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Settlement prediction model of slurry suspension based on sedimentation rate attenuation

Shuai-jie GUO*[1, 2], Fu-hai ZHANG[1, 2], Bao-tian WANG[1, 2], Chao ZHANG[3]

1. Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, P. R. China
2. Institute of Geotechnical Engineering, Hohai University, Nanjing 210098, P. R. China
3. Bureau of Hydrology, Changjiang Water Resources Commission, Wuhan 430012, P. R. China

Abstract: This paper introduces a slurry suspension settlement prediction model for cohesive sediment in a still water environment. With no sediment input and a still water environment condition, control forces between settling particles are significantly different in the process of sedimentation rate attenuation, and the settlement process includes the free sedimentation stage, the log-linear attenuation stage, and the stable consolidation stage according to sedimentation rate attenuation. Settlement equations for sedimentation height and time were established based on sedimentation rate attenuation properties of different sedimentation stages. Finally, a slurry suspension settlement prediction model based on slurry parameters was set up with a foundation being that the model parameters were determined by the basic parameters of slurry. The results of the settlement prediction model show good agreement with those of the settlement column experiment and reflect the main characteristics of cohesive sediment. The model can be applied to the prediction of cohesive soil settlement in still water environments.

Key words: *cohesive sediment; sedimentation rate attenuation; slurry suspension; settlement prediction model; settlement column experiment*

1 Introduction

Solid particles of slurry suspension in still water environments settle freely under gravity, forming a high-void ratio, high-water content, and high-compressibility soil (Yang and Zhang 1997). The existence of a large amount of soil will cause serious hydraulic problems, such as river and port deposition and dredging problems. The estuary and bay areas can be regarded as the natural still water environment, which is favorable for the deposition of silt soil (Shi 2004; Tsuneo et al. 2009). Pollutant enrichment in silt soil will also lead to serious environmental problems. Therefore, research on the hydrostatic settlement process of solid particles is urgently needed in hydraulic projects for flood control, dredging, and environmental protection.

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*Corresponding author (e-mail: *ggssjj@hhu.edu.cn*)
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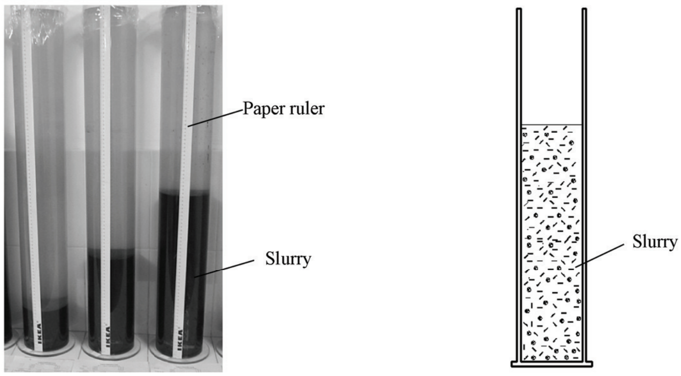
Sediment deposition in still water is classified as non-cohesive and cohesive settlements according to the content of fine particles (Fei 1992). Interactions between particles are ignored in non-cohesive settlement, and the settlement of particle obeys Stokes' law (Winterwerp 1998; Yang et al. 2003a). Due to the development of flocculation and influence of particle weight, different sedimentation stages can be defined in cohesive settlement, and the settlement process can be found by investigating the variation of interface. For the first stage, interactions can be ignored as the particle settlement following Stokes' law due to the large distance between particles. When the particle distance reaches a certain limit, Stokes' law will not be applicable due to the development of electrostatic forces and flocculation, which means that flocculation needs to be introduced (Zhu et al. 2009; Yang et al. 2003b; Lin et al. 2007). Microstructure formation of flocs is subject to the law of fractal growth (Zhu et al. 2009; Ma and Pierre 1998; Pierre and Ma 1999), and the attenuation of the interface sedimentation rate is log-linear. With the particle distance decreasing and effective stress coming into being, the consolidation of soil begins (Xie and Leo 2004) and the sedimentation rate finally attenuates to zero.

Numerous scholars have studied the sedimentation rate formula. Li et al. (2006) summarized current research on the interface sedimentation rate formula and concluded that the modified sedimentation rate formula for single particles and infiltration theory formula are two most meaningful ways. Li and Yang (2006) obtained fractal dimension values of flocs from microstructure pictures through laser scanning. Zhang and Xiong (1991) studied the settlement and resistance characteristics of single particles with plastic sands of standard size. Yang et al. (2003a, 2003b) studied the influences of fine particle flocculation on the interface sedimentation rate and provided a modified formula. Han (1997) conducted research on the distribution of dry bulk density of soil along the sedimentation direction to predict the final sedimentation height. Cook et al. (2004) developed a direct simulation equipment to test the settlement characteristics of partial-fluid systems. Fox et al. (2005) and Fox (2007) researched the characteristics of mud soil based on the large strain consolidation theory and carried out many experiments with a centrifuge.

