Analysis of variation characteristics of negative excess pore pressure of soft clay under graded unloading

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Abstract. At present, the study of soft clay under unloading action mainly focuses on the strength and deformation under unloading action. In order to clarify the change characteristics of negative superstatic pore pressure of soft clay under the action of graded unloading, a theoretical analysis is conducted based on the derived analytical solution of arbitrary discharge series and MATLAB unloading rate. In order to clarify the variation characteristics of the negative superstatic pore pressure of soft clay under hierarchical unloading, on the basis of the analytical solution of water absorption consolidation under arbitrary unloading level and unloading rate, the theoretical analysis is carried out by MATLAB programming assignment, and compared with the monitoring values obtained in practical engineering, so as to verify the accuracy analysis of the theory. Based on the influence of gradient unloading in the initial consolidation state on the change of negative superstatic pore pressure, it is divided into strong and weak phases, and the duration of the strong phase is related to the properties of soft soil, and increases with the decrease of the unloading level of the initial consolidation state of negative superstatic pore pressure. The extreme value of the negative superstatic pore pressure and its fluctuation amplitude were positively correlated with the graded unloading capacity, and the dissipation rate was negatively correlated with the unloading stage. The unloading level of the unloading layer of the actual project is solved by the analytical solution of suction consolidation. The theoretical values of the rebound and the change law of water absorption obtained from the actual engineering unloading level are compared and analyzed with the measured values, and the matching degree.

Keywords: Geotechnical engineering; Graded unloading; Water absorption and consolidation; Negative excess pore pressure; theoretical analysis.

1 Introduction

In recent years, with the rapid development of infrastructure construction in China, the foundation pit excavation, road prepressing and other projects on the soft foundation are faced with the problem of rebound deformation under the action of graded unloading. The unique characteristics of soft soil lead to its extremely complex deformation

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laws under different stress states, stress histories and load changes. Due to the large fluctuation of low-frequency cyclic load, soft soil foundation is easy to cause problems such as large deformation, long settlement time and difficult prediction under the action of low-frequency cyclic load, which may lead to uneven settlement of foundation and stress redistribution, affect the stability of the superstructure, and may lead to the instability and damage of the superstructure in serious cases, resulting in major economic losses. In this paper, the variation law of water absorption and rebound under graded unloading of soft foundation is compared and analyzed as the research background, and the theoretical value of water absorption rebound obtained by the actual unloading stage is calculated, and the deformation of soft soil foundation under graded unloading is studied in depth, which is conducive to further understanding the principle of the deformation mechanism of soft soil foundation during the operation of storage facilities

According to the effective stress principle, understanding the change characteristics of the negative superstatic hole pressure caused by graded unloading is the premise of solving the problem of rebound deformation. Some scholars have studied the relationship between negative superstatic pore water pressure and effective stress, stress path, strain and rebound index under unloading action [1-4]; By Sivajogi[5] The generation and dissipation rules of negative pore pressure are analyzed by establishing a mathematical model; Zhou Qiujuan [6] studied the axial and lateral average unloading path, The change law of negative hole pressure and the conclusion that negative hole pressure increases with the increase of unloading amount; Li Yuqi [7] et al. studied the dissipation law of the superstatic hole pressure caused by the foundation pit excavation and the calculation method of the rebound deformation caused by the pit bottom; Fu Yanbin [8] et al. conducted a series of indoor experiments on silt soft soil in Shanghai, This paper systematically discusses the different characteristics of foundation pit; Zhou Jian [9] et al. Based on the chamber test, they concluded that the normalized pore pressure and the main strain should become quadratic, and the quadratic relationship between the normalized pore pressure and the main strain is closely related to the unloading path. Zhang Jingjing [10] found that the positive pore pressure generated by the generalized shear stress in the early stage of unloading is not enough to offset the negative pore pressure generated by the average main stress, which revealed the mechanism of the hyperstatic pore pressure under the unloading action. Hu Qizhi [11] et al. obtained the conclusion that the soil of the consolidation stress level with the consolidation stress under the same deviation stress; Shi Xu Chao [12] et al. analyzed the rebound water absorption characteristics of the soft soil under the discharge action through the indoor test; the lower the consolidation circumference pressure and the higher the initial superstatic pore water pressure, the higher the discharge damage of the soft soil is more sudden. Liu Yan Dong [13] et al.The test results show that the larger the initial excess pore water pressure, the smaller the consolidation confining pressure, and the more sudden the unloading failure of soft soil.Wang Dajun [14] analyzed the envelope structure, the pit bottom uplift and the surface deformation law through the actual foundation pit excavation. The research of domestic and foreign scholars mainly focuses on the analysis of the strength and deformation of soil through indoor experiments, while the research on negative superstatic pore pressure focuses on its influence on the strength, and rarely involves the effect of graded unloading. In this paper, based on the consolidation theory of Taisha, the consolidation equation under cyclic load is solved, and the consolidation equation is compared to the solution, so as to know the main consolidation and secondary consolidation deformation characteristics of soft soil foundation under cyclic load, and the elastoplastic viscoelastic-plastic consolidation theory should be good in function.So s to provide some reference for the construction design of soft soil foundation under the action of graded unloading.

