KSCE Journal of Civil Engineering (2024) 28(2):596-608
DOI 10.1007/s12205-023-2353-5

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Geotechnical Engineering

Experimental Study on the Migration and Clogging of Fine Particles in Coarse-Grained Soil with Seepage

Tao He[a,b], Haitao Mao[a], Chao Zhang[b], Yi Gu[b], and Bin Yang[a]

[a]College of Urban and Rural Construction, Shanxi Agricultural University, Jinzhong 030600, China
[b]School of Civil Engineering, Chongqing Three Gorges University, Chongqing 404120, China

ARTICLE HISTORY

Received 10 December 2022
Accepted 16 October 2023
Published Online 28 December 2023

KEYWORDS

Coarse-grained soil
Particle size ratio
Migration mode
Clogging

ABSTRACT

The migration and clogging of fine particles in the pores of coarse-grained soil with seepage is of great significance to reduce the leakage of soil at the dam base and lower the permeability of soil. Therefore, the homemade infiltration test device was used to test the infiltration and clogging of soil samples with different particle size ratios D_{15}/d_{85} (D_{15} represents the particle size corresponding to the cumulative percentage content of soil particles smaller than a certain particle size in the coarse particles which is 15%, and d_{85} represents the particle size corresponding to the cumulative percentage content of soil particles smaller than a certain particle size in the fine particles group which is 85%). The factors affecting the deposition of fine particles in coarse-grained soil and the characteristics of fine particle migration and penetration were analyzed. The clogging of coarse-grained soil, hydraulic gradient and pore changes characteristics before and after clogging were studied. The results show that: 1) The main factor affecting the retention of fine particles in coarse-grained soil is the particle size ratio, and the retention rules conforms to the Peak-Gauss function relationship. The penetration law of fine particles satisfies the Logistic function relationship, which can directly predict the internal clogging of coarse-grained soil. 2) The particle size ratio is the main factor affecting the blockage in each mode, followed by the influence of the water head, When the particle size ratio is less than 13.10, the clogging ratio decreases with the increase of particle size ratio, and the hydraulic gradient increases with the increase of particle size ratio. When is greater than 13.10, the clogging ratio increases with the increase of particle size ratio, and the hydraulic gradient decreases with the increase of particle size ratio. 3) The degree of clogging in coarse-grained soil is closely related to the change in porosityand and can be judged according to the change of porosity in coarse-grained soil. The research results deepen the understanding of fine particle migration on the rules of coarse-grained soil clogging and can provide a theoretical basis for related engineering applications.

1. Introduction

The complex system composed of a solid skeleton and pore space divided by the skeleton is called a porous medium (Abdelkader and Sharqawy, 2022). Coarse-grained soil is considered a typical porous medium because it contains many interconnected pores. The migration of fine particles in pores with seepage can involve many engineering fields.Particle transport plays a positive role in some working conditions, such as clogging the soil pores in the dam foundation, which can reduce the seepage problem of the dam foundation soil, and sediment deposition can improve the seepage prevention effect of the dam foundation (Cao et al., 2019). In contrast, particle migration will also cause adverse effects, such as the loss of fine particles from the seepage, causing erosion in the soil, leading to the piping effect, and particle loss in slope engineering, leading to landslides (Guo and Cui, 2017; Luo et al., 2022). Therefore, the study of particle migration in coarse-grained soil is of great significance for the safe operation of hydraulic structures.

Physical clogging caused by particle migration is affected by

CORRESPONDENCE Haitao Mao maohaitao1234@163.com College of Urban and Rural Construction, Shanxi Agricultural University, Jinzhong 030600, China

many factors, such as the particle size and concentration of suspended particles, particle size of coarse-grained soil, and fluid velocity. The main factors can be attributed to geometric (Aboufoul and Garcia, 2017) and hydraulic conditions (Kim et al., 2010). The geometric conditions provide pore channels for particle migration, while the hydraulic conditions provide water power for particle migration. For the study of geometric conditions, it has been considered that the pore structure of soil is one of the main factors affecting particle migration, and its internal channels usually exhibit high curvature and large diameter changes and are connected with each other (Kia et al., 2017). When the pore size of the skeleton composed of coarse particles is larger than that of fine particles, migration will occur (Xiao and Shwiyhat, 2012). Due to the heterogeneity and complexity of the soil particle distribution, it is difficult to select appropriate parameters to quantitatively describe the pore size and distribution in the study. Scholars at home and abroad have conducted much research on the selection of appropriate parameters. Yousif et al. (2017) used the particle size ratio D_{15}/d_{85} (D_{15} represents the particle size corresponding to the cumulative percentage content of soil particles smaller than a certain particle size in the coarse particles which is 15%, and d_{85} represents the particle size corresponding to the cumulative percentage content of soil particles smaller than a certain particle size in the fine particles group which is 85%) as the parameter to study the physical clogging of uniformly graded porous media under a constant flow rate. The particle size ratio D_{15}/d_{85} has a great influence on the physical silting of porous media, and the larger the size is, the less likely it is to produce silting. Yao et al. (2016) studied the influence of particle size on the development of the piping effect and pointed out that when the particle size ratio D_{15}/d_{85} is 6, the self-filtration phenomenon will occur in the soil at this time, so that the soil system has the self-stability ability. Garcia et al. (2019) found that pore diameter is the main factor affecting particle migration through seepage and silting tests of asphalt mixtures. For the study of hydraulic conditions, most of them take the flow rate as the index. Alem et al. (2013) studied the physical silting of porous media at different flow rates and found that the suspended particles are mainly deposited on the surface of the media at low flow rates, and the depth of particles entering the porous media increases with it at high flow rates. Chen et al. (2012) studied the migration and deposition characteristics of suspended particles in saturated porous media through soil column tests and found that under a certain concentration of suspended particles, the relative concentration of suspended particles in the penetration curve also increases with increasing seepage velocity.

Therefore, in order to fully understand the migration law of fine particles in coarse-grained soil. In this paper, a self-made penetration test device is used and based on previous research experience, different particle size ratios are set according to D_{15}/d_{85}, and the migration, clogging and deposition rules of fine particles in coarse-grained soil are analyzed under different water heads to provide a reference for further study of the silting mechanism and stability analysis of coarse-grained soil.

2. Materials and Methods

2.1 Experimental Material

2.1.1 Coarse Particle Characteristics

In the study of coarse-grained soil, 1 mm is usually selected as the dividing point between coarse and fine particles (Zhu et al., 2021). To easily observe the experimental phenomenon in the indoor test and ensure the connectivity of pores, Fig. 1(a) illustrates spherical quartz sand as the filled coarse-grained soil in this test. The screening test is divided into four types according to the particle size, and the particle size is divided into 4 – 5 mm, 5 – 6 mm, 6 – 7 mm and 7 – 8 mm. The dry density, initial porosity and initial permeability coefficient are measured by the drainage method (the sample is vibrated and compacted during loading) and constant head permeability coefficient test. The basic parameters are shown in Table 1.

2.1.2 Fine Particle Characteristics

Figure 1(b) shows the displays of fine particles consisting of glass sand with an irregular granular shape and dry density $\rho_d = 2.48 - 2.59\ g \cdot cm^{-3}$, which can be rapidly deposited in still water and separated from water. The fine particles are divided into 4 groups according to the size of the characteristic particle diameter d_{85}. The gradation curves of each group are shown in Fig. 2 and the Table 2 shows the relevant physical parameters of fine particles measured by conventional geotechnical tests.

Table 2 shows that the d_{85} values of the four particle sizes are 0.721 mm, 0.546 mm, 0.417 mm and 0.316 mm from large to small, which are all greater than 0.030 mm. Therefore, the

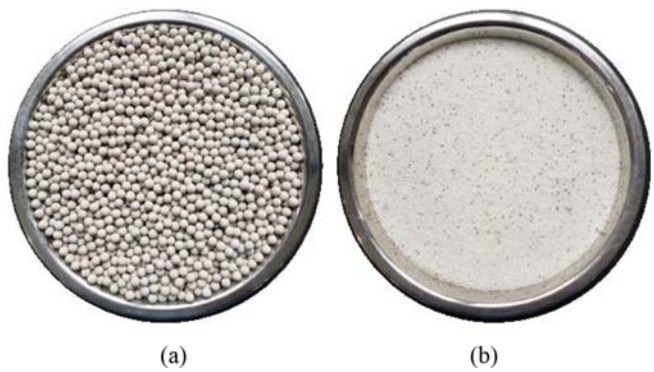

Fig. 1. Experimental Materials: (a) Coarse Particles, (b) Fine Particles

Table 1. Physical Parameters of Clogged Coarse Particles

Particle size/mm	D_{15}/mm	Dry density/ ($g \cdot cm^{-3}$)	Original Porosity n_0	Permeability coefficient
4 – 5	4.15	2.59	0.445	10.49
5 – 6	5.15	2.38	0.441	11.62
6 – 7	6.15	2.48	0.455	12.23
7 – 8	7.15	2.31	0.462	13.44

