Research Article

Investigation on Calculation Method of Permeability Coefficient in the Consolidation Process of Cohesive Soil

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In order to study the permeability characteristics of cohesive soil in the consolidation process more accurately, in this work, the pores occupied by the combined water were defined as invalid pores, and the effective pores and ineffective pores were decoupled to study the relationship between effective pores and permeability coefficient. The widely used empirical formulas of the permeability coefficient were modified, and the empirical formulas of the permeability coefficient suitable for the consolidation process of cohesive soil were obtained. Combined with the $e-\lg\sigma'$ relationships of normally consolidated soil, underconsolidated soil, and overconsolidated soil, the formulas of permeability coefficient, which considering the influence of initial consolidation state and consolidation stress, in the consolidation process of cohesive soil, were proposed. Finally, the rationality of the new formulas proposed in this paper was analyzed by indoor consolidation-permeability test and existing research. The results showed that the permeability coefficient of cohesive soil in the consolidation process predicted by the new formulas were more consistent with the measured average value. This study possesses practical engineering significance to solve the problem of foundation consolidation settlement.

1. Introduction

How to improve the accuracy of consolidation settlement calculation of soft soil foundation has attracted much attention in geotechnical engineering field. In 1925, Terzaghi et al. proposed the one-dimensional consolidation theory and has been widely used [1–6]. However, Terzaghi’s one-dimensional consolidation theory is based on a series of assumptions, and the nonlinear variation of the permeability coefficient in the consolidation process is simplified. Many research results indicated that without considering the change of permeability coefficient with the consolidation process, the foundation settlement of prediction was quite different from the measured value [7–10]. In order to reduce the difference between the predicted and measured values, many researches have been done and obtained some beneficial results. For example, based on the Fredlund’s one-dimensional consolidation theory of unsaturated soil, Ai-fang and Jiu-long obtained the semianalytical solution that simultaneously considered the nonlinear variation of liquid and gas permeability coefficients in the consolidation process of foundation and acquired the semianalytical solution that only considered the change of the liquid permeability coefficient [11]. Considering the relationship among the permeability coefficient, consolidation stress, and void ratio, Lin et al. derived the relational expression between the consolidation coefficient and consolidation stress and improved the traditional consolidation theory [12, 13]. Xie et al. used the $e-\lg\sigma'$ and $e-\lg k_v$ nonlinear relationships to describe the deformation and permeability characteristics of soil, respectively, and established a large deformation nonlinear consolidation model of soft soil with excess pore pressure as variable and its analytical solution [14, 15]. Under an arbitrary unloading rate, the general solution of one-dimensional consolidation equation of soft soil foundation was explored by Shi and Sun, through the one-dimensional...
consolidation theory of Terzaghi and effective stress principle and solved the analytical solution of consolidation equation under linear unloading [16]. Kim et al. gave the analytical solution of one-dimensional nonlinear consolidation equation of saturated clay layer with variable compressibility and permeability under different cyclic loading [17]. Based on a huge amount of indoor experiment data, Liu et al. gave the relation expression between the permeability coefficient and the consolidation stress in the compression process, which considered the influence of the preconsolidation stress on the permeability coefficient under the normal consolidation state [18]. Dumais and Komrad used the nonlinear relationships of effective stress, void ratio, and hydraulic conductivity to characterize the properties of thawing soil and established a one-dimensional model for consolidation of thawing soil based on the large strain consolidation theory and heat-transfer equations [19]. Based on Terzaghi’s theory, Dobak and Gazyński obtained a parameter evaluation method related to compressibility and permeability coefficient and improved the one-dimensional consolidation test method [20]. Yazdani et al. derived a set of nonlinear partial differential equations by utilizing the relationship between the void ratio and effective stress as well as the relationship between the void ratio and permeability, which are used to predict the consolidation characteristics of normally consolidated and overconsolidated soft clay subjected to cyclic loading [21, 22]. Zhang et al. carried out a series of one-dimensional consolidation and permeability combined tests using GDS triaxial apparatus and systematically studied the influence of consolidation stress ratio and stress history on one-dimensional consolidation of saturated clay [23, 24]. Gao et al. constructed the permeability coefficient prediction formula in the preloading process of soft foundation, which took into account the influence of initial consolidation state and stress state during consolidation and substituted it into the consolidation coefficient expression to modify Terzaghi’s one-dimensional consolidation equation [25, 26].