The research mentioned above mainly focuses on the initial free sedimentation stage or some indicators of consolidation rather than the entire settlement process. Slurry settlement, from non-Newtonian fluid status to steady consolidation status, is a complete process. Therefore, it is necessary to determine the sedimentation rate attenuation of the whole settlement process. Different sedimentation rate attenuation equations were established for the corresponding sedimentation stages in this study. The time-integrated sedimentation rate equations are the control equations for the sedimentation stages, and the equation parameters are determined by the sedimentation rate attenuation parameters and the physical properties of slurry. The study of Merckelbach (2000) shows that there are some relationships between sedimentation rate attenuation parameters and the initial concentration. A settlement prediction model was built up based on basic soil parameters and the attenuation parameters of the settlement process of slurry with a reference concentration.

2 Settlement column experiment

The main experimental device was a 1 000 mm-high and 130 mm-inner diameter plexiglass (PMMA) settlement column (Merckelbach 2000; Liu and Wang 2006). Two rulers were set outside to record the sedimentation height. The settlement column is shown in Fig. 1.



(a) Plexiglass settlement column (b) Slurry settlement process

Fig. 1 Settlement column experiment

2.1 Sedimentation soil materials

The sedimentation soil came from the deposited soil, which is 20 cm under the water bottom, in the Shenzhen River and Bay, and the mixing water was from the upper river or sea. There were 40 soil groups in all, and three types of slurry with initial concentrations of 100 g/L, 50 g/L, and 20 g/L, respectively, were prepared for each group in settlement experiments. The slurry concentration was defined as the soil particle weight per unit slurry volume. One group of soil was chosen as the reference soil, and the rest were used as fitted data to determine the equation parameters. The soil specific gravity (G_s), liquid limit (ω_L), plastic limit (ω_P), plasticity index (I_P), and water specific gravity (G_W) of the reference soil were, respectively, 2.73, 50.5%, 21.7%, 28, and 1.024, and the contents of the reference soil with grain sizes of less than 0.001 mm, 0.002 mm, 0.004 mm, 0.01 mm, and 0.02 mm were 14.2%, 28.7%, 49.2%, 79.8%, and 100%, respectively. According to the physical properties and the classification in the plasticity chart of soil, the reference soil can be defined as the high liquid-limit clay.

2.2 Sedimentation curves of reference soil

The initial sedimentation height was defined as the slurry height at the beginning of the settlement experiment. According to the settlement column experiment, relationships between sedimentation height and time can be expressed in natural coordinates and double logarithmic coordinates (Fig. 2).

The reference soil sedimentation curves in natural coordinates (Fig. 2(a)) have linear relationships in the beginning. But because of the limitations of the natural coordinate scale, the log-linear attenuation and consolidation stage cannot be expressed properly. In double logarithmic coordinates, sedimentation curves can be expressed as in Fig. 2(b), from which three sedimentation stages can be defined, and the sedimentation attenuation stage is shown to have significant linear characteristics.

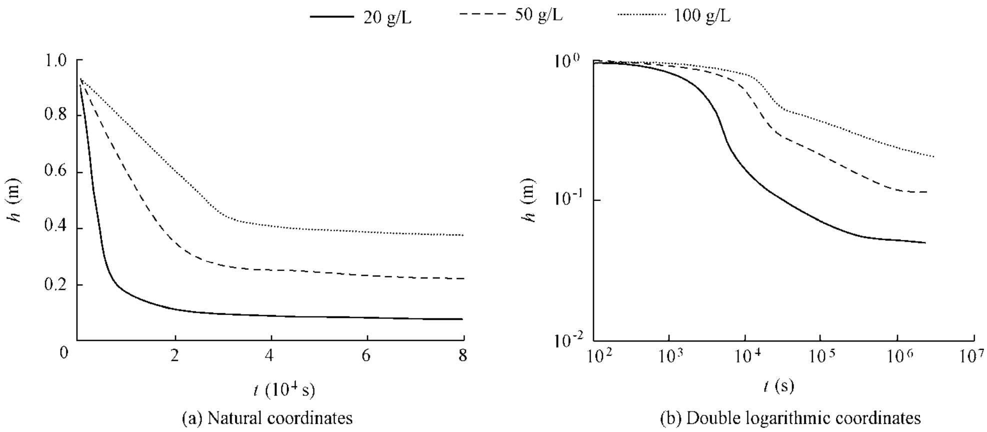


Fig. 2 Slurry sedimentation curves of reference soil with different concentrations in different coordinates

2.3 Sedimentation rate attenuation curves

According to the relationship between sedimentation height and time, settlement equations of different stages can be determined, and sedimentation rate attenuation curves can be obtained through the time differential method. The sedimentation rate is written as (Liu and Wang 2006)

$$v_i = -\frac{\Delta h}{\Delta t} = -\frac{h_i - h_{i-1}}{t_i - t_{i-1}} \tag{1}$$

where v_i is the sedimentation rate at time t_i, Δh is the difference of sedimentation height at different times, Δt is the time interval, and h_i is the sedimentation height at time t_i.