2 The consolidation equation of water absorption under graded unloading

According to the theory of taisha consolidation, the pressure dissipation of soft clay is consolidation. In this paper, it is assumed that negative superstatic pore pressure dissipation causes water absorption consolidation, which is shown in Figure 1.

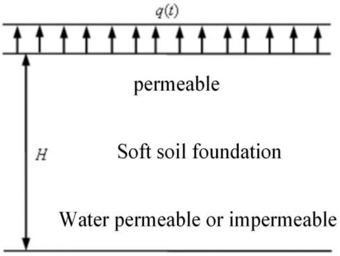


Fig. 1. Schemdiagram of one-dimensional water-absorption consolidation calculation

Taisha base consolidation theory [15], except for the load change on the soft clay, the rest can make the same hypothesis as the taisha base consolidation theory, which can get the one-dimensional water absorption consolidation of soft clay under the action of unloading:

$$C_{ve}\frac{\partial^2 u}{\partial z^2}=\frac{\partial u}{\partial t}+f(t) \tag{1}$$

the formula:

Cve——Water absorption consolidation coefficient(m2/s), A coefficient of the velocity of negative superstatic hole pressure dissipation generated under the action of soil unloading:

$$C_{\mathrm{ve}}=\frac{k_{\mathrm{v}}}{\gamma_{\mathrm{w}}m_{\mathrm{v}}}=\frac{k_{\mathrm{v}}\left(1+e_0\right)}{a_{\mathrm{v}}\gamma_{\mathrm{w}}} \tag{2}$$

f(t)——Unload rate, $f(t) = \frac{dq(t)}{dt}$, (kPa);

u——Pore water pressure(kPa);

k_{v} ——The permeability coefficient of soil unloading load(m/s);

mv——Volume rebound coefficient(kPa−1);

γ_{w} ——The pore fluid was severe（kN/m−3）;

av——resilience factor (kPa−1);

e0——Initial pore ratio of the soil body.

The initial boundary condition of the basic equation (1) is[12].

$$\begin{cases} (a)t = 0, 0 \le z \le H, u|_{t=0} = u_0(z) \\ (b) 0 < t < \infty, u|_{z=0} = 0(\text{Top surface drainage}) \\ (c) 0 < t < \infty; \left.\frac{\partial u}{dz}\right|_{z=H} = 0(\text{The bottom surface is not drained}) \\ \qquad\qquad u|_{z=H} = 0(\text{Bottom surface drainage}) \end{cases} \tag{3}$$

From Figure 1 and boundary conditions (3), the above surface drainage, the lower surface no drainage as an example, the application of the heat conduction equation solution method [16] to solve the 1 D water absorption and consolidation basic equation (1), can make the pore pressure and unloading rate:

$$u(z,t) = \sum_{n=1}^{\infty} M_n(t) \sin\frac{N}{H} z \tag{4}$$

$$f(t) = \sum_{n=1}^{\infty} X_n(t) \sin\frac{N}{H} z \tag{5}$$

By equation (5) is available:

$$X_n(t) = \frac{2}{H} \int_0^H f(t) \sin\frac{N}{H} z dz = \frac{N}{H} f(t) \tag{6}$$