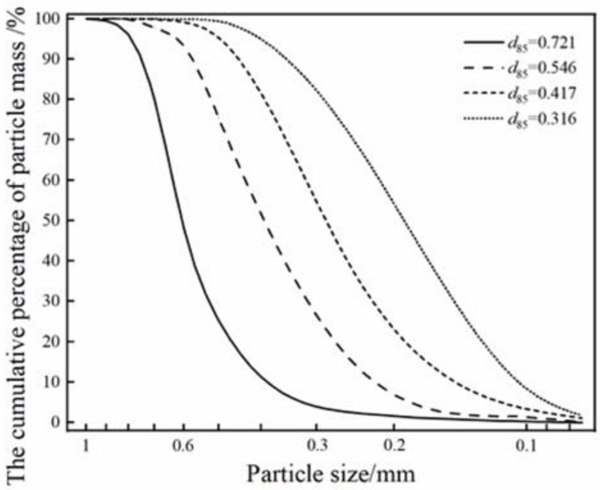

Fig. 2. Fine Particle Size Distribution of Materials

Table 2. Physical Parameters of Clogged Fine Particles

d_{85}/mm	Inhomogeneity coefficient	Curvature coefficient	Dry density /(g·cm^{-3})	Permeabilitycoef-ficient/(cm·s^{-1})
0.721	1.63	1.12	2.59	9.6×10^{-2}
0.546	1.96	1.02	2.54	6.7×10^{-2}
0.417	2.18	1.09	2.50	5.8×10^{-2}
0.316	2.07	0.95	2.48	3.1×10^{-2}

Table 3. Particle Size Ratio of Coarse to Fine (D_{15}/d_{85})

d_{85}/mm	D_{15}/mm			
	4.15	5.15	6.15	7.15
0.721	5.76	7.14	8.53	9.92
0.546	7.60	9.43	11.26	13.10
0.417	9.95	12.35	14.75	17.15
0.316	13.13	16.29	19.46	22.63

Brownian motion effect of the particles and the electrostatic interaction between the particles can be ignored (Zamani and Maini, 2009). In addition, the nonuniformity coefficient is less than 5, the particle size distribution is relatively uniform, and the selected particle size is representative.

2.2 Testing Method

2.2.1 Test Scheme

Table 3 shows the different particle size ratios for the test setup. In this test, 16 groups of soil column tests with different particle size ratios are set. Three different water heads (0.5 0.9 and 1.20 m) are set in each group of tests to observe the fine particle migration and sedimentation rules of each group of tests under different water heads and particle size ratios. Among them, three different water heads were used under the condition of 16 particle size ratios, and a total of 48 sets of test series were carried out.

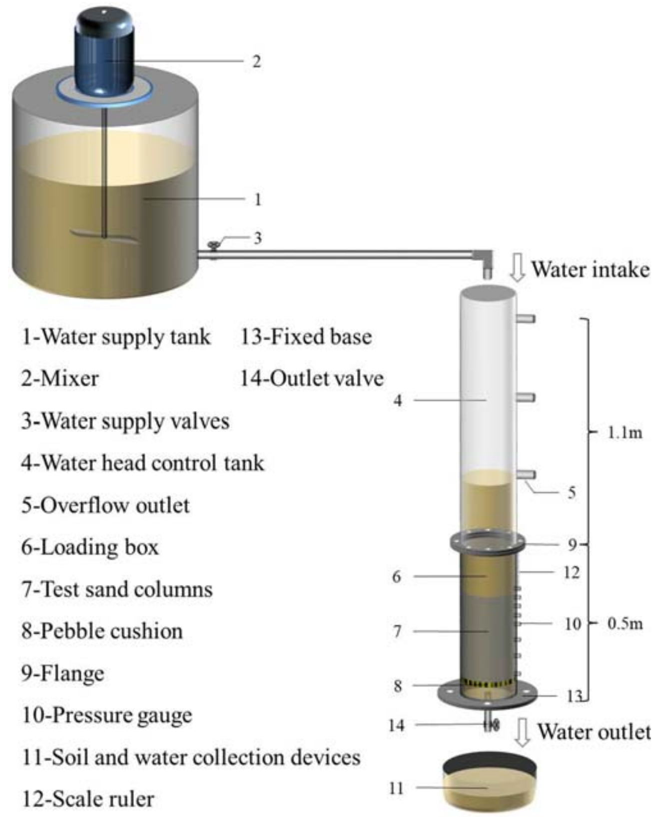

Fig. 3. Experimental Device

2.2.2 Test Apparatus

The device refers to the laboratory constant head permeability coefficient test (Li et al., 2013) and has been slightly adjusted on this basis. According to the Standard For Soil Test Methods (GB/T50123-2019), the diameter of the penetration test instrument should be 10 times the maximum particle diameter of the sample. As shown in Fig. 3, the test device is a plexiglass drum, which is divided into three parts: a water supply tank, a water head control tank and a sample loading tank.

To avoid the influence of human factors on the materials, the fine particles to be put in should be mixed uniformly at a concentration of 10% (the concentration is actually the volume sediment content, i.e., the mass of sediment per unit volume, g·cm^{-3}) by mixing, and the water supply tank was used to prepare muddy water for the infiltration supplement of the test. The head control box had a diameter of 0.14 m and a height of 1.1 m. The box body is provided with three overflow outlets, and the spacing between the box body and the top of the sample is 0.5 m, 0.9 m and 1.2 m, which is used to control the height of the test infiltration water head. The size of the sample box is 1.40 m in inner diameter and 0.5 m in height. The bottom is the water outlet. The metal mesh at the bottom of the sample can support the sample to ensure that the sample particles will not be lost. Eight pressure measuring holes are set outside the loading box to divide the soil into seven layers. The thickness of each layer of the first four layers is 0.02 m, and the thickness of each layer of the last three layers is 0.04 m. Pressure measuring pipes are connected externally to monitor the changes in pore water pressure at different depths of the soil samples during the test.

A 0.03 m thick pebble is set on the metal net at the bottom of the sample to prevent the influence of bottom silting on the test. A water outlet and a water and soil collection device are set at the bottom of the sample box to collect the water and fine particles exuded during the test. A scale with a 0 scale starting from the top surface of the soil sample is pasted on the outside of the loading box to record the thickness of the sediment layer formed on the surface of the soil sample during the test.

2.2.3 Test Procedure

Before the experiment, the impurities on the surface of spherical quartz sand were washed with water, dried at 105°C for 24 hours, and then loaded into the sample box after screening. Before loading, Vaseline should be evenly applied on the inner wall of the loading box (Zhu et al., 2021) to reduce the influence of the boundary effect on seepage. To ensure that the sample is always saturated, the layered loading method is adopted to load the sample. The sand column is filled seven times. The water surface is 0.01 – 0.02 m higher than the top surface of the sample during each filling, and tamping and bubble removal are carried out. At the same time, tamping is carried out for the same times for each layer to ensure the uniformity of the sample.

During the test, first open the water supply valve, control the water level to reach the preset height and keep it stable, then rotate the knob of the water outlet valve to the fixed position, and use the measuring cylinder to measure the seepage flow twice. When the two consecutive times are the same, the seepage flow is stable. The preprepared fine particles were placed into the water supply tank, and the stirrer was used to fully stir the fine particles to evenly infiltrate the water flow. During the test, the exudate liquid Volume Q was measured every 30 s, and the reading $H_{(t)}$ of each piezometer was read. During the test, the water flow carries fine particles from the top of the device and flows out from the outlet at the bottom of the device after flowing through the coarse-grained soil sample. The test can be completed when the seepage flow in the adjacent time period measured at the outlet remains relatively stable.

After the test, the water in the device was slowly discharged, and the soil samples were excavated in layers after standing for 24 h. After water screening, the soil samples were dried, and the screening test was carried out to obtain the quality of fine particles retained in the soil samples of each layer after the test.

3. Test Results

3.1 Description of the Seepage Process

It is found that with the increase in particle size ratio, there are obvious differences in the seepage process of fine particles in coarse-grained soil. The particle size ratio (7.14, 11.26, 14.75, 19.46) corresponding to each representative working condition (hereafter referred to as working Condition 1, working Condition 2, working Condition 3 and working Condition 4) is selected as the research object. The migration and deposition process of fine particles in coarse-grained soil under each working condition is shown in Fig. 4.