The sedimentation rates at different times can be evaluated and determined by Eq. (1), so the sedimentation rate attenuation curves responding to sedimentation height and time can be obtained in different coordinate systems (Fig. 3).

2.4 Discussion of sedimentation rate attenuation curves

(1) Sedimentation rate curve characteristics: Figs. 3(a) and (b) are the sedimentation rate attenuation curves responding to sedimentation height and time. The initial section in Fig. 3(b) is almost horizontal, which means that the sedimentation rate remains constant in the free sedimentation stage, and the constant values are associated with the initial concentration of slurry. When the sedimentation height reaches a certain limit, the sedimentation rate attenuates significantly. Fig. 3(c) shows that the sedimentation rate curves in double logarithmic

coordinates are two attached lines including the initial horizontal part and the subsequent log-linear part. The connection of the two parts is the turning limit.

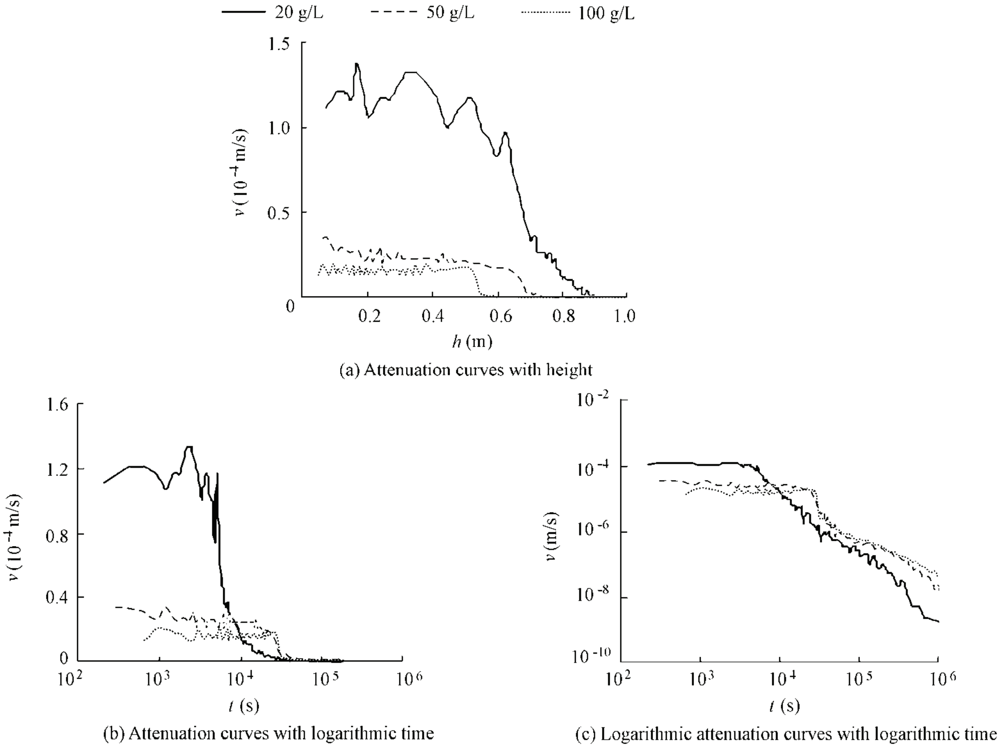


Fig. 3 Sedimentation rate attenuation curves with sedimentation height and time

(2) Relationships between sedimentation curves and control forces: Particle gravity is the control force in the free sedimentation stage, and the sedimentation rate remains constant when gravity equals the resistance effect. When the sedimentation height reaches a certain limit, flocculation will be fully developed. Therefore, equilibrium will be destroyed, and the resistance effect grows more significant, so the sedimentation rate continues to attenuate. Flocs are three-dimensional in microstructure and subject to fractal structure in micro-growth, so sedimentation rate attenuation relationships are double log-linear. Effective stresses begin to develop with the contact of particles, which means that the deposited soil reaches a final stable consolidation stage under gravity, and the sedimentation rate is almost zero.