In the formula:

$$N = \frac{2n-1}{2}\pi \qquad (n = 1, 2, 3, \cdots) \tag{7}$$

Add the above equations (4) and (5) into equation (1):

$$M'_n(t) + C_{\mathrm{ve}} \frac{N^2}{H^2} M_n(t) - X_n(t) = 0 \tag{8}$$

$$\text{Demand: } a = C_{\mathrm{ve}} \frac{N^2}{H^2} \tag{9}$$

Equation (7) is solved generally:

$$M_n(t)=e^{-at}\left(\frac{2}{N}\int_0^t f(\tau)e^{at}dt+C\right) \tag{10}$$

Add (8) into formula (4) and know from the initial condition (3) (a):

$$C=\frac{2}{H}\int_0^H u_0(z)\sin\frac{N}{H}zdz \tag{11}$$

Therefore, it can be solved:

$$M_n(t)=e^{-at}\left(\begin{array}{l}\frac{2}{N}\int_0^t f(\mathrm{t})e^{at}dt+\\ \frac{2}{H}\int_0^H u_0(z)\sin\frac{N}{H}zdz\end{array}\right) \tag{12}$$

Add formula (10) into the basic equation (1) of soft clay under graded discharge into formula (4):

$$u(z,t)=\sum_{n=1}^{\infty}e^{-at}\sin\frac{N}{H}z\left(\begin{array}{l}\frac{2}{N}\int_0^t f(\mathrm{t})e^{at}dt+\\ \frac{2}{H}\int_0^H u_0(z)\sin\frac{N}{H}zdz\end{array}\right) \tag{13}$$

3 Analysolution of water absorption consolidation under graded unloading

3.1 Analytic solution of one-dimensional water absorption consolidation under primary unloading

If the load$q(t)$is unloaded linearly, the specific change of the load over time is shown in Figure 2,3 and 4.

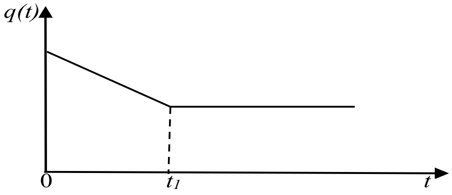


Fig. 2. Load under primary unloading changes with time

Make the initial pore pressure u0(t)=q0, and bring the graded unloading rate into formula (11) to solve the one-dimensional water-absorbing consolidation under the first discharge action:

$$u(z,t)=\begin{cases} \sum\limits_{n=1}^{\infty}\dfrac{2e^{-at}}{aN}\left\{\begin{matrix} k_1\left(e^{at}-1\right) \\ +aq_0 \end{matrix}\right\}\sin\left(\dfrac{N}{H}z\right) & 0\le t\le t_1 \\ \sum\limits_{n=1}^{\infty}\dfrac{2e^{-at}}{aN}\left\{\begin{matrix} k_1\left(e^{at_1}-1\right) \\ +aq_0 \end{matrix}\right\}\sin\left(\dfrac{N}{H}z\right) & t_1\le t \end{cases} \tag{14}$$

In the formula: k1for the discharge rate; H is the maximum drainage distance.

3.2 Analytic solution of one-dimensional water absorption consolidation under tertiary unloading

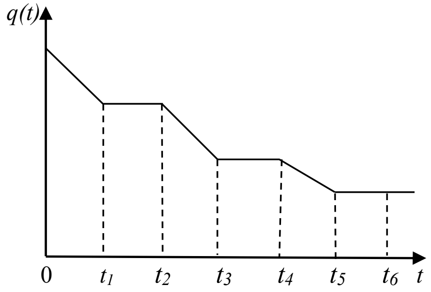


Fig. 3. The load changes with time under tertiary unloading

When the variable is in 0 ≤t ≤t 1:

$$u_1(z,t)=\sum_{n=1}^{\infty}\frac{2e^{-at}}{aN}\left[k_1\left(e^{at}-1\right)+aq_0\right]\sin\left(\frac{N}{H}z\right) \tag{15}$$

When the variable is in $t_1 \le t \le t_2$:

$$u_2(z,t)=\sum_{n=1}^{\infty}\frac{2e^{-at}}{aN}\left[k_1\left(e^{at_1}-1\right)+aq_0\right]\sin\left(\frac{N}{H}z\right) \tag{16}$$