Working Condition 1: As shown in Fig. 4(a), in the first 6 min, fine particles gradually migrated to the interior of coarse-grained soil with seepage. Fine particles were mainly silted up at the upper part and gradually blocked the downward path of fine

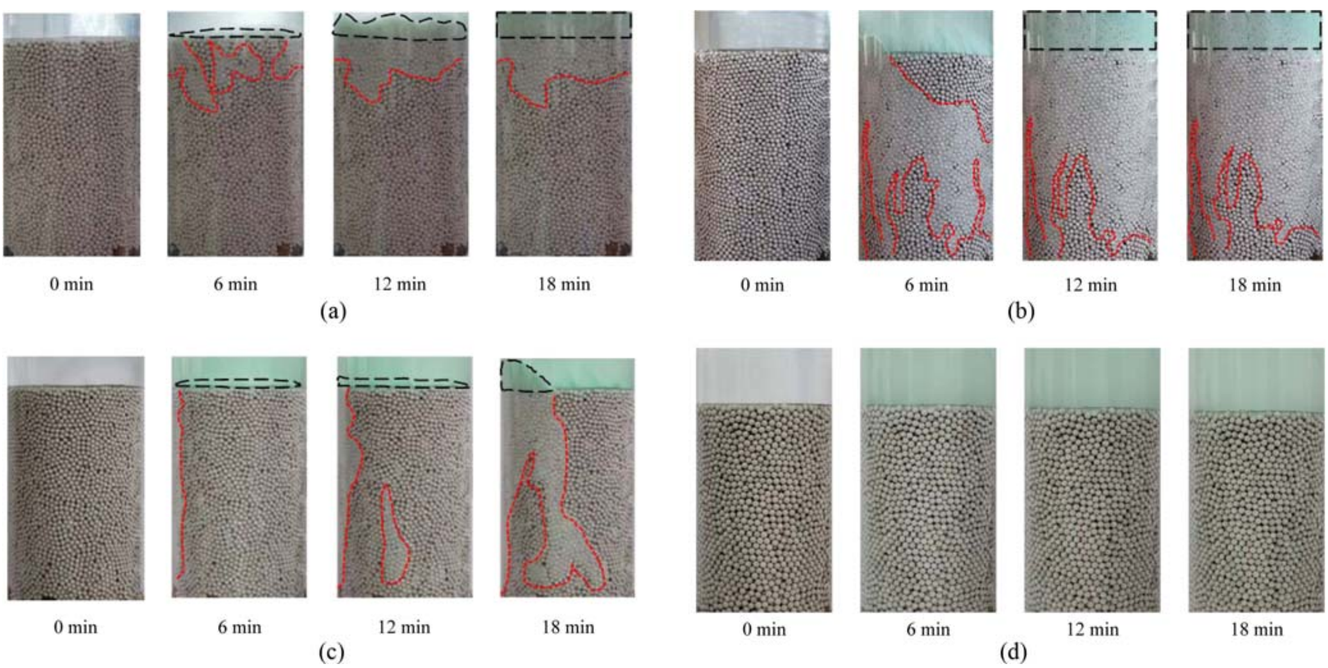

Fig. 4. Fine Particle Migration Process: (a) Working Condition 1, (b) Working Condition 2, (c) Working Condition 3, (d) Working Condition 4

particles. At 12 min and 18 min, fine particles filled the 2 cm range of the upper part of coarse-grained soil, completely blocking the downward migration channel of fine particles. Fine particles in water can only accumulate on the top of coarse-grained soil, with obvious vertical anisotropy. Gibson et al. (2009) also found that the smaller the particle size ratio is, the more surface layer accumulates. In this stage, fine particles mainly accumulate on the surface of coarse-grained soil, and this stage is called surface sedimentation clogging.

Under working Condition 2, as shown in Fig. 4(b), compared with working Condition 1, fine particles could enter all positions of coarse-grained soil in the first 6 min, and sedimentation and clogging extended from the bottom to the top. Although there was a fine particle deposition layer on top of the coarse-grained soil, the fine particles continued to move downward under the action of the water head. From 6 – 18 min, the overall filling rate of the coarse-grained soil increased from 61% to 82%, the upper sediment layer of the coarse-grained soil became thicker, and the water head effect failed. Therefore, it can be considered that internal sedimentation clogging (Ye et al., 2019) played a major role.

Under working Condition 3, as shown in Fig. 4(c), the test phenomenon changed dramatically. In the first 12 min, most of the fine particles migrated freely and were lost with the seepage force, and all of them were stagnated due to the poor connectivity of pores. There was no fine particle deposition on the top of coarse-grained soil. At 18 min, except for the internal and top clogging caused by poor pore connectivity, the fine particles in other parts were lost. Under this working condition, it can be considered that the fine particles had undergone transient deposition clogging (Wang et al., 2012). After that, with a further increase in the particle size ratio, the fine particles mainly migrated freely. At this time, it was more likely to be scoured by the water flow, and the deposited fine particles gradually reached complete loss. In this stage, the deposition of fine particles under the action of the water head was extremely unstable and gradually tends to be dominated by loss, which is called transient deposition clogging.

Under working Condition 4, as shown in Fig. 4(d), with a further increase in the particle size ratio, no fine particles were deposited in each time period. At this time, fine particles were mainly lost and gradually reached complete loss. This stage can be called freely migration loss.

3.2 Migration Laws of Fine Particles

3.2.1 Sedimentation Laws of Fine Particles

After the test, calculate the fine particle retention rate under different particle size ratios according to the stratified sampling results, and the expression is Eq. (1):

$$m^* = \frac{m_1}{M} \times 100\% \tag{1}$$

M = Total mass of the input particles (g)

m_1 = Fine particle mass deposited in coarse-grained soil (g)

The retention relationship of fine particles in coarse-grained

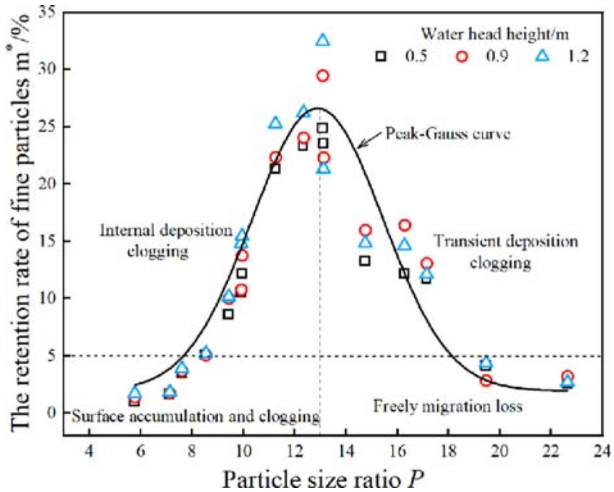

Fig. 5. Results of the Particle Retention Rate

soil under different particle size ratios and water heads is calculated by Eq. (1), as shown in Fig. 5.

From Fig. 5, it can be seen that the retention rate of fine particles in the early stage increased with increasing particle size ratio, indicating that the degree of silting in coarse-grained soil gradually increases and peaks. Then, with the increase in the particle size ratio, the fine particle retention gradually decreased and tended to 0. At the same time, before the peak value, the higher the water head was, the greater the fine particle retention, whereas the higher the water head was, the smaller the fine particle retention. Fitting the relationship between the fine particle retention rate and particle size ratio under various operating conditions, the comprehensive rule under each operating condition basically conforms to the peak-Gauss function relationship, and its expression is Eq. (2):

$$m^* = 1.92 + \frac{158.12}{5.12\sqrt{\pi/2}} e^{-2\left(\frac{P-12.89}{5.12}\right)^2} \tag{2}$$

$$P = D_{15}/d_{85}$$

The whole process can be divided into four stages, with the retention rate of fine particles in coarse-grained soil less than 5% defined as weak retention and the peak value (P = 13.10) as the interval point.

When $P \leq 8.53$, the fine particle retention under different water heads is not more than 5.0%, and the water head has little influence on the fine particle transport. When $8.53 < P \leq 13.10$, the retention rate increases with increasing water head and particle size ratio. When the particle size ratio is 13.10, the maximum retention rates corresponding to 0.5 0.9 and 1.2 m are 24.8%, 29.5% and 32.5%, respectively. In addition, the retention rate increases with increasing water head at each particle size ratio, and the higher particle size ratio is, the more obvious the influence of the water head on the retention rate. When $13.10 < P < 18.12$, the change rule of the retention rate in this stage is the opposite of that in the previous stage. The retention rate of fine particles with

Table 4. Particle Transport Mode

Migration mode category	Particle size ratio interval	Particle migration mode
Mode 1	≤ 8.53	Surface sedimentation clogging
Mode 2	8.53 – 13.10	Internal sedimentation clogging
Mode 3	13.10 – 18.12	Transient deposition clogging
Mode 4	≥ 18.12	Freely migration loss

$P \geq 18.12$ is less than 5% and gradually drops to 0. From the above analysis, it can be seen that the retention rate of fine particles in coarse-grained soil is mainly determined by the particle size ratio, which shows the variation rule of the Gaussian curve as a whole. With the increase in the particle size ratio, the influence of the water head on the retention rate first increases and then decreases.