Clearly, it can be found from the above analysis that when the problems related to ground consolidation settlement are studied, scholars always consider that permeability coefficient is closely related to void ratio and correlate the void ratio with consolidation stresses to study. However, pores in clay can be divided into effective pores and ineffective pores. In the actual seepage process, only the former has high permeability and occurs seepage, while the latter has little effect on seepage [27–29]. At present, there are few reports on the study of the effect of effective pores on the permeability coefficient of soft foundation during preloading. In view of this, this paper decoupled effective pores and ineffective pores, only considered the effect of effective pores on the permeability coefficient. Based on the $e - \lg \sigma$ curves of soil under different consolidated states and the commonly used permeability coefficient formulas, the permeability coefficient formulas in the consolidation process of soft clay obtained, which can consider the influence of initial consolidation state and consolidation stress. And their rationality was verified by a series of indoor consolidation and penetration tests, which can predict the permeability coefficient in the consolidation process more accurately. This study possesses practical engineering significance to study the seepage and settlement problems in the process of foundation consolidation.

2. Calculation Method of the Effective Void Ratio of Cohesive Soil

The void ratio is the main factor affecting the permeability of soil [30]. Generally speaking, the larger the void ratio, the larger the infiltration space, the stronger the permeability, that is, the greater the permeability coefficient. However, the clay does not follow this law, which is that the void ratio is large, the permeability coefficient is small. The reason is that clay particles generally have negative charges, and the polarized water molecules within a certain range around them are adsorbed on the surface of soil particles, forming a layer of bound water film, which is insoluble, and cannot produce and transfer hydrostatic pressure, and does not obey the gravity law of water flowing to low places. For seepage, it has solid properties, which is equivalent to occupy a part of the permeable space, leading to the decrease of permeability of soil. Therefore, the pores occupied by bound water film should be “solidified” when calculating the permeability coefficient, that is, they should be regarded as ineffective pores.

In this paper, the ratio, pore volume occupied by bound water film to the volume of soil particles, was defined as ineffective void ratio, which was expressed as $e_i$. The difference between total void ratio $e$ and ineffective void ratio $e_i$ was defined as effective void ratio, denoted as $e_e$ [27].

Existing studies have shown that there is an inseparable relationship between the limit moisture content of cohesive soil and the content of bound water in the soil [31, 32]. When $w \leq w_p$, most of the clay is strong bound water, and there is little loose bound water, and the cohesive soil is in solid or semi-solid; when $w_p < w \leq w_L$, most of the clay is loose bound water, a small amount is free water, and the cohesive soil is in plastic state; when $w > w_L$, there is a large amount of free water among soil particles and the soil is in flow state. Where $w$ is water content, $w_p$ is plastic limit of cohesive soil, and $w_L$ is liquid limit of cohesive soil. In addition, the bound water content $w_{bw}$ can be estimated by $w_p$ [33], by the following relationship: $w_{bw} = 0.885w_p$. To facilitate the calculation of ineffective void ratio, this paper makes the following assumptions for saturated clay:

(a) only the pores occupied by the bound water are considered
(b) under external load, the free water in soil mass seeps first, then the loose bound water, and finally the strong bound water
(c) both soil particles and water are incompressible
(d) the total bound water content $w_{bw}$ is equal to $\alpha w_L$, namely, $w_{bw} = \alpha w_L$, where $0 < \alpha < 1$

According to the conversion formulas of three-phase proportion index of soil, the bound water content in
cohesive soil can be calculated with following equation:

\[ u_{bw} = \frac{m_{bw}}{m_s} = \frac{\rho_{bw} V_{bw}}{\rho_s V_s} = \alpha w_1, \]  

(1)

where \( m_{bw} \) and \( m_s \) are the mass of bound water and soil particles, respectively; \( \rho_{bw} \) and \( \rho_s \) are the density of bound water and soil particles, respectively, \( g/cm^3 \); and \( V_{bw} \) and \( V_s \) are the total volume of bound water and soil particles, respectively, \( cm^3 \).