When the variable is in $t_2 \le t \le t_3$:

$$u_3(z,t)=\sum_{n=1}^{\infty}\frac{2e^{-at}}{aN}\left\{\begin{matrix} k_2\left(e^{at}-e^{at_2}\right)+ \\ k_1\left(e^{at_1}-1\right)+aq_0 \end{matrix}\right\}\sin\left(\frac{N}{H}z\right) \tag{17}$$

When the variable is in $t_3 \le t \le t_4$:

$$u_4(z,t)=\sum_{n=1}^{\infty}\frac{2e^{-at}}{aN}\left\{\begin{array}{l}k_2\left(e^{at_3}-e^{at_2}\right)+\\k_1\left(e^{at_1}-1\right)+aq_0\end{array}\right\}\sin\left(\frac{N}{H}z\right) \tag{18}$$

When the variable is in $t_4 \le t \le t_5$:

$$u_5(z,t)=\sum_{n=1}^{\infty}\frac{2e^{-at}}{aN}\left\{\begin{array}{l}k_3\left(e^{at}-e^{at_4}\right)+\\k_2\left(e^{at_3}-e^{at_2}\right)+\\k_1\left(e^{at_1}-1\right)+aq_0\end{array}\right\}\sin\left(\frac{N}{H}z\right) \tag{19}$$

When the variable is in $t_5 \le t \le t_6$:

$$u_6(z,t)=\sum_{n=1}^{\infty}\frac{2e^{-at}}{aN}\left\{\begin{array}{l}k_3\left(e^{at_5}-e^{at_4}\right)+\\k_2\left(e^{at_3}-e^{at_2}\right)+\\k_1\left(e^{at_1}-1\right)+aq_0\end{array}\right\}\sin\left(\frac{N}{H}z\right) \tag{20}$$

3.3 Analysis of one-dimensional water absorption consolidation under N stage unloading

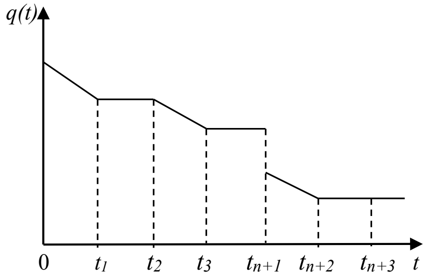


Fig. 4. Load changes with time under class N unloading

When the variable is in t(n+1) ≤t ≤t(n+2): n=0.1.2.3………n.

$$u_n(z,t)=\sum_{n=1}^{\infty}\frac{2e^{-at}}{aN}\left\{\begin{array}{c}k_{(n+1)/2}\left(e^{at}-e^{at_{n+1}}\right)+\ldots+\\k_2\left(e^{at_3}-e^{at_2}\right)+\\k_1\left(e^{at_1}-1\right)+aq_0\end{array}\right\}\sin\left(\frac{N}{H}z\right) \tag{21}$$

When the variable is in $t_{(n+2)} \le t \le t_{(n+3)}$:$n$=1.2.3………$n$.

$$u_n(z,t)=\sum_{n=1}^{\infty}\frac{2e^{-at}}{aN}\left\{\begin{array}{c}k_{n/2}\left(e^{at_{n+2}}-e^{at_{n+1}}\right)+\ldots+\\k_2\left(e^{at_3}-e^{at_2}\right)+\\k_1\left(e^{at_1}-1\right)+aq_0\end{array}\right\}\sin\left(\frac{N}{H}z\right) \tag{22}$$

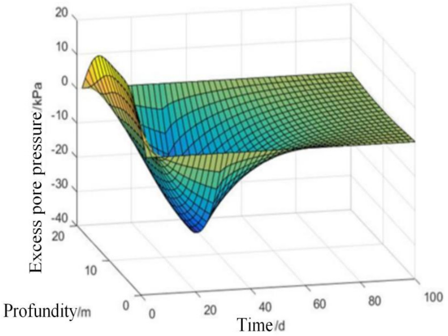
In the formula:k_i is the level i unloading rate.