In conclusion, the movement behavior of fine particles under various conditions can be preliminarily judged by the change in the particle size ratio, which means that the movement behavior of fine particles between coarse particles is different. Fine particle transport corresponding to each operating condition is summarized into four transport modes, as shown in Table 4.

It is worth noting that the four transport modes describe the process of fine particles moving and depositing in the soil. The test coarse-grained soil samples did not undergo seepage damage in the end, and only the loss of input fine particles occurred when the particle size was relatively large.

3.2.2 Sedimentation Characteristics of Fine Particles

As previously analyzed, the sedimentation rules of fine particles in coarse-grained soil in different migration modes are in a dynamic change process. Studying the final vertical deposition state of fine particles in coarse-grained soil can further clarify its migration characteristics and rules. After the test, the coarse-grained soil is divided into 7 layers (the thickness of each layer of the first four layers is 0.02 m, and the thickness of each layer of the last three layers is 0.04 m). After drying and sieving, the retention content of fine particles in each layer is obtained. Taking the 1.2 m water head as an example, the retention rule is shown in Fig. 6.

In mode 1, the deposition amount of fine particles in coarse-grained soil decreases gradually from top to bottom and is mainly concentrated in the first three layers, accounting for approximately 5% of the total amount, especially in the first layer, accounting for 4%. The content of fine particles increases with increasing

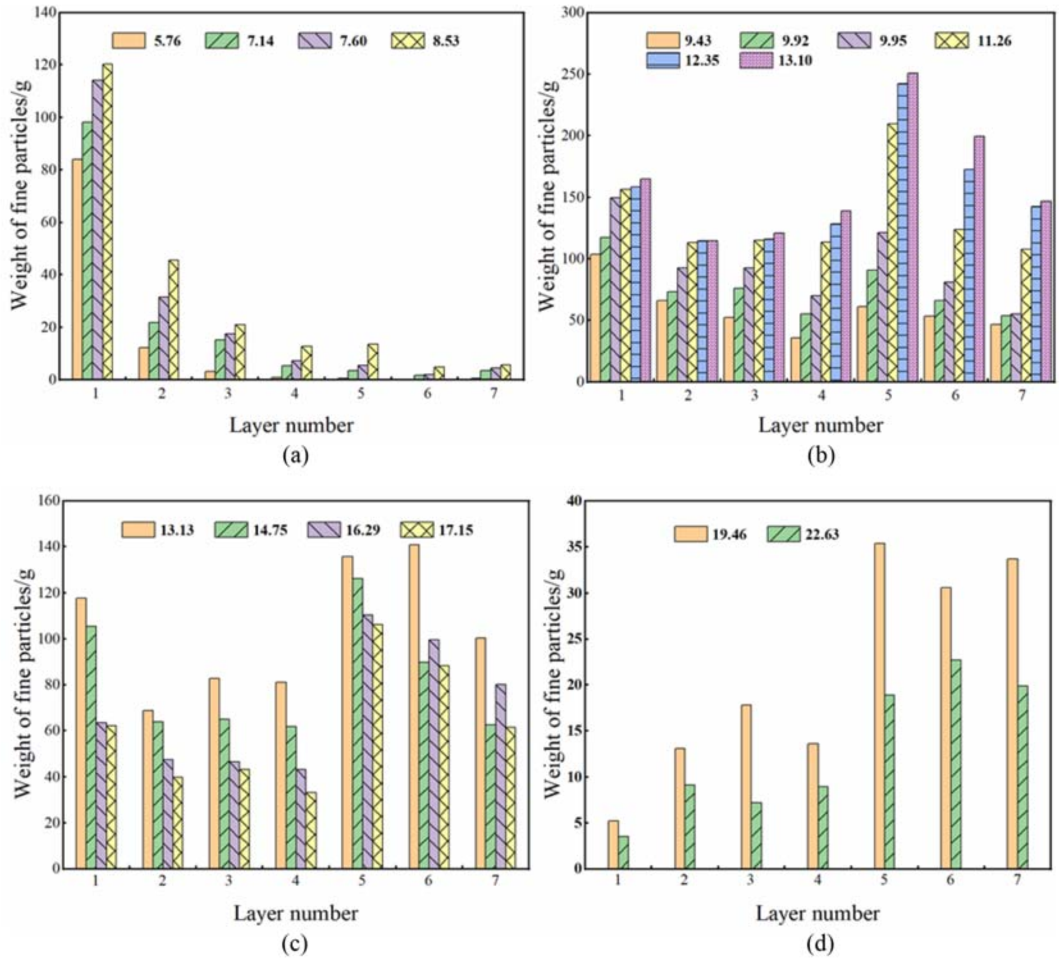

Fig. 6. Weight of Fine Particles:(a) Mode 1, (b) Mode 2, (c) Mode 3, (d) Mode 4

particle size ratio. The distribution of fine particles in each layer in mode 2 is relatively uniform, and the relationship between particle content and particle diameter ratio is similar to that in mode 1. The distribution of fine particles in each layer of mode 3 is relatively uniform, but the content of particles in each layer has changed greatly; specifically, the larger the particle size ratio is, the smaller the particle content. Compared with mode 1, the fine particle content of each layer has the opposite rule from top to bottom; the closer to the bottom, the more fine particles, and the fine particle composition of each layer is the same as that of mode 3.

3.2.3 Analysis of Loss Fine Particles

Fine particles escape from the bottom through the coarse-grained soil column. From the perspective of mass conservation, the mass of escaping particles is equal to the total mass of entering minus the retention mass, and then the escape rate of particles β can be calculated by Eq. (3):

$$\beta = \frac{M - m_1}{M} \tag{3}$$

M = Total mass of the input particles (g)
m_1 = Fine particle mass deposited in coarse-grained soil (g)

β as an indicator of fine particle migration, the escape of fine particles under each mode is shown in Fig. 7.

Figure 7 shows that the overall penetration rate of fine particles in mode 1 is small, and the overall penetration rate is less than 1%. Taking the 1.2 m water head and the particle size ratio of 8.53 as an example, the penetrating particles account for 0.38% of the total penetrating mass. The total mass of fine particles penetrating in mode 2 is greatly increased compared with mode 1, but the maximum penetration rate does not exceed 25%. For example, when the particle size ratio is 13.10, the maximum penetration rate is 24.22%. In mode 3, the penetration ratio of fine particles increases with increasing particle diameter ratio, and the maximum penetration rate is 88.29%. In mode 4, most of the particles penetrate, with a penetration rate of 97.44%, and almost all of the input particles penetrate. At this time, the internal pores of coarse-grained soil are not clogged up; it can be seen that the penetrations of fine particles in different modes are not the same.

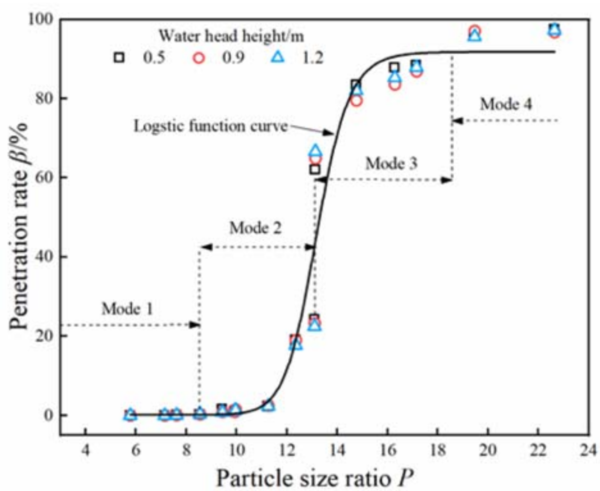

Fig. 7. Result of Fine Particle Penetration Rate

Fitting Fig. 7 shows the penetration rate of fine particles β with the change in the particle size ratio in the *S*-shape curve, the fitting overall change can be regarded as a Logistic regression model, and its expression is Eq. (4):

$$\beta = 91.83 - \frac{\alpha 91.67}{1 + (P/13.18)^{20.51}} \tag{4}$$

$P = D_{15}/d_{85}$
α = The water head correction coefficient.

When the water head is 0.5 m, $\alpha = 1.02$, and when the water head is 1.2 m, $\alpha = 0.98$.

The particle penetration rate changes with the particle size ratio as a nonlinear probability function of the *S*-type. According to Eq. (4), the fine particle penetration rate under different particle size ratios can be calculated to predict the clogging of coarse-grained soil.