According to Equation (1), the total volume of bound water can be expressed as

\[ V_{bw} = \alpha \rho_s V_s w_1. \]  

(2)

From Equation (2) and the definition of ineffective void ratio, it can be known that the calculation method of ineffective void ratio of cohesive soil is

\[ e_i = \frac{V_{bw}}{V_s} = \frac{\rho_s}{\rho_{bw}} e_u, \]  

(3)

where \( \alpha \) is the proportionality coefficient of bound water to liquid limit, which can be obtained by thermal gravimetric analysis. For a specific clay, it can be approximated as a constant. \( \rho_{bw} \) and \( \rho_s \) represent the density of bound water and soil particles, respectively, \( kg/cm^3 \). Wang et al. showed that average density of strong bound water was about \( 1.3 g/cm^3 \) and that of loose bound water was about \( 1.16 g/cm^3 \) \cite{34, 35}. For the convenience of research, the \( \rho_{bw} \) in this paper is taken as \( 1.20 g/cm^3 \). In summary, the ineffective void ratio of a particular soil can be considered a constant.

Then, the effective void ratio of clay can be calculated by Equation (4).

\[ e_u = e - \alpha \frac{\rho_s}{\rho_{bw}} w_1. \]  

(4)

**3. Permeability Coefficient in the Process of Consolidation**

The existing empirical formulas for the permeability coefficient in the preloading process of soft foundation considering both the effect of initial consolidation state and consolidation stress does not decouple the effective and ineffective void ratios of cohesive soil, which leads to a large error between the calculated results and the actual results. To solve this problem, the permeability coefficient empirical formulas of cohesive soil in the consolidation process were further improved in the following part.

The following equations are the widely used empirical formulas for the permeability coefficient of cohesionless soil.

Darcy’s empirical formula of permeability coefficient is as follows:

\[ k = \frac{\beta d^2 \gamma_w}{\lambda \eta} \frac{e^2}{1 + e}, \]  

(5)

where \( \lambda \) is a coefficient that depending on the influence of adjacent particles; \( \beta \) is the volumetric coefficient of soil particles, and the \( \beta \) of sphere is \( \pi/6 \); \( d \) is the diameter of soil particles, \( cm \); and \( \eta \) is the coefficient of dynamic viscosity of free water, \( g/s/cm^2 \).

Kozeny-Carman’s empirical formula of permeability coefficient is as follows:

\[ k = \frac{c_2 \rho_{bw} e^3}{s \eta (1 + e)}, \]  

(6)

where \( \rho_{bw} \) is the density of free water, \( g/cm^3 \); \( c_2 \) is the coefficient related to particle shape and actual flow direction of water, which is about \( 0.125 \); and \( s \) is the specific surface area of soil particles, \( cm^{-1} \).

In the process of soil compression, the basic physical parameters such as particle size, specific surface area, and unit weight of water are constant, and the variables are only the void ratio and permeability coefficient. It is noteworthy that initial permeability coefficient \( k_0 \) and initial total void ratio \( e_0 \) can be obtained from investigation data. Therefore, \( k_0 \) and \( e_0 \) can be used to represent other constant physical parameters of soil particles. Then, by substitution, it can be obtained that

\[ \frac{\beta d^2 \gamma_w}{\lambda \eta} = k_0 \frac{1 + e_0}{e_0}, \]  

(7)

\[ \frac{c_2 \rho_{bw}}{s \eta} = k_0 \frac{1 + e_0}{e_0}. \]  

(8)

Substituting Equations (7) and (8) into Equations (5) and (6) yields

\[ k = k_0 \frac{1 + e_0}{e_0^2} \frac{e^2}{1 + e}, \]  

(9)

\[ k = k_0 \frac{1 + e_0}{e_0^3} \frac{e^3}{1 + e}. \]  

(10)