Through the effective stress principle and the relationship between rebound quantity and effective stress, the analytical solution of rebound quantity is as follows:

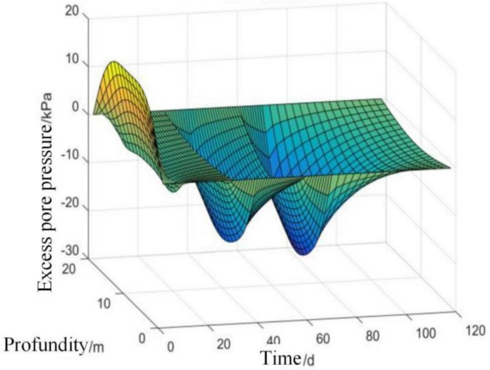
$$S(t) = -\int_0^H \frac{q(t) - u(z,t)}{E_s} dz \tag{23}$$

4 Analysis of theoretical results under graded unloading

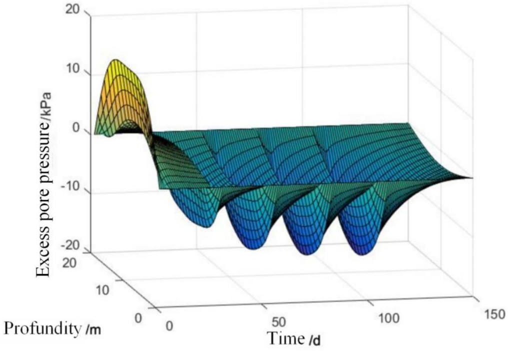
From the analytical formula (19) ~ (20) of soft clay under the action of N stage discharge, the change characteristics of negative superstatic pore pressure caused by the unloading rate of each stage, the amount of each stage, the degree of soft soil consolidation and the properties of soft soil. The analytical solution (19) to (20) is calculated by MATLAB, where the initial overstatic hole pressure is 20 kPa; the consolidation coefficient is Cve=2m2/d;; the maximum discharge amount is 60kPa; the maximum drainage distance is H=10m. Then the negative superstatic hole pressure over time and depth is shown in Figure 5.



(a) Negative hyperstatic pore pressure change under primary discharge



(b) Negative hyperstatic pore pressure change under tertiary discharge



(c) Negative hyperstatic pore pressure change under the action of five-stage discharge

Fig. 5. Change of negative hyperstatic pore pressure under graded unloading

As can be seen from Figure 5: negative overstatic hole pressure; the change path of negative superstatic hole pressure caused by discharge; the pressure of negative overstatic hole pressure increases with the drainage distance, indicating that the depth can slow the dissipation speed of negative overstatic hole pressure, that is, the foundation depth has a delay effect on the change of negative superstatic hole pressure; and the dissipation of negative superstatic hole pressure will cause water absorption rebound [12], indicating that the rebound time of the deep soil is longer than that of the soil in the shallow layer.

Figure 6. Changing the unloading path only, The rest of the parameters must be, It can be seen from the figure that the unloading series affects the dissipation path of the negative hyperstatic hole pressure caused by unloading; The negative hyperstatic hole pressure gradually increases during the discharge period and decreases during the interval, Has been in a fluctuating state; When the total unloading amount is certain, As the unloading series increases, The fluctuation amplitude of the negative hyperstatic hole pressure gradually decreases; The negative hyperstatic hole pressure maximum decreases with the discharge series, The time required for complete dissipation increases with the increase of the discharge series, indicating that the unloading series affects the dissipation rate of the negative hyperstatic pore pressure, The more the unloading series, The slower the negative hyperstatic hole pressure is dissipated; That is, the accurate fitting of unloading series in actual engineering is the premise of understanding the real change of negative superstatic hole pressure under the action of graded unloading.

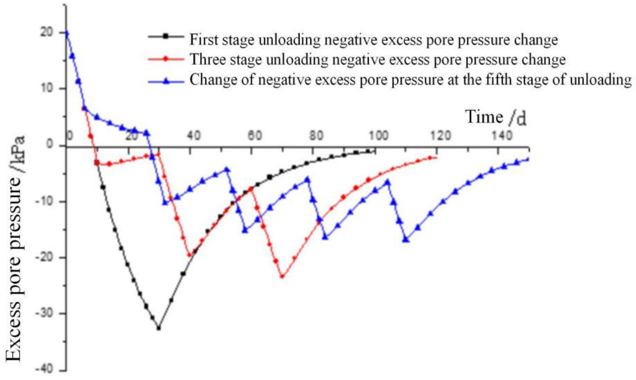


Fig. 6. Change of negative hyperstatic pore pressure under different unloading stages