(3) Fitting of sedimentation rate curves: Sedimentation rate curves in Fig. 3(c) are obviously piecewise linear. The settlement equation and equation parameters can be obtained by the fitting of the initial linear and subsequent log-linear parts.

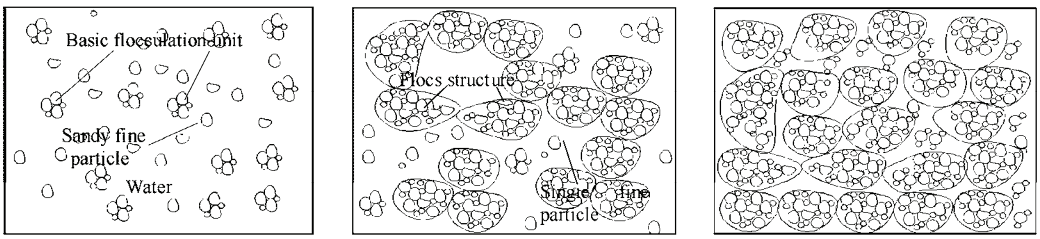
3 Process of establishing settlement equation

3.1 Definition of sedimentation stages

From the sedimentation curves in Fig. 2 and sedimentation rate attenuation curves in

Fig. 3, it can be seen that there are different sedimentation stages throughout the process of cohesive sedimentation. Therefore, the key is to determine the time limits. Three different sedimentation stages, the free sedimentation stage, the sedimentation rate log-linear attenuation stage, and the consolidation stage, can be determined according to the sedimentation curves in Fig. 2.

(1) Free sedimentation stage: The sedimentation curves of the free sedimentation stage are shown in Fig. 2(a). The main settlement materials of the stage are sandy particles and basic flocculation units. Particle states and structures are shown in Fig. 4(a). The sedimentation rate of large-size sandy particles is larger than others and follows Stokes' law of sedimentation rate, that is, the sedimentation rate remains proportional to the particle size. Sandy particles have little flocculation and concentrate at the bottom due to greater sedimentation rates. The sedimentation rate in Fig. 3 is the settlement rate of the slurry interface formed by fine particles except sandy particles. It is mainly determined by the sizes of fine particles and basic flocculation units and remains constant in the initial free sedimentation stage. Distances between particles are greater than the interaction distance, so there are no significant forces between particles. Flocculation occurs in the initial development state, and basic flocculation with a simple structure is formed, as shown in Fig. 4(a). Sedimentation rates of fine sandy particles and basic flocculation units determine the interface settlement rate. The end of the free sedimentation stage is defined as the first time limit t_0. For the case $t < t_0$, it is in the free sedimentation stage and the sedimentation rate remains constant.



(a) Free sedimentation stage (b) Log-linear attenuation stage (c) Consolidation stage

Fig. 4 Particle state and structure in different sedimentation stages

(2) Log-linear attenuation stage: With ongoing settlement, distances between single particles and basic flocculation units get smaller, leading to full flocculation development. Flocs with a large size are formed at this time, and connections between flocs appear, as shown in Fig. 4(b). With the formation and connections of large amounts of flocs, integrated flocs with loose structures come into being: this is the second log-linear stage. Many studies (Yang et al. 2003b) have shown that cohesive sediment aggregates or flocs exhibit fractal properties and form greater flocs with a constant fractal dimension. This is why the sedimentation rate maintains log-linear attenuation. Due to the loose structure of the formed flocs, there is no effective stress. When the distances between particles come to a limit, the effective stress begins to appear, and this time boundary point for the consolidation stage is

defined as t_1.

(3) Consolidation stage: With the slurry interface decreasing, the average void ratio of the cohesive sediment decreases to about 12.0, the effective stress passing in the network forms, and the slurry develops into consolidation, as shown in Fig. 4(c). In the consolidation process, the excessive pore water pressure is dissipated and the effective stress begins to work, and the applicable settlement theory applied here is the consolidation theory. The consolidation stage is very slow, and the sedimentation rate is almost zero. When the excessive pore pressure is totally dissipated, the consolidation stage is over. The sedimentation curves of the consolidation stage are shown in Fig. 5.

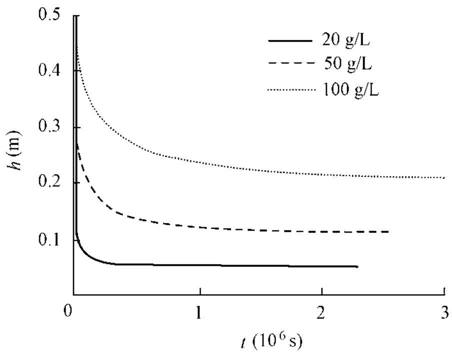


Fig. 5 Sedimentation curves of consolidation stage

3.2 Settlement equations of different stages

(1) Free sedimentation equation: The sedimentation rate remains constant in the initial free sedimentation stage, and the relationship between the sedimentation rate v and the sedimentation height h is as follows:

$$v = -\mathrm{d}h/\mathrm{d}t \tag{2}$$

The initial free sedimentation governing equation (Eq. (3)) can be obtained by integration of t in Eq. (2) from 0 to t as follows:

$$h = \int_0^t v\mathrm{d}t = h_0 - v_c t \tag{3}$$

where h_0 is the initial sedimentation height, and v_c is the constant free sedimentation rate.