Equations (9) and (10) are Darcy’s formula and Kozeny-Carman’s formula of the permeability coefficient in the process of soil consolidation expressed by initial total void ratio \( e_0 \) and initial permeability coefficient \( k_0 \), respectively. Obviously, the permeability coefficient \( k \) in the consolidation process is a unitary function of void ratio \( e \). It is worth noting that the void ratio \( e \) in Equations (9) and (10) actually refers to the effective void ratio that contributes to seepage, and the void ratio occupied by the bound water film should be excluded. Therefore, using the effective void ratio \( e_u \) in Equation (4) to replace the void ratio \( e \) in Equations (9) and (10), which can obtain the following:

\[ k = k_0 \frac{1 + e_0 - \alpha (\rho_s/\rho_{bw}) w_1}{(e_0 - \alpha (\rho_s/\rho_{bw}) w_1)^2} \frac{e - \alpha (\rho_s/\rho_{bw}) w_1}{1 + e - \alpha (\rho_s/\rho_{bw}) w_1}, \]  

(11)
The compression curve of normally consolidated soil is shown in Figure 1(a). Assuming that the self-weight stress under three consolidation states are discussed separately. The permeability coefficient in the process of consolidation is also different, as shown in Figure 1, and thus, the permeability coefficient applicable to the consolidation process of cohesive soil, where \( e_0 \) is the initial total void ratio and \( e \) is the total void ratio in the consolidation process of soil.

The \( e - \lg \sigma \) curves of soil under three consolidated states are different, as shown in Figure 1, and thus, the permeability coefficient in the process of consolidation is also different. Therefore, the permeability coefficients of cohesive soil under three consolidation states are discussed separately.

(1) Normally consolidated soil

The compression curve of normally consolidated soil is shown in Figure 1(a). Assuming that the self-weight stress acting on the midpoint of soil layer is \( \sigma_0 \), the corresponding initial void ratio is \( e_0 \). And the additional stress at this point is \( \Delta \sigma \), then the actual stress is \( \sigma_0 + \Delta \sigma \), \( e_c \) is the corresponding void ratio, and its expression is as follows:

\[
e = e_0 - C_c \lg \frac{\sigma_0 + \Delta \sigma}{\sigma_0}, \tag{13}
\]

where \( C_c \) is the compression index.

Substituting Equation (13) into Equations (11) and (12) yields

\[
k = k_0 \frac{1 + e_0 - a(\rho_s/\rho_w)w_L (e_0 - a(\rho_s/\rho_w)w_L)}{(1 + e_0 - a(\rho_s/\rho_w)w_L)} \frac{\sigma_0 + \Delta \sigma}{\sigma_0}. \tag{14}
\]

Equations (11) and (12) are the empirical formulas of the permeability coefficient applicable to the consolidation process of cohesive soil, where \( e_0 \) is the initial total void ratio and \( e \) is the total void ratio in the consolidation process of soil.

The \( e - \lg \sigma \) curves of soil under three consolidated states are different, as shown in Figure 1, and thus, the permeability coefficient applicable to the consolidation process of cohesive soil, where \( e_0 \) is the initial total void ratio and \( e \) is the total void ratio in the consolidation process of soil.

(2) Overconsolidated soil

Compared with normal consolidated soil, the compression curve of overconsolidated soil is divided into recompression curve and field compression curve. According to the magnitude of additional stress \( \Delta \sigma \), there are two possibilities for the actual upper load \( (\sigma_0 + \Delta \sigma) \) of soil. One is greater than the preconsolidation stress \( \sigma_c \), that is, \( \sigma_0 + \Delta \sigma \geq \sigma_c \), as shown in Figure 1(b), the void ratio can be obtained by Equation (16). The other is less than the preconsolidation stress \( \sigma_c \), namely, \( \sigma_0 \leq \sigma_0 + \Delta \sigma \leq \sigma_c \); as shown in Figure 1(c), the void ratio can be expressed by Equation (17).

\[
e = e_0 - \left( C_c \frac{\sigma_0 + \Delta \sigma}{\sigma_0} \right), \tag{16}
\]

where \( C_s \) represents the swelling index.
Substituting Equation (16) into Equations (11) and (12), it can be shown that

\[ k = k_0 \frac{1 + e_c - a(\rho / \rho_m)w_l}{1 + e_1 - a(\rho / \rho_m)w_l} \frac{(e_1 - a(\rho / \rho_m)w_l - C_c \log (\sigma / \sigma_c))}{(e_c - a(\rho / \rho_m)w_l)} \]

Equations (18) and (19) are calculation formulas of the permeability coefficient in the compression process of overconsolidated soil when \( \sigma_0 + \Delta \sigma \geq \sigma_c \).