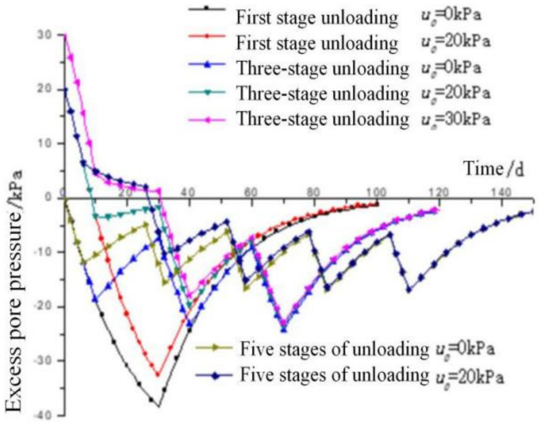


Fig. 7. Effect of different consolidation states on negative hyperstatic pore pressure changes under graded unloading

According to the consolidation theory, the consolidation state of soft clay depends on the degree of superstatic hole pressure dissipation. Assuming that soft clay is not completely consolidated at the initial discharge, A certain amount of hyperstatic hole pressure has not dissipated, As can be seen from Figure 7, the change of negative hyperstatic pore pressure under the graded unloading effect of different initial consolidation states: the initial consolidation state directly affects the change path and extreme value of negative hyperstatic pore pressure, The lower the soft clay consolidation level, The greater the influence on the negative hyperstatic hole pressure change, the smaller the negative hyperstatic hole pressure extreme value; The degree to which the initial consolidation state affects the negative hyperstatic pore pressure depends on the unloading series, The less the unloading series, The greater the impact; Under the graded load-unloading action, The negative hyperstatic pore pressure change can be divided into strong period and weak period, influenced by the initial consolidation state; When soft clay consolidation is low, The initial stage of unloading will not occur in the soft soil, Only when the soft clay is fully consolidated, Unloading and water absorption rebound occurs at the same time..

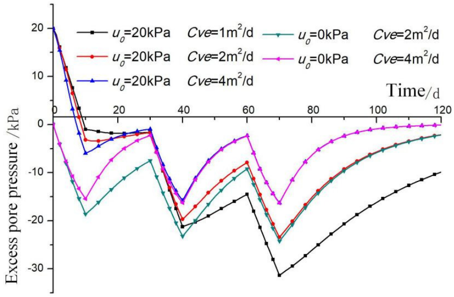


Fig. 8. Influence of soft soil properties on the change of negative superstatic pore pressure under graded unloading

According to the definition of water absorption consolidation coefficient Cve, the size of the pore water fluidity in soft clay is affected by the water absorption consolidation coefficient, and the pore water fluidity increases with the increase of the water absorption consolidation coefficient. Figure 8 analyzes the change of negative super static hole pressure of soft clay of different properties under the effect of consolidation coefficient of water absorption. The better the negative super static hole pressure, the faster the dissipation rate of the negative super static hole pressure; the influence of the negative super static hole pressure, and the fluctuation range and the time required for the complete dissipation of soft soil.

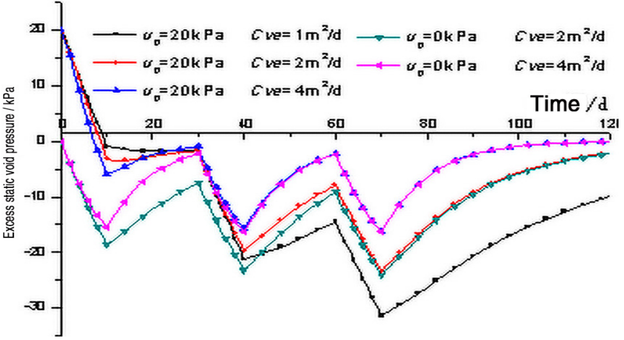


Fig. 9. Influence of graded unloading rate on negative hyperstatic hole pressure

Figure 9 Taking the tertiary unloading as an example, it can be seen that the change path of negative superstatic hole pressure under the action of graded unloading is directly affected by the unloading rate of each level; the extreme value and its fluctuation range increase with the graded unloading rate; the greater the graded unloading rate, the faster the negative hyperstatic hole pressure is dissipated; and the last unloading rate has the most significant influence on the negative hyperstatic hole pressure.