(2) Log-linear sedimentation equation: There are apparent log-linear parts on the sedimentation rate attenuation curves in Fig. 3(c). The log-linear equation of the sedimentation rate can be established by fitting the linear parts. The log-linear equation is

$$\lg v = R \lg t + b \tag{4}$$

where R and b are the log-linear parameters.

The log-linear governing equation can be found by integration of t from t_0 to t:

$$h(t) = \frac{10^b}{R+1}\left(t_0^{R+1} - t^{R+1}\right) + C \tag{5}$$

Substituting Eq. (3) into Eq. (5) yields the constant C in Eq. (5) after mathematical derivation:

$$C = h_0 - v_c t_0 \tag{6}$$

Substituting Eq. (6) into Eq. (5) yields the final log-linear sedimentation equation:

$$h = \frac{10^b}{R+1}\left(t_0^{R+1} - t^{R+1}\right) + h_0 - v_c t_0 \tag{7}$$

(3) Consolidation sedimentation equation: The sedimentation rate is almost zero, so it is not accurate by integrating the sedimentation rate to establish the sedimentation equation. The consolidation sedimentation equation can be built according to the characteristics of consolidation curves. Consolidation curves can be modified by hyperbolas, and the two variables are the sedimentation height and the time increment. The consolidation sedimentation equation is

$$h_s - h = \frac{t - t_1}{p(t - t_1) + q} \tag{8}$$

where h_s is the solid height; and *p* and *q* are the hyperbolic parameters, which can be given and determined from the consolidation sedimentation curves in Fig. 5.

After the sedimentation equations of the three stages are determined, the subsequent key is the determination of the equation parameters. Sedimentation equation parameters include the sedimentation rate of the initial free stage v_c, the fluid-limit time t_0, the solid-limit time t_1, the log-linear parameters *R* and *b*, and the hyperbolic parameters *p* and *q*. These seven independent parameters can be determined by the settlement column test, physical properties of soil, and initial concentration. After the determination of these parameters, a whole settlement prediction model will be set up based on soil properties.

3.3 Determination of sedimentation equation parameters

(1) Determination of fluid height and solid height: The interaction force between particles keeps developing with the decrease of particle distance, so there are certain relationships between the sedimentation height, interaction degree, and void ratio. Monte and Krizek (1976) first introduced the concept of fluid limit, which means that the shear stress is zero. In this situation, it is reasonable to define the fluid moisture content and fluid void ratio. With the concept of the fluid void ratio, the corresponding fluid height can be defined, i.e., the connection point of the free sedimentation stage and log-linear attenuation stage. Carrier (1983) proposed that there are constant multiple relationships between the initial void ratio and liquid-limit void ratio. The initial void ratio of different soil has been shown to be from 9 to 30 through many different experiments, and the relationship between the initial void ratio and liquid-limit void ratio is

$$e_i = 7e_L = 7G_s\omega_L \tag{9}$$

where e_i is the initial void ratio, and e_L is the liquid-limit void ratio.

Similarly, the solid void ratio concept can also be proposed for the log-linear attenuation stage and consolidation stage. If $e(t) > e_s$, where $e(t)$ is the void ratio at time *t*, there are no contacts between particles, and the electrostatic force is repulsive; otherwise, if $e(t) < e_s$, the effective stress begins to develop when the bound water coincides, and the main electrostatic force is gravitational. The fluid void ratio and solid void ratio are larger than the liquid-limit void ratio, and they can be expressed as the multiples of liquid-limit void ratio:

$$e_{\mathrm{f}} = fG_{\mathrm{s}}\omega_{\mathrm{L}}\ ,\ e_{\mathrm{s}} = sG_{\mathrm{s}}\omega_{\mathrm{L}} \tag{10}$$

where e_{f} and e_{s} are the fluid void ratio and solid void ratio, respectively, and *f* and *s* are the scale factors of fluid void ratio and solid void ratio to liquid-limit void ratio, respectively.

According to the relationships between the statistical scale factors of the fluid, solid, and liquid-limit void ratios based on settlement column experiments, final results are obtained as shown in Fig. 6, where *n* is the number of statistical soil samples.