Similarly, Equation (17) is substituted into Equations (11) and (12), respectively. It is obvious that Equations (18) and (19) can be reduced to Equations (14) and (15), respectively. When \( \sigma_c = \sigma_0 \), Equations (20) and (21) can be simplified to Equations (14) and (15), respectively. It is obviously that the permeability coefficient empirical formulas of overconsolidated soil and underconsolidated soil can be reduced to that of normally consolidated soil. Hence, only the rationality and reliability of the permeability coefficient prediction formulas of normally consolidated soil are studied here. For the convenience of analysis, the formulas for calculating the permeability coefficient during the consolidation process of cohesive soil before modification are listed here [25].

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<table>
<thead>
<tr>
<th>Soil type</th>
<th>( G_s )</th>
<th>( w )</th>
<th>( W_L )</th>
<th>( \rho_d )</th>
<th>( e_0 )</th>
<th>( k_0 )</th>
<th>( C_c )</th>
<th>( I_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty clay</td>
<td>2.73</td>
<td>21.68</td>
<td>30.7</td>
<td>1.69</td>
<td>0.62</td>
<td>1.21e-6</td>
<td>0.15</td>
<td>13.90</td>
</tr>
<tr>
<td>Loess</td>
<td>2.72</td>
<td>16.80</td>
<td>34.5</td>
<td>1.62</td>
<td>0.67</td>
<td>3.14e-5</td>
<td>0.13</td>
<td>15.85</td>
</tr>
</tbody>
</table>

4. Reliability Verification of Formulas

When \( C_c = C_c \) and \( \sigma_c = \sigma_0 \), Equations (18)–(20) and Equations (19)–(21) can be reduced to Equations (14) and (15), respectively. When \( \sigma_c = \sigma_0 \), Equations (23) and (24) can be simplified to Equations (14) and (15), respectively. It is obviously that the permeability coefficient empirical formulas of overconsolidated soil and underconsolidated soil can be reduced to that of normally consolidated soil. Hence, only the rationality and reliability of the permeability coefficient prediction formulas of normally consolidated soil are studied here. For the convenience of analysis, the formulas for calculating the permeability coefficient during the consolidation process of cohesive soil before modification are listed here [25].
The samples used in this study were saturated remolded soil samples, and the preparation steps were as follows. The two kinds of soil were air-dried and grinded and sifted through sieve with 0.25 mm aperture. Then, carried out test on the sifted soil particles to measure the air-dried moisture content \( w_0 \). The soil mass \( m_s \) required for each sample was calculated according to the sample size, moisture content \( w \), and dry density \( \rho_d \), and calculated by

\[
m_s = \rho_d (1 + 0.01w) \cdot V.
\]

And calculated the weight of water needed for the corresponding soil mass by

\[
m_w = \frac{m_s}{1 + 0.01w_0} \times 0.01(w - w_0).
\]

The soil needed for sample preparation was weighed, and the corresponding water was sprayed. Then, they were stirred fully and kept in the sealed bag for 24 hours to make them moisture uniform.

According to the “Standard of Geotechnical Test Method” (GB/T50123; National Standards of People’s Republic of China 2019), the sample was prepared by pressure sampling method. And the samples of consolidation test with 30 cm\(^2\) in cross-section area and 2 cm in height were used, and the samples of percolation test with 30 cm\(^2\) in cross-section area and 4 cm in height were used. Finally, the sample was saturated by the vacuum saturation method.

4.2. Test Scheme. The indoor consolidation compression test was carried out with WG lever-type compressor apparatus, and the consolidation compression process was driven by application of load step by step. And the applied pressures were 50 kPa, 100 kPa, 200 kPa, 400 kPa, 600 kPa, 800 kPa, 1000 kPa, 1200 kPa, and 1600 kPa, respectively. Firstly, the soil sample was consolidated under the consolidation stress of 50 kPa until it was in a stable state of consolidation, and the deformation of the soil sample at this time was recorded. Then, the next level of consolidation stress was applied and the above steps were repeated to 1600 kPa. According to the Chinese standard for soil test method, the sample was in a stable state of consolidation when its compression rate was less than 0.005 mm/h.