3.3 Analysis of Clogging in Coarse-Grained Soil

3.3.1 Variation Laws of the Clogging Ratio in Each Migration Mode

The permeability of the materials used in this test is relatively high, so the constant head permeability method can be used to calculate the permeability coefficient, and the expression is Eq. (5):

$$k = \frac{QL}{A\Delta ht} \tag{5}$$

A = The cross-sectional area of the sample box (cm^2)
L = The height of the sample (cm)
Q = The amount of water flowing through the sample at time t (cm^3)
Δh = The water head difference between the bottom and the bottom of the sample (cm)

Equation (5) shows the change in the permeability coefficient of the test soil during the seepage process, which leads to the defect of comparability of the test results due to time differences. The clogging ratio (Garcia et al., 2019) can be calculated by Eq. (6).

$$R = \frac{k_i}{k_0} \tag{6}$$

k_i = The permeability coefficient at any time
k_0 = The initial permeability coefficient
R = Represents the decrease in the permeability coefficient in each silting period.

When there is no clogging, its value is 1. The higher the clogging degree is, the closer it is to 0.

As a parameter that can intuitively reflect clogging in coarse-grained soil, the clogging ratio is calculated to select the minimum clogging corresponding to each working condition, as shown in Fig. 8.

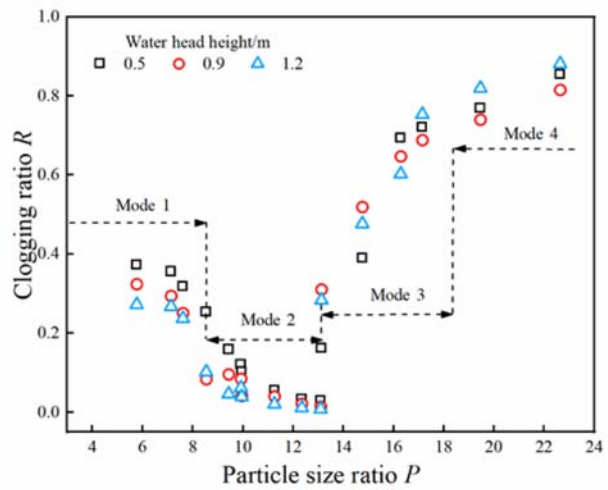

Fig. 8. Results of the Minimum Clogging Ratio

When $P \le 13.10$ (Modes 1 and 2), the clogging ratio gradually decreases with increasing particle size ratio and tends to infinity 0, which indicates that the clogging degree in coarse-grained soil becomes increasingly serious. In addition, the water head has a greater influence on the degree of clogging. The higher the water head is, the better the clogging effect at the same particle size ratio. When $P > 13.10$ (Modes 3 and 4), the clogging ratio increases with increasing particle size ratio and reaches infinitely close to 1, indicating that the degree of clogging worsens, and no clogging occurs at last. During this period, with the increase in the particle size ratio, the influence of the water head on the clogging ratio gradually increases.

In conclusion, the particle size ratio is the main factor affecting clogging in each mode, followed by the water head, with a particle size ratio of 13.10 as the critical value. When the particle size ratio is less than 13.10, the clogging ratio decreases with increasing particle size ratio, and when the particle size ratio is greater than 13.10, the clogging ratio increases with increasing particle size ratio.

3.3.2 The Clogging Ratio of Typical Working Conditions in Each Migration Mode

In mode 1, operating Condition 1 (particle size ratio $P = 7.14$) is selected as the analysis object, as shown in Fig. 9(a). The clogging ratio under each water head drops sharply at first and then rebounds at the bottom and tends to be stable gradually. The minimum clogging ratios of 0.5 , 0.9 ,and 1.2 m are 2.5 , 2.3 , and 2.0 min, respectively, and then rise and reach a stable value within 1 – 2 min. The corresponding stable values are 0.36, 0.16 and 0.18, which

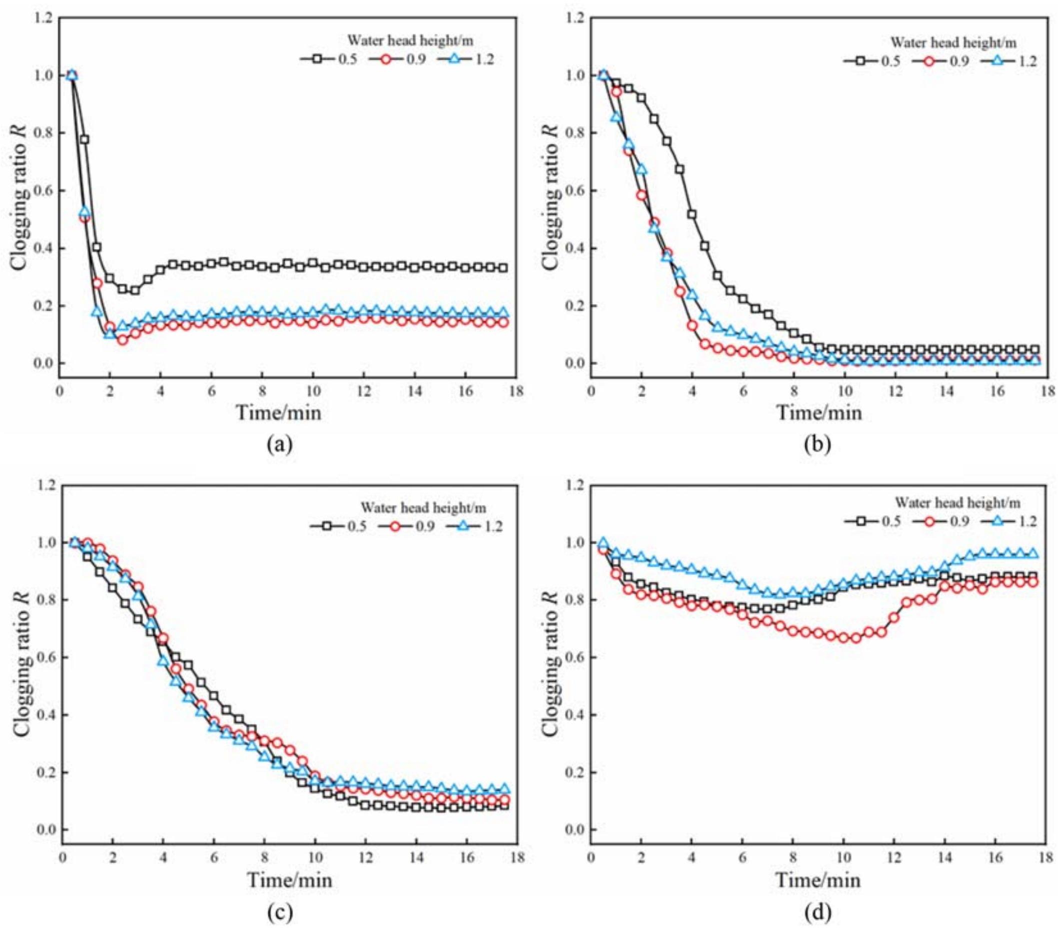

Fig. 9. Results for a Typical Working Clogging Ratio: (a) Working Condition 1, (b) Working Condition 2, (c) Working Condition 3, (d) Working Condition 4

are 64%, 84% and 82% lower than the initial clogging ratio, respectively. Compared with Fig. 9(d) (particle size ratio P = 19.46), it is found that the clogging ratio also decreases first and then increases, but the gradients of decrease and increase are very small. The final clogging ratios corresponding to 0.5 , 0.9 and 1.2 m are 0.96, 0.85 and 0.86, respectively, and the decrease in the clogging ratio is not more than 15%.

Although the retention rates under operating Conditions 1 and 4 are all less than 5%, the rules of the clogging ratio are quite different. The reason for this is different from that of low retention in two stages: the former occurs fine particle deposition and clogging at the top, while the latter loses after free shuttling in coarse-grained soil. Therefore, the clogging ratio under Condition 1 is much smaller than that under Condition 4.

Similarly, representative operating Conditions 2 and 3 (Figs. 9(b), 9(c)) in migration modes 2 and 3 are selected for comparison. It is found that both silting ratios decrease with time and reach a stable value. After stabilization, the clogging ratio decreases by more than 80% or even 96% compared with the initial value. The difference is that the stable clogging ratio in Condition 2 is lower than that in Condition 3, which indicates that the final clogging effect in Condition 2 is better than that in Condition 3.

3.4 Variation in Hydraulic Gradient with Progress of Time

The hydraulic gradient is an important physical parameter. In the test, the water heads (H_1, H_2) at the upper and lower ends of the coarse-grained soil column (excluding the top sediment layer) are measured, and the hydraulic gradient during the test is Eq. (7):

$$J = \frac{H_1 - H_2}{L} \tag{7}$$

L = The height of the sample (cm)

3.4.1 Variation in the Hydraulic Gradient in Modes 1 and 4

The retention rate of fine particles in coarse-grained soil in modes 1 and 4 is less than 5%, which can be compared and analyzed, As shown in Fig. 10.

