port, Coastal, and Ocean Engineering. 136(6), 306-318. DOI: https://doi.org/10.1061/(ASCE)WW.1943-5460.0000053

[12] Qiao, G.Q., Zhang, Q.H., Zhang, J.F., et al., 2013. Ji yu XDLVO li lun de nian xing ni sha xu ning mo ni ge zi bo er zi man mo xing (Chinese) [Lattice Boltzmann model of cohesive sediment flocculation simulation based on the XDLVO Theory]. Tian Jin Da Xue Xue Bao (Zi Ran Ke Xue Yu Gong Cheng Ji Shu Ban). 46(3), 232-238.

[13] Zhang, J.F., Zhang, Q.H., Qiao, G.Q., 2015.

Nian xing xi ke li ni sha xu ning fa yu shi kong guo cheng de shu zhi mo ni (Chinese) [Temporal and spatial variations of the flocculation process of fine cohesive sediments: A numerical simulation]. Shui Li Xue Bao. 46(11), 1305-1311.

[14] Lee, B.J., Toorman, E., Fettweis, M., 2014. Multimodal particle size distributions of fine-grained sediments: Mathematical modeling and field investigation. Ocean Dynamics. 64, 429-441.
DOI: https://doi.org/10.1007/s10236-014-0692-y

[15] Guo, Ch., He, Q., 2021. Nian xing ni sha xu ning yan jiu zong shu yu zhan wang (Chinese) [Review of the research on cohesive sediment flocculation]. Jni Sha Yan Jiu. 46(2), 66-73.
DOI: https://doi.org/10.16239/j.cnki.0468-155x.2021.02.011

[16] Chai, Zh.H., Yang, G.L., Chen, M., 2012. Ji yu SEM tu xiang de xi ke li ni sha xu ti 3 wei fen xing yan jiu ji qi ying yong (Chinese) [3-D fractal study of fine sediment floc using SEM image and its application]. Gong Cheng Ke Xue Yu Ji Shu. 44(1), 88-92.

[17] Chai, Zh.H., Yang, G.L., Chen, M., 2011. Tu xiang fen xi nian xing xi ke li ni sha xu ti kong xi chu tan (Chinese) [Study of floc pores of viscous fine sediment by image analysis]. Ni Sha Yan Jiu. 55(5), 24-29.
DOI: https://doi.org/10.16239/j.cnki.0468-155x.2011.05.003

[18] Wang, D.W., Yang, G.L., Yu, M.H., 2009. Jing shui zhong nian xing xi ke li ni sha xu ning lin jie li jing de que ding ji qi ying xiang yin su fen xi (Chinese) [Method to determine the maximal diameter of fine sediment aggregation and influence factors analysis]. Ni Sha Yan Jiu. (1), 74-80.
DOI: https://doi.org/10.16239/j.cnki.0468-155x.2009.01.012

[19] Liu, Y., Reng, T.W., Wang, P., 2010. Ji yu Matlab li yong fen xing li lun kao cha bian po an quan zhuang tai fang fa yan jiu (Chinese) [Study on inspection of slope safety with fractal theory based on Matlab]. Shui Li Shui Dian Ji Shu. 41(7), 17-19+23.
DOI: https://doi.org/10.13928/j.cnki.wrahe.2010.07.017

[20] Varkouhi, S., Tosca, N.J., Cartwright, J.A., 2020. Pore-water chemistry: A proxy for tracking the signature of ongoing silica diagenesis. Journal of Sedimentary Research. 90(9), 1037-1067.
DOI: https://doi.org/10.2110/jsr.2020.56

[21] Wang, J.Sh., Chen, L., Wang, Zh.G., et al., 2006. Han li zi nong du can shu de nian xing ni sha chen su gong shi yan jiu (Chinese) [Study on the fine sediment settling velocity formula with the parameter of Ca^{2+} concentration]. Shui Ke Xue Jin Zhan. 17(1), 1-6.

[22] Zhang, R.J., 1998. He liu ni sha dong li xue (Chinese) [River sediment dynamics]. China Water & Power Press: Beijing.

[23] Dou, G.R., 1963. Ni sha yun dong li lun (Chinese) [Theory of sediment movement]. Nanjing Hydraulic Research Institute: Nanjing.

[24] Sha, Y.Q., 1965. Ni sha yun dong xue yi lun (Chinese) [Kinematics of sediment]. China Industry Press: Beijing.

[25] Zhang, R.J., 1961. He liu dong li xue (Chinese) [Dynamics of rivers]. China Industry Press: Beijing.

[26] Chen, Y.P., Luo, W., Xu, Ch.Y., et al., 2020. Gao nong du nian xing ni sha xu tuan wei guan jie gou ji qi dui chen jiang te xing de ying xiang (Chinese) [Microstructure of cohesive sediment flocs with high concentration and its influence on the deposition characteristics]. Ni Sha Yan Jiu. 45(6), 8-14.
DOI: https://doi.org/10.16239/j.cnki.0468-155x.2020.06.002

[27] Chen, J.Sh., Li, H.B., Xia, X.H., et al., 2000. Jin 30 nian lai huang he shui zhi bian hua qu shi ji yuan yin fen xi (Chinese) [A study on water-quality trend in the Yellow River System

from 1960 to 1990]. Huan Jing Hua Xue. (2), 97-102.

[28] Jiang, G.J., Yao, Y.M., Tang, Z.W., 2002. Chang jiang kou xi ke li ni sha xu ning chen jiang ying xiang yin su fen xi (Chinese) [The analysis for influencing factors of fine sediment flocculation in the Changjiang Estuary]. Hai Yang Xue Bao. 24(4), 51-57.

[29] Chai, Ch.H., Fang, H.W., Wang, X., et al., 2017. Shui liu he dian jie zhi dui nian xing ni sha xu ning chen jiang ying xiang shi yan (Chinese) [Effect of flow and electrolyte on the flocculation-settling of cohesive sediment]. Shui Ke Xue Jin Zhan. 28(2), 285-292.
DOI: https://doi.org/10.14042/j.cnki.32.1309.2017.02.014