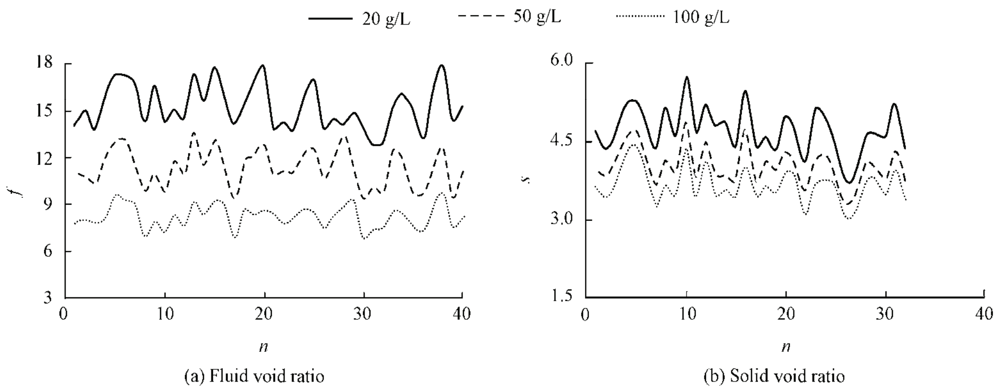


Fig. 6 Statistics of scale factors of fluid and solid void ratios

Figs. 6(a) and (b) show that the scale factors of the fluid and solid void ratios with the same initial concentration almost remain constant. However, there is a significant difference for different concentrations, which means that the scale factors rely on concentration and are not constant, yielding this equation for the scale factors and concentration:

$$f_{\alpha} = f_{1.0}\alpha^{-0.4},\ s_{\alpha} = s_{1.0}\alpha^{-0.144} \tag{11}$$

where α is the ratio of objective to reference (100 g/L) concentrations; f_{α} and s_{α} are fluid and solid scale factors of objective concentration, respectively; and $f_{1.0}$ and $s_{1.0}$ are fluid and solid scale factors of the reference concentration, respectively. The statistical results of scale factors in Figs. 6(a) and (b) give $f_{1.0} = 8.2$ and $s_{1.0} = 3.5$. The combination of Eqs. (10) and (11) yields the fluid and solid heights $h_{\mathrm{f}\alpha}$ and $h_{\mathrm{s}\alpha}$:

$$h_{\mathrm{f}\alpha} = \left(e_{\mathrm{f}\alpha} + 1\right)\xi\ ,\ h_{\mathrm{s}\alpha} = \left(e_{\mathrm{s}\alpha} + 1\right)\xi \tag{12}$$

where ξ is the material height, which can be derived from the initial concentration n_0 and initial height h_0 :

$$\xi = n_0 h_0 \big/ \left(G_{\mathrm{s}}\rho_{\mathrm{w}}\right) \tag{13}$$

where ρ_{w} is the density of water.

(2) Free sedimentation rate and fluid-limit time: The sedimentation rate of the initial free stage relies on the clay content and initial concentration. It is reasonable to obtain functional relationships between objective and reference concentrations for the same soil, and thus,

$$v_\alpha = v_{1.0}\alpha^{-0.23/\alpha-0.07} \tag{14}$$

where v_α is the sedimentation rate of objective concentration, and $v_{1.0}$ is the sedimentation rate of reference concentration.

Substituting Eq. (14) into Eq. (3) yields the free sedimentation stage lasting time t_0:

$$t_0 = \left(h_0 - h_{\mathrm{f}\alpha}\right)/v_\alpha \tag{15}$$

(3) Log-linear parameters and solid-limit time: There are functional relationships between log-linear parameters and initial concentrations for the same soil sample. According to the settlement column test results, fitting equations of log-linear parameters can be derived based on reference concentrations. The log-linear parameter-fitting equation is as follows:

$$R_\alpha = R_{1.0}\alpha^{-0.33} \tag{16}$$

where R_α is the slope of the logarithmic line of soil with the objective concentration, and $R_{1.0}$ is the slope of the logarithmic line with reference concentration .

$$b_\alpha = 1.964\,5\ln\alpha + 2.3 + 0.02/\alpha \tag{17}$$

where b_α is the intercept of the logarithmic line of sedimentation rate of the objective concentration.