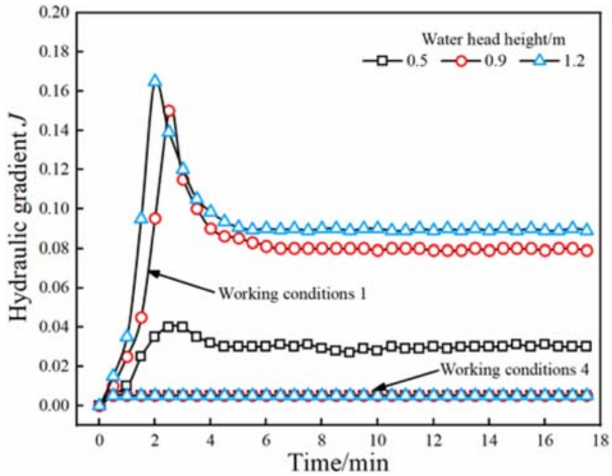

Fig. 10. Variation in Hydraulic Gradient with Time

In Fig. 10, working Condition 1 is selected as the research object in mode 1. The hydraulic gradient under each water head presents a process of rapid increase, rapid decrease and gradual slowing. The corresponding hydraulic gradient extreme values of 0.5 , 0.9 and 1.2 m are 0.04, 0.15 and 0.17, respectively, and the times are 2.8 , 2.6 and 2 min, respectively. The greater the water head is, the shorter the time for the hydraulic gradient to reach the extreme value. The corresponding water head stability values are 0.04, 0.08 and 0.09, respectively. The larger the water head is, the larger the stability value. Further analysis shows that when the particle size ratio is small, fine particles are deposited on the surface, which makes the subsequent particles unable to enter the coarse-grained soil, and weakens the gradient of the lower part of the coarse-grained soil. Therefore, the hydraulic gradient increases first at the beginning of seepage, and then decreases gradually after reaching the extreme value.

Typical working Condition 4 in mode 4 is selected. Under this working condition, the pores of coarse-grained soil are large, and

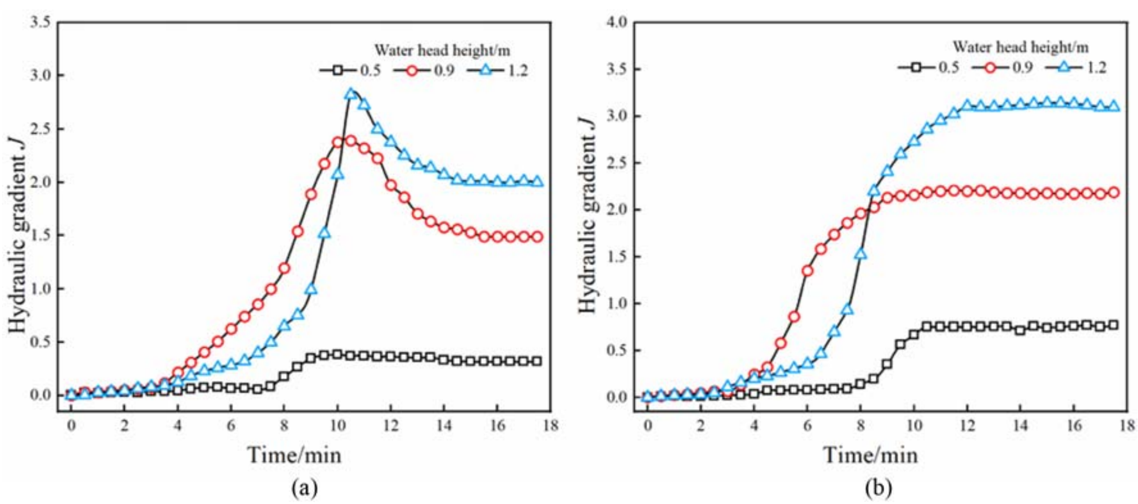

Fig. 11. Variation in Hydraulic Gradient with Time: (a) Working Condition 2, (b) Working Condition 5

the fine particles are mainly lost after entering, and they will hardly deposit on the top and stay inside. The hydraulic gradient of coarse-grained soil is unchanged, which is significantly different from that of working Condition 1.

3.4.2 Variation in the Hydraulic Gradient in Mode 2

As shown in Fig. 11(a). There is no obvious change in the hydraulic gradient in the first 3.5 min under the action of each water head. At approximately 3.8 min, the hydraulic gradient under the 0.9 and 1.2 m water heads increases rapidly and reaches the extreme values at 9.8 min and 10.2 min, respectively. The corresponding maximum hydraulic gradients are 2.39 and 2.73, respectively. After that, the hydraulic gradient gradually decreases and tends to be stable in approximately 15 min, and the corresponding stable water heads become 1.51 and 2.23, respectively. However, the hydraulic gradient under the action of the 0.5 m water head began to increase at 7.6 min and reached an extreme value at 9.2 min, with a maximum value of 0.38. After that, the hydraulic gradient slightly decreased and finally stabilized at 0.36. It can be seen that in mode 2, the hydraulic gradient increases first, then decreases, and finally tends to be stable. The larger the water head is, the longer the time required for the hydraulic gradient to reach stability, and the larger the hydraulic gradient value corresponding to each stage.

When the end particle diameter ratio in mode 2 reaches 13.10 (Working Condition 5), as shown in Fig. 11(b). Compared with Fig. 11(a), it is found that the hydraulic gradient under this working condition does not decrease after reaching the maximum value but tends to be stable, and the final stable values are 0.70, 2.12 and 3.14.

3.4.3 Variation in the Hydraulic Gradient in Mode 3

The representative particle size ratio 14.75 in mode 3 is selected as the research object, which is recorded as working Condition 3, as shown in Fig. 12.

The hydraulic gradient under each water head shows the rule of increasing–stabilizing–increasing–stabilizing with time. Under a 50 cm water head, the intermediate stability stage lasts for 6 min (1 – 7 min), then rapidly increases to the extreme value within 4 min, and then stabilizes at 0.26. Under 0.9 m and 1.2 m water heads, there is only a short stable value in 1 – 3 min, and then it gradually increases to the extreme value of 0.19 and 0.21, respectively, and tends to be stable. When relative mode 2 is stable, the larger the water head is, the smaller the extreme value. Obviously, the hydraulic gradient presents the characteristics of "transient sedimentation and silting", and the intermediate process is unstable. The increase in water head will weaken the transient time; that is, the lower the water head is, the more obvious the transient process and the longer the duration of the intermediate stable stage. At this time, the water head plays a major role in the migration of fine particles. At low water head, it is more conducive to the deposition of particles. At high water head, it will accelerate the migration of fine particles and is not easy to deposit. The hydraulic gradient will gradually decrease with the increase of water head.

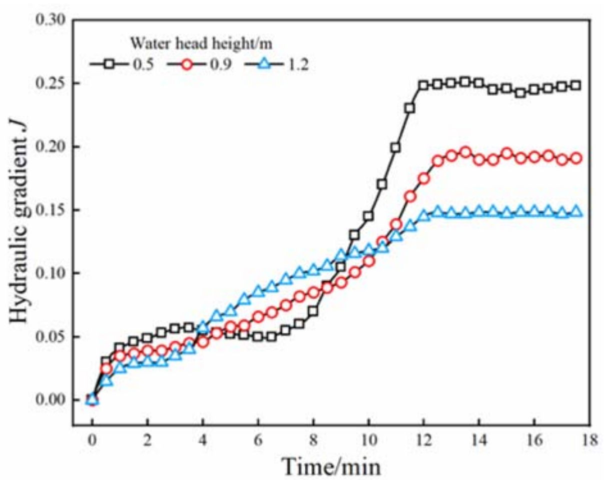

Fig. 12. Variation in Hydraulic Gradient with Time: Working Condition 3

3.5 Change in Coarse-Grained Soil Porosity

3.5.1 Relationship between Clogging Ratio and Porosity

The sedimentation behavior of fine particles occurs in the course of migration (Yang et al., 2019). Because different migration modes represent different migration behaviors, the change in soil porosity is also different. The porosity of the soil samples at different positions is occupied by fine particles. Therefore, when particles move, the particle volume occupies the pore volume of the soil, and the soil porosity decreases. The most representative empirical formula for the study of soil porosity and permeability is the Kozeny-Carman Eq. (8) (Ren et al., 2016)

$$k = C\frac{1}{S^2}\frac{\gamma_w}{\mu\rho_s^2}\frac{e^3}{1+e} \tag{8}$$

$$e = \frac{n_0}{1-n_0} \tag{9}$$

C = A dimensionless constant
m = The liquid viscosity coefficient (N·s/m^2).
n_0 = Soil sample porosity
S = The specific surface area (m^2/g)
γ_w = The water gravity (N·m^{-3})