According to the void ratio and moisture content corresponding to different consolidation stress, the samples needed for permeability test were remolded, and each has three parallel samples. The permeation test instrument in this study was south-55 permeameter, and the test method was variable head permeability. In the test, the pipe clamp was closed after the head height in the piezometer tube reached 160 cm, and the water temperature was measured and recorded. The stopwatch was started when the water head dropped to 155 cm, of which 155 cm was the initial water head height \( h_1 \). After 5 minutes, the water head height was recorded as \( h_2 \). Then, the permeability coefficient was calculated by Equation (29). Finally, the mean value of the calculation results of three groups of parallel samples was taken as the permeability coefficient of soil samples corresponding to various consolidation stress.

\[
K_T = 2.3 \frac{aL}{A \cdot t} \cdot \log \frac{h_1}{h_2},
\]

Figure 3: Particle size distribution curve of soil samples.

Figure 4: Relation curves between void ratio and consolidation stress.
where \( a \) represents the cross-section area of piezometric tube, 0.225 cm\(^2\); \( A \) is the cross-section area of the sample, 30 cm\(^2\); \( L \) is sample height, 4 cm; and \( t \) represents time interval, which is 5 minutes in this study.

### 4.3. Results and Analysis.

The relationship curves between the void ratio and consolidation stress are shown in Figure 4. Obviously, there is a negative correlation between void ratio \( e \) and consolidation stress \( \sigma \), and the slope of the curve decreases gradually with the increase of consolidation stress, which indicates that with the increase of consolidation stress, the void ratio inside the soil sample becomes smaller and smaller, and the consolidation compression becomes more and more difficult. According to the Casagrande method, the preconsolidation stress \( \sigma_c \) of silty clay and loess are 115 kPa and 105 kPa, respectively. It is considered that they were all in normally consolidation state, that is, \( \sigma_c = \sigma_0 = 115 \) kPa of silty clay in Jingbian and \( \sigma_c = \sigma_0 = 105 \) kPa of loess in Binzhou.

Figures 5(a) and 5(b) are the curves of permeability coefficient \( k \) and consolidation stress \( \sigma \) of Jingbian silty clay and Binzhou loess, respectively, which can be seen that the permeability coefficient of cohesive soil is not constant in the consolidation process. In addition, compared with the figures, it can be found that the variation trends of \( k - \sigma \) curve and \( e - \sigma \) curve are similar. The permeability coefficient decreases with the increase of consolidation stress, and the rate of reduction decreases with the increase of consolidation stress. The reason is that the void ratio is the main factor affecting the permeability coefficient, and there is a positive correlation between them. With the increase of consolidation stress, the void ratio becomes smaller and smaller, the permeability becomes more and more difficult, and the decrease of permeability coefficient becomes less and less.

It can be seen from Figures 5(a) and 5(b) that the overall change trend of the calculation results of the formula is basically consistent with the test results, which is that the permeability coefficient decreased with the increase of consolidation stress. For Jingbian silty clay, when the consolidation stress \( \sigma \) is 1600 kPa, the average permeability coefficient measured by indoor permeability test is about \( 3.26 \times 10^{-5} \) cm/s, which is about 0.27 times of the initial permeability coefficient of \( 1.21 \times 10^{-4} \) cm/s. The permeability coefficients obtained by Equations (14), (15), (25), and (26) are \( 4.45 \times 10^{-5} \) cm/s, \( 2.54 \times 10^{-5} \) cm/s, \( 7.03 \times 10^{-5} \) cm/s, and \( 5.06 \times 10^{-5} \) cm/s, respectively, which are about 0.37, 0.21, 0.59, and 0.42 times of the initial permeability coefficient, and about 1.37, 0.78, 2.16, 1.55 times of the test results. For Binzhou loess, when the consolidation stress \( \sigma \) is 1600 kPa, the average permeability coefficient measured in laboratory was about \( 1.10 \times 10^{-5} \) cm/s, which is about 0.35 times of the initial permeability coefficient of \( 3.14 \times 10^{-5} \) cm/s. The permeability coefficients calculated by Equations (14), (15), (25), and (26) are \( 1.25 \times 10^{-5} \) cm/s, \( 0.95 \times 10^{-5} \) cm/s, \( 1.95 \times 10^{-5} \) cm/s, and \( 1.43 \times 10^{-5} \) cm/s, respectively, which are about 0.39, 0.30, 0.62, and 0.46 times of the initial permeability coefficient and about 1.14, 0.86, 1.78, and 1.31 times of the test results.