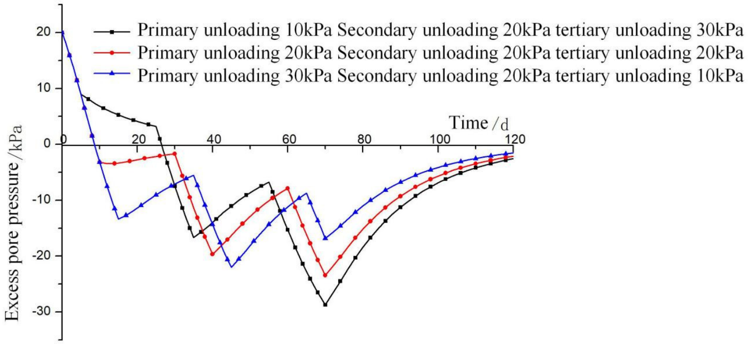


Fig. 10. Effect of graded discharge path on negative hyperstatic hole pressure

As can be seen from Figure 10, When the unloading volume is small, Does not produce a negative superstatic pore pressure, From the assumption of water-absorption consolidation theory, Soft clay will absorb water and cement when the negative hyperstatic hole pressure will dissipate, And then causes the rebound deformation, That is, the generation and dissipation of negative superstatic hole pressure is the premise of unloading and rebound, Whether unloading occurs depends on the initial consolidation state and the amount of unloading, When the unloading volume is small, There will be no rebound, The same conclusion can be obtained from the unloading test of Super [12]; Mutual validation from the test results and the theoretical analysis, It explains the correctness of the theoretical solution in this paper; The change path of negative hyperstatic hole pressure depends on the amount of graded discharge; Change only, The negative hyperstatic pore pressure change is most affected by the final unloading volume, The greater the unloading amount of the final stage, The greater the extreme value of the negative hyperstatic hole pressure, and the longer the time required for the negative hyperstatic hole pressure to completely dissipate; When the total unloading amount is determined, The negative hyperstatic hole pressure of soft clay can be reduced by reducing the final discharge.

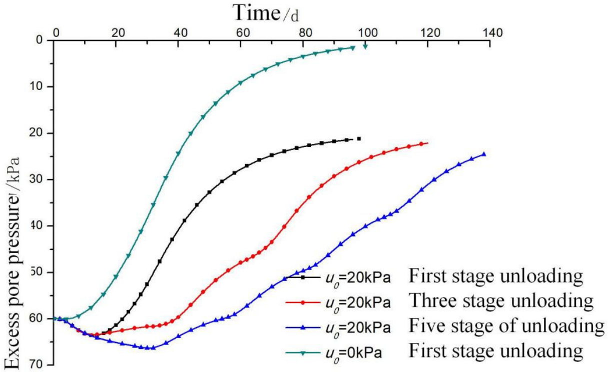


Fig. 11. Effective stress change under graded unloading

According to Figure 11, The change path of the effective stress under the action of graded unloading is related to the unloading series and the initial consolidation state; When the unloading amount is certain, The more the unloading series, The more gradual the effective stress changes; The effective stress reduction rate during the unloading period is significantly faster than the interval period; When the soft clay is consolidated, Under unloading, Effective stress first increases and then decreases, Note that at the initial stage of unloading, The load discharge amount is first borne by the ultra-static hole pressure, And the dissipation speed of the superstatic hole pressure in the initial stage of unloading is greater than the unloading rate, When the hyperstatic hole pressure has completely dissipated, Unload quantity is borne by the effective stress, The effective stress begins to decrease with the unloading of the load; When the soft clay is fully consolidated, Effective stress decreases with "S".