Therefore, the clogging ratio can be expressed as the relationship between the soil porosity before and after clogging is Eq. (10):

$$R = \frac{k_i}{k_0} = \frac{n_1^3}{(1-n_1)^2}\frac{(1-n_0)^2}{n_0^3} \tag{10}$$

k_0 = The initial saturated permeability coefficient of the soil sample
k_i = The saturated permeability coefficient corresponding to soil porosity n
n_0 = The initial porosity of the soil sample
n_1 = The clogging porosity of soil samples

Table 5. Porosity Under Different Water Heads Within Each Mode

Particle size ratio (D_{15}/d_{85})		Original Porosity n_0	Water head height/cm		
			50	90	120
Mode 1	5.76	0.445	0.436	0.429	0.427
	7.14	0.441	0.421	0.416	0.415
	7.60	0.445	0.414	0.406	0.403
	8.53	0.455	0.418	0.411	0.407
Mode 2	9.43	0.441	0.382	0.377	0.369
	9.92	0.462	0.396	0.390	0.386
	9.95	0.445	0.340	0.337	0.336
	11.26	0.455	0.340	0.328	0.324
	12.35	0.441	0.309	0.307	0.293
	13.10	0.462	0.314	0.303	0.302
Mode 3	13.13	0.445	0.329	0.338	0.344
	14.75	0.455	0.386	0.374	0.374
	16.29	0.441	0.385	0.363	0.376
	17.15	0.462	0.409	0.398	0.405
Mode 4	19.46	0.455	0.435	0.442	0.436
	22.63	0.462	0.451	0.449	0.451

3.5.2 Porosity Change before and after Clogging

Equation (10) shows that the variation in soil porosity is closely related to the degree of clogging, and the smaller the porosity is, the better the clogging effect. According to particle retention under different particle size ratios, the soil porosity after clogging under different conditions is calculated, and its value is shown in Table 5.

From Table 5, it can be seen that the porosity decreases to some extent under different particle size ratios, which indicates that the clogging degree of different soils is also different. In mode 1, the porosity under each water head decreases slightly, with a decrease rate below 10%, and the change in porosity in mode 4 is similar to this law. With the increase in the particle size ratio in mode 2, the porosity decreases greatly under various conditions, which indicates that the degree of soil clogging in this mode is higher. For example, the corresponding porosity decreases of 0.5 , 0.9 and 1.20 m are 32.1%, 34.4% and 34.6%, respectively, taking the critical particle size ratio of 13.10 as an example. The porosity in mode 3 increases with increasing particle size ratio. It is not difficult to find that the range with the greatest decrease in porosity is within mode 2, which indicates that clogging in this mode is the best.

3.5.3 Comparison of Calculation Results

Through the above analysis, the change in porosity in coarse-grained soil can be used to judge the clogging condition of coarse-grained soil. Taking a 1.2 m water head as an example, the test results are compared with the calculation results of Eq. (10), as shown in Fig. 13.

Figure 13 shows that the clogging ratio measured by the test is less than the theoretical calculation value, and the overall average error is approximately 6.0%. The comparison shows that when mode 1 is used, the error between the two is relatively large, and the maximum error can reach 16.4%. In modes 2 and 3, the average error is approximately 3.0%. The Mode 4 error is even lower, at 1.8%. Therefore, there are some differences between the test results and the calculation results. To accurately measure the degree of deviation between the two, the determination coefficient (R^2) and the root mean square error (Root Mean Square Error) statistical indices can be used for analysis. Shown as Eqs. (11) and (12)

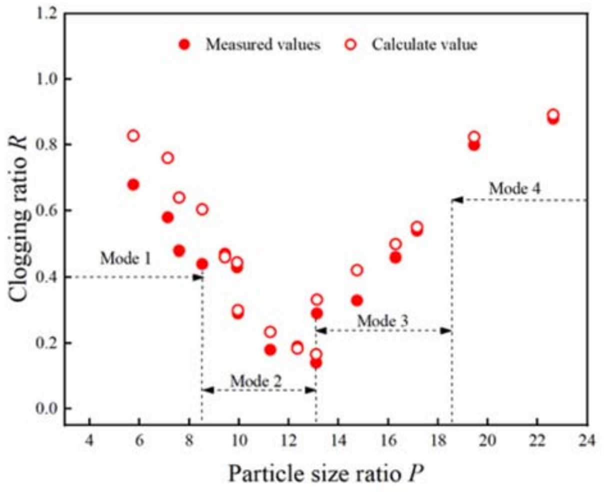

Fig. 13. Comparison of Clogging Ratio Results

$$R^2 = 1 - \frac{\sum_i^n (y_i - f_i)^2}{\sum_i^n (y_i - \overline{y})^2} \tag{11}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_i^n (y_i - f_i)^2} \tag{12}$$

f_i = The measured value
n = The number of sample data
y_i = The calculated value
$\overline{y}$ = The measured average value.

When R^2 is close to 1, it indicates a high accuracy of data, and the smaller the *RMSE* value is, the smaller the data deviation. Taking a 1.2 m water head as an example, the calculation error index is shown in Table 6.

From Table 6, the coefficient R^2 of modes 2 and 3 is greater than 0.9, and R^2 of mode 4 is 0.89, which indicates that the precision of the linear regression model is relatively high, while

Table 6. Error Analysis of the Test

Migration model	Particle size ratio interval	R^2	*RMSE*
Mode 1	≤ 8.53	0.76	0.164
Mode 2	8.53 – 13.10	0.95	0.026
Mode 3	13.10 – 18.12	0.93	0.055
Mode 4	≥ 18.12	0.89	0.020

the coefficient R^2 of mode 1 is relatively low. Similarly, *RMSE* values are less than 0.1 in modes 2, 3 and 4 and 0.164 in mode 1. It also shows that the theoretical values of modes 2, 3 and 4 deviate slightly from the test values and that the test results of mode 1 deviate relatively greatly. This is because fine particles only deposit on the surface of coarse-grained soil; although clogging occurs, the overall porosity of coarse-grained soil does not change significantly until the process is completed. In addition, during the test, the layered method is used to sample the tested soil layers, which results in artificial errors in the structure of each layer of soil.

4. Discussion

4.1 Reason Analysis of Migration

The migration pattern of fine particles in turbid water in coarse-grained soil can be determined preliminarily according to the particle size ratio. In mode 1, the particle size ratio is relatively small at this time, fine particles mainly accumulate on the surface of coarse-grained soil, and the maximum deposition depth occurs on the surface of coarse-grained soil (approximately 2 cm). This is because under the condition of a small particle size ratio, fine particles are more likely to encounter pore passages similar to their own particle size during their migration, resulting in clogging and deposition, on which subsequent fine particles accumulate continuously, resulting in a large number of fine particles finally depositing at shallow locations. In mode 2, the deposition depth of fine particles is significantly improved with increasing particle size ratio. Specifically, the surface deposition is reduced, free penetration of fine particles is obvious, fine particles begin to deposit at the bottom of coarse-grained soil, and subsequent particles continue to accumulate, which ultimately leads to silting of the entire pore. In mode 3, although some fine particles are deposited in the pore, their state is not stable, and further movement is possible under the action of penetration force. At this time, the particle size is larger, which indicates that the pore size of coarse-grained soil is larger than that of fine-grained soil, resulting in unstable clogging in the pores and random clogging and deposition. In mode 4, there is no apparent deposition or clogging of fine particles. At this time, the particle size is larger, which indicates that the pore size is obviously larger than the particle size range of the fine particles themselves, and the fine particles can shuttle freely in the pore. It can be seen that there are obvious differences in the migration mechanism among the four modes.

4.2 Main Factors Affecting Particle Migration

The main factors affecting the migration and deposition of fine particles in coarse-grained soil are the particle size of coarse/fine particles, concentration of turbid water, soil gradation and nonuniformity coefficient, thickness of coarse-grained soil and water head size. The particle size and nonuniformity coefficient of coarse-grained soil determine its pore size and connectivity and affect the migration ability of fine particles. The relationship between the particle size and pore structure of coarse-grained soil is the key to determining its migration mode. Four modes of fine particle migration, i.e., Surface deposition clogging, internal deposition clogging, transient deposition clogging, and freely migration loss are obtained by taking the particle size ratio as a geometric parameter and according to the particle size ratio range. The influence of other factors on the migration of fine particles is controlled by variables on the basis of the particle size ratio, which conforms to the general law of scientific research.