The solid-limit time t_1 is the boundary point between the log-linear attenuation stage and consolidation stage. Substituting the solid height in Eq. (12) into Eq. (7) yields solid-limit time t_1:

$$t_1 = \left[t_0^{R_\alpha+1} - \frac{\left(h_{\mathrm{f}\alpha} - h_{\mathrm{s}\alpha}\right)\left(R_\alpha + 1\right)}{10^{b_\alpha}}\right]^{\frac{1}{R_\alpha+1}} \tag{18}$$

(4) Hyperbolic parameters p and q of consolidation stage: Hyperbolic parameters can be determined by consolidation curve characteristics. Through the curve-fitting process, hyperbolic parameters can be derived based on the concentration ratio and solid-limit time t_1:

$$p_\alpha = 40/\alpha,\ q_\alpha = t_1^{1.2} \tag{19}$$

where p_α and q_α are the hyperbolic parameters of the objective concentration.

Substituting Eq. (19) into Eq. (8) yields the governing equation of the consolidation stage:

$$h_{\mathrm{s}\alpha} - h = \frac{1}{40/\alpha + t_1^{1.2}/\left(t - t_1\right)} \tag{20}$$

4 Settlement prediction model of slurry suspension

4.1 Modeling process

After establishment of the settlement governing equations of different stages, and based on the fact that governing equation parameters can be determined by the relationship between the objective and reference concentrations, a whole prediction model for slurry suspension settlement has been built. The keys of the model are (1) establishment of sedimentation governing equations for different stages, and (2) determination of governing equation parameters. The modeling process is shown in Fig. 7.

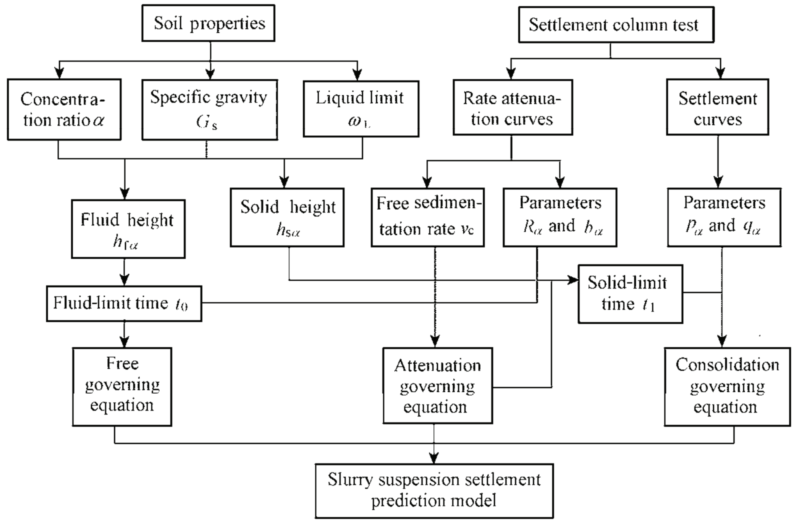


Fig. 7 Sedimentation prediction modeling process

According to the modeling process in Fig. 7, a slurry suspension sedimentation prediction model can be set up based on basic soil physical properties and settlement column experiments of reference concentration. The sedimentation governing equations for a fixed soil are as follows:

$$h=\begin{cases} h_0 - v_{1.0}\alpha^{-0.23/\alpha-0.07}t & 0<t\le t_0 \\ h_{f\alpha} - 10^{b_\alpha}\left(t_0^{R_\alpha+1}-t^{R_\alpha+1}\right)\Big/\left(R_\alpha+1\right) & t_0<t\le t_1 \\ h_{s\alpha} - 1\Big/\left[40/\alpha + t_1^{1.2}/\left(t-t_1\right)\right] & t>t_1 \end{cases} \tag{21}$$

where the fluid-limit time t_0, solid-limit time t_1, fluid height $h_{f\alpha}$, and solid height $h_{s\alpha}$ are expressed as

$$\begin{cases} t_0=\left(h_0-h_{f\alpha}\right)/v_\alpha \\ t_1=\left[t_0^{R_\alpha+1}-\left(h_{f\alpha}-h_{s\alpha}\right)\left(R_\alpha+1\right)/10^{b_\alpha}\right]^{\frac{1}{R_\alpha+1}} \\ h_{f\alpha}=\left(e_{f\alpha}+1\right)n_0h_0/\left(G_s\rho_w\right) \\ h_{s\alpha}=\left(e_{s\alpha}+1\right)n_0h_0/\left(G_s\rho_w\right) \end{cases} \tag{22}$$

The log-linear attenuation parameters of the sedimentation rate can be determined by Eqs. (16) and (17). The governing equation parameters can be obtained by soil properties, which means that the settlement process can be predicted beforehand.

4.2 Prediction model performance

In order to verify the reliability and accuracy of the prediction model, reference soil properties were taken as the model input, and the settlement process was verified with different concentrations. The model parameters with different concentrations are listed in Table 1, where C' is the concentration.