5 Analysis of engineering examples

In order to verify the accuracy of the above theoretical analysis method, the subway foundation pit excavation project in literature [14] is taken as an example. The foundation pit is about 204.34m long and 21.2m wide. The excavation is divided into four sections. The first and second sections are continuously excavated, and the third and fourth sections have a time interval. (μ_0 is 0-30 kPa). The specific excavation process is shown in the four-level unloading fitted in Figure 12. The foundation pit excavation is constructed by open excavation method, and the foundation pit has three steel pipe supporting structures, and a single row of bored pile retaining structure. The foundation pit belongs to the long strip foundation pit to reduce the spatial effect. The groundwater level is deep, and the foundation pit precipitation reduces the underground stable water level to about 1m below the bottom of the foundation pit at one time.

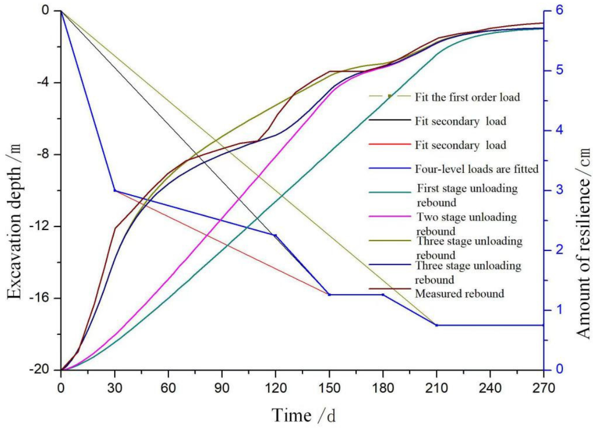


Fig. 12. Comparison of the theoretical value and the measured value of the foundation excavation process and the rebound value

As can be seen from Figure 12, the greater the unloading rate, The faster the rebound volume increases; Under the action of graded unloading, The character and frequency of the band are related to the unloading path and the soft soil properties; As the simplified unloading series gradually approaches the actual unloading series, The theoretical rebound volume gradually coincides with the actual monitoring rebound volume and its change law, And the error gradually decreases with the proximity of the fitting series; The unloading path directly affects the change process of the rebound deformation, Since the unloading rebound is caused by the dissipation of the negative hyperstatic hole pressure, That is, the accurate fitting of the unloading series is the premise of understanding the real change of the soft base negative superstatic hole pressure under the action of graded unloading; At the same time, the practicability and reliability of the theoretical solution and the measured value.

6 Conclusion

(1) Through the one-dimensional consolidation theory of Taisha base, the analytical solution of arbitrary discharge series and discharge rate is derived, and the analytical solution of the consolidation equation under linear loading is given. In the soft clay foundation, the analytical solution of the linear loading consolidation equation provides a basis for the subsequent study of the theoretical value and change law.

(2) The change of negative super static pore pressure can be affected by the initial consolidation state: the strong and weak periods and the duration of the duration of soft clay; when the soft soil is low at the beginning of the soft clay, the lower the influence

of the negative super static pore pressure, the greater the influence depends on the unloading series, and the less the unloading series, the greater the impact.

(3) The extreme value of negative overstatic hole pressure and its fluctuation range increase with the graded unloading rate and quantity; the negative overstatic hole pressure change is significantly affected by the final unloading rate and quantity; the initial unloading amount is borne by the overstatic hole pressure or the effective stress depends on the initial consolidation state.

(4) Based on the engineering example, the theoretical and measured data of the rebound under the effect of graded unloading, and found that the theoretical value of the rebound based on the corresponding unloading series are in good agreement with the measured value, which shows the reliability of the theoretical solution in this paper.

(5) This chapter mainly uses MATLAB to program and assign the analytical solutions of hole pressure, settlement and consolidation, and studies the macroscopic deformation of soft soil foundation under low-frequency cyclic loads through theoretical solutions, and subsequent scholars can focus on the types of cyclic loads, loading\resting of loads\ empty time, consolidation coefficient of the foundation, low-frequency cyclic load, cyclic load period, drainage distance required for theoretical calculation and other data are studied

(6)) However, through the comparison of theory, experiment and simulation, there are several aspects that need to be further studied in this paper, and in actual engineering geology, the ultrastatic pore pressure caused by soft soil foundation under low-frequency cyclic load will dissipate in three directions, so in order to be more in line with the realistic situation, the follow-up research should be explored to solve the three-dimensional consolidation equation.

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