It has been shown that the particle size ratio also affects the deposition position of fine particles in coarse-grained soil and the maximum clogging depth (Suzanne et al., 2016). Therefore, the influence of the thickness of coarse-grained soil on the fine-grained pattern needs to be discussed. The thickness of coarse-grained soil determines the length of the path in which fine particles move and increases the time for particles to penetrate. The hydraulic gradient under each water head changes in a short time (2.5 min) and then tends to stabilize. For example, the maximum deposit depth of mode 1 is within 2 cm of the surface layer, and then all deposits are on the top of coarse-grained soil. Mode 2 clogging starts at the bottom of the coarse-grained soil, and the thickness of the coarse-grained soil does not change the migration pattern. The clogging and sedimentation in mode 3 are random, while the fine particles in mode 4 move freely shuttles, and the thickness of coarse-grained soil does not change its migration pattern. Of course, the influence of the thickness of coarse-grained soil on the migration pattern of fine-grained soil is also related to the particle size ratio, water head and nonuniformity coefficient, which cannot be separately analyzed. As far as this test is concerned, the selection of 20 cm thick coarse-grained soil has no influence on each migration mode.

5. Conclusions

1. The particle size ratio is the main factor affecting the retention of fine particles in coarse-grained soil, and its retention rule conforms to the Peak-Gauss function, and The penetration law of fine particles satisfies the change of Logistic curve.
2. Four migration modes of fine particles are proposed according to the particle size ratio interval. When $P \leq 8.53$, the cloggng pattern is surface accumulation clogging. When $8.53 < P \leq 13.10$, the clogging pattern is mainly internal deposition clogging. When $13.10 < P \leq 18.12$, transient sedimentation clogging is likely to occur, while $P > 18.12$ is freely migration loss.
3. The particle size ratio is the main factor affecting the clogging in each mode, followed by the influence of water head. Taking the particle size ratio of 13.10 as the critical value, the clogging ratio decreases with the increase of the particle size ratio when it is less than 13.10, and the clogging ratio increases with the increase of the particle size ratio when it is greater than 13.10.
4. The hydraulic gradients of the four migration modes are obviously different. The hydraulic gradient of mode 1 increases rapidly and then slows down. The hydraulic gradient of mode 2 increases with increasing particle size ratio and tends to

stabilize after reaching the extreme value. The hydraulic gradient of mode 3 is unstable, which conforms to the characteristics of “transient sedimentation and clogging”. The hydraulic gradient of mode 4 before and after clogging does not change significantly.

5. The degree of clogging in coarse-grained soil is closely related to the change in porosity. The maximum decrease range of porosity in the four models is mode 2, which indicates that the clogging effect in this model is the best. The degree of internal clogging can be determined by the change of porosity of coarse-grained soil.

Acknowledgments

This research was financially supported by National Natural Science Youth Foundation of China, No.42207102; Shanxi Province Natural Science Foundation Project, Nos. 202103021224151, 202103021223132; Provincial Reform High-level Talent Introduction Project of Shanxi Agricultural University, No. 2021XG009. The design of the test apparatus and the carrying out of the tests were supported by Mr. HT. MAO who belongs to the Professor from Shanxi Agricultural University, provided much advice and many useful comments for this paper. The authors also thank for the help from C. Zhang, Y. Gu, B. Yang for their help in the study.

ORCID

Not Applicable

References

Abdelkader BA, Sharqawy MH (2022) Pressure drop across membrane spacer-filled channels using porous media characteristics and computational fluid dynamics simulation. *Desalination and Water Treatment* 247:28-39, DOI: 10.5004/dwt.2022.28044

Aboufoul M, Garcia A (2017) Influence of air voids characteristics on the hydraulic conductivity of asphalt mixture. *Road Materials and Pavement Design* 18(2):39-49, DOI: 10.1080/14680629.2017.1304256

Alem A, Elkawafi A, Ahfir ND, Wang HQ (2013) Filtration of kaolinite particles in a saturated porous medium: Hydrodynamic effects. *Hydrogeology Journal* 21(3):573-586, DOI: 10.1007/s10040-012-0948-x

Cao H, Zhu DF, Fan Z, Luo GY, Pan H (2019) Laboratory study of leakage process for cut-off wall with crack. *Journal of Hydraulic Engineering* 50(6):699-709, DOI: 10.13243/j.cnki.slxb.20181117 (in Chinese)

Chen XX, Bai B, Yan YL, Jia DY (2012) Influence of concentration of suspended particles on transport and deposition characteristics in saturated porous media. *Rock and Soil Mechanics* 33(8):2343-2348, DOI: 10.16285/j.rsm.2012.08.010 (in Chinese)

Garcia A, Aboufoul M, Asamoah F, Jing D (2019) Study the influence of the air void topology on porous asphalt clogging. *Construction and Building Materials* 227:0950-0618, DOI: 10.1016/j.conbuildmat.2019.116791

Gibson S, Abraham D, Heath R, Schoellhamer D (2009) Vertical gradational variability of fines deposited in a gravel framework. *Sedimentology* 56(3):661-676, DOI: 10.1111/j.1365-3091.2008.00991.x

Guo CX, Cui P (2017) Fine particle migration in wide grading and poorly consolidated soil: An overview. *Journal of Mountain Science* 35(2):179-186, DOI: 10.16089/j.cnki.1008-2786.000210 (in Chinese)

Kia K, Wong HS, Cheeseman CR (2017) Clogging in permeable concrete: A review. *Environmental Management* 19(3):221-233, DOI: 10.1016/j.jenvman.2017.02.018

Kim HN, Walker SL, Bradford SA (2010) Coupled factors influencing the transport and retention of cryptosporidium parvum oocysts in saturated porous media. *Water Research* 44(4):1213-1223, DOI: 10.1016/j.watres.2009.09.041

Li SB, Wang CM, Wang GC, Ma JQ (2013) Clogging types distinguishing of coarse-grained soil and determination of optimal range of clogging grain size. *Journal of Hydraulic Engineering* 44(10):1217-1224, DOI: 10.13243/j.cnki.slxb.2013.10.011 (in Chinese)

Luo YL, Zhang XJ, Zhang HB, Sheng JC, Zhan ML,Wang HM, He SY (2022) Review of suffusion in deep alluvium foundation. *Rock and Soil Mechanics* 43(11):3094-3106, DOI: 10.16285/j.rsm.2021.2175 (in Chinese)

Ren XW, Zhao Y, Deng QL, Kang JY, Li DX, Wang DB (2016) A relation of hydraulic conductivity-void ratio for soils based on Kozeny-Carman equation. *Engineering Geology* 213:89-97, DOI: 10.1016/j.enggeo.2016.08.017

Suzanne F, Ali AM, Anvar K, Hamed AB, Said AI, Mohamed AB (2016) Migration and deposition of fine particles in a porous filter and alluvial deposit: Laboratory experiments. *Arabian Journal of Geosciences* 9(4):1866-7511, DOI: 10.1007/s12517-016-2309-x

Wang ZJ, Du XQ, Ye XY, Song XM, Zhang JQ, Gao CP (2012) Suspended solid surface clogging during urban stormwater groundwater recharge. *Journal of Jilin University* (*Earth Science Edition*) 42(2):492-498, DOI: 10.13278/j.cnki.jjuese.2012.02.031 (in Chinese)

Xiao M, Shwiyhat N (2012) Experimental investigation of the effects of suffusion on physical and geomechanic characteristics of sandy soils. *Geotechnical Testing Journal* 35(6):890-900, DOI: 10.1520/GTJ104594

Yang J, Yin ZY, Laouafa F, Hicher PY (2019) Modeling coupled erosion and filtration of fine particles in granular media. *Acta Geotechnica* 14(6):1615-1627, DOI: 10.1007/s11440-019-00808-8

Yao ZX, Zhou J, Zhang G, Wu B (2016) Experimental study of particle grading impact on piping mechanism. *Journal of Hydraulic Engineering* 47(2):200-208+218, DOI: 10.13243/j.cnki.slxb.20150703 (in Chinese)

Ye XY, Cui RJ, Du XQ, Ma SJ, Zhao JT, Lu Y, Wan YY (2019) Mechanism of suspended kaolinite particle clogging in porous media during managed aquifer recharge. *Ground Water* 57(5):764-771, DOI: 10.1111/gwat.12872

Yousif OSQ, Karakouzian M, Rahim NOA, Rashed KA (2017) Physical clogging of uniformly graded porous media under constant flow rates. *Tansport in Prous Media* 120(3):643-659, DOI: 10.1007/s11242-017-0946-5

Zamani A, Maini B (2009) Flow of dispersed particles through porous media-Deep bed filtration. *Journal of Petroleum Science and Engineering* 69(1-2):71-88, DOI: 10.1016/j.petrol.2009.06.016

Zhu Q, Su LJ, Liu ZY, Yang SH (2021) Study of seepage in wide-grading soils with particles migration. *Rock and Soil Mechanics* 42(1):125-134, DOI: 10.16285/j.rsm.2020.0623 (in Chinese)