Table 1 Model parameters of objective concentration

C' (g/L)	α	v_c (mm/d)	$h_{f\alpha}$ (m)	$h_{s\alpha}$ (m)	t_0 (s)	t_1 (s)	Log-linear parameters		Consolidation parameters	
							R_α	b_α	p_α	q_α
20	0.2	10 060	0.157	0.049	6 813	21 826	−1.884 9	5.561 7	200	160 978
30	0.3	3 866	0.201	0.070	16 727	375 196	−1.648 8	4.731 9	133	4 887 766
40	0.4	2 550	0.241	0.091	24 027	742 259	−1.499 5	4.150 1	100	11 083 236
50	0.5	2 039	0.277	0.110	28 522	830 946	−1.393 0	3.701 7	80	12 690 756
60	0.6	1 780	0.310	0.129	31 045	925 893	−1.311 7	3.336 9	67	14 450 166
80	0.8	1 529	0.372	0.167	32 659	1 280 360	−1.192 9	2.763 4	50	21 320 556
100	1.0	1 412	0.428	0.203	31 929	1 937 133	−1.108 2	2.320 0	40	35 042 204
120	1.2	1 346	0.481	0.238	30 124	3 037 233	−1.043 5	1.958 5	33	60 113 743
150	1.5	1 290	0.554	0.290	26 532	5 942 000	−0.969 4	1.516 8	27	134 499 048

After the determination of the model parameters and initial input in the governing equations, slurry sedimentation prediction curves can be given based on the model output. Sedimentation curves with different concentrations are shown in Fig. 8. Prediction model outputs shown in Fig. 8 successfully reflect basic characteristics of the slurry suspension settlement process, compared with the settlement curves obtained from settlement column experiments described in Fig. 2. If applied to practical engineering, the sedimentation height at any time can be determined effectively. Thus, the settlement lasting time, consolidation degree, and sediment concentration can also be predicted and given reasonably.

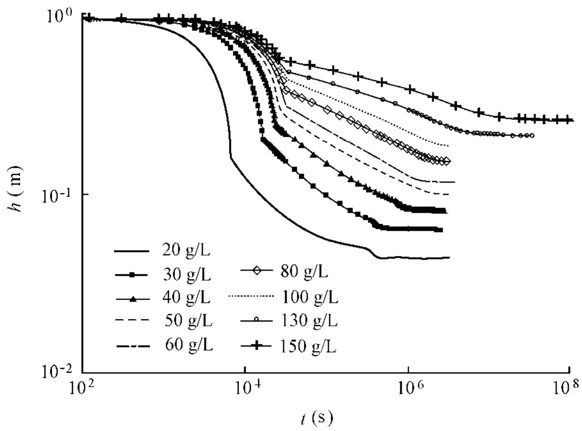


Fig. 8 Settlement prediction curves with different objective concentrations

The reference concentration here is 100 g/L, and it is more accurate when the objective concentration is close to the reference concentration, which can also be reflected in Fig. 3. Moreover, the model prediction results are sensitive to some model parameters, and there are many limitations for the whole sedimentation stage simulation, especially for the turning point, so the determination of applicable model parameters needs to be improved in future research.

Slurry suspension is fully mixed beforehand, and there is a high degree of random variability in the initial settlement process for the flocculation effect. As slurry sedimentation is very sensitive to the external disturbance factors, the prediction model developed in this study merely simplified some features rather than all the random factors.

5 Conclusions

(1) Three sedimentation stages, the initial free sedimentation stage, the log-linear attenuation stage, and the consolidation stage, of the whole slurry suspension settlement process were defined by the characteristics of sedimentation rate curves. Boundary indicators were expressed by the fluid void ratio and solid void ratio and the corresponding fluid height and solid height. It was found that there are constant multiple relationships between the fluid void ratio, solid void ratio, and liquid-limit void ratio.

(2) Stokes' law for the sedimentation rate of a single particle is applicable to sand soil but not to cohesive sediment, and it is necessary to research the influences of flocculation on the sedimentation rate. The evaluation formula of the interface sedimentation rate also needs to be more deeply discussed.

(3) There are apparent segmentations on the double logarithmic sedimentation rate curves, and the settlement governing equations of the first two sedimentation stages were set by integration of the sedimentation rate. Equation parameters were determined by the physical properties of soil, and then a settlement prediction model was built based on the physical properties of soil and parameters from settlement column experiments of the reference concentration.

(4) The settlement prediction model shows a high degree of sensitivity to certain model parameters, and some parameters need modification, which will affect the prediction results. Sensitive parameters, such as the slope and intercept of the logarithmic line, must be determined by a series of different settlement column experiments, in order to obtain the most applicable parameters. The settlement prediction model can give a reasonable output of different objective concentrations, especially near the reference concentration. Improvements can be made on the selection of a reference concentration and the determination of model parameters.

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