Obviously, the permeability coefficients predicted by Equations (14) and (15) are closer to the experimental results, while the calculation results of Equations (25) and (26) are relatively poor in agreement with the experimental results. This is because Equations (14) and (15) decouple effective pores and ineffective pores in the derivation process, and only consider the influence of effective pores on permeability coefficient, which is more in line with the actual working conditions, whereas, as Equations (25) and (26) does not consider that ineffective pores cannot be percolated, which is equivalent to increasing the number of
permeable pores, resulting in the predicted permeability coefficient of cohesive soil in the consolidation process is much larger than the actual measured value. Therefore, it is more recommended to use Equations (14) and (15) to predict the permeability coefficient of cohesive soil in the consolidation process.

4.4. Validation of Formula by Reference Test Result. In this section, the experimental results in reference [23] are used to further verify the rationality of the newly proposed formula. Taking the test data in reference [23] as the original data, the test soil sample belongs to Luochuan silty clay. And its original moisture content \( \omega = 13.3\% \), dry density \( \rho_d = 1.34 \text{ g/cm}^3 \), liquid limit \( \omega_l = 28.4\% \), compression index \( C_s = 0.88 \), initial permeability coefficient \( k_0 = 1.80 \text{ cm/s} \), initial void ratio \( e_0 = 1.015 \), and preconsolidation stress \( \sigma_c = \sigma_0 = 115 \text{ kPa} \).

Figure 6 shows the comparison between the calculation results of the permeability coefficient formulas and the test results in reference [23]. As the figure shows that the overall variation trend of the results calculated by the formulas is consistent with that of the experimental results, when the consolidation stress \( \sigma \) is 200 kPa, the permeability coefficients calculated by Equations (14), (15), (25), and (26) are \( 0.67e - 5 \text{ cm/s} \), \( 0.39e - 5 \text{ cm/s} \), \( 0.99e - 5 \text{ cm/s} \), and \( 0.68e - 5 \text{ cm/s} \), respectively, which are 1.48, 0.87, 2.21, and 1.50 times of the test result \( 0.45e - 5 \text{ cm/s} \). When the consolidation stress \( \sigma \) is 400 kPa, the permeability coefficients obtained by Equations (14), (15), (25), and (26) are 1.70, 0.63, 4.42, and 2.26 times of the test values, respectively.

Obviously, the calculation results of Equation (15) coincided with the test results the most, followed by Equation (14). It can be seen that the permeability coefficient pre-
dicted by the revised calculation formulas in this paper is closer to the experimental values, which further proved the reliability of the improved empirical formula of the permeability coefficient.

5. Conclusion

In this paper, the pores occupied by the combined water were defined as ineffective pores, the effective pores and ineffective pores were decoupled, and the relationship between effective pores and permeability coefficient was studied. The main conclusions were as follows.

The calculation methods of effective pore and ineffective pore in cohesive soil were given, and the empirical formulas, which were suitable for calculating permeability coefficient, in the consolidation process of clay, were obtained by modifying the widely used empirical formulas of permeability coefficient with effective void ratio.

Combined with the \( e - \lg \sigma \) relationships of normally consolidated soil, underconsolidated soil, and overconsolidated soil, the empirical formulas of permeability coefficient, which considering the influence of the initial consolidation state and consolidation stress, in the consolidation process of cohesive soil, were improved.

Compared with those of the indoor consolidation-permeability tests and the existing research results, it was found that the new formulas proposed in this paper were more consistent with the measured average values, indicating the rationality of the improved permeability coefficient calculation formulas.

Data Availability

Data supporting the results of this study can be obtained from the article.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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