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Settlement deformation characteristics and control of soft soil through groundwater discharge zone

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ABSTRACT

The control of settlement deformation of soft soil is essential to improve the success rate of the project, especially the uneven settlement control. The deep soft soil layer of the four runways in an airport is taken as the research object to be conducted on the preloading test. The settlement deformation characteristics of the foundation soil layer are studied under the two conditions of inserting plastic drainage plates and not inserting plastic drainage plates. It is found that the settlement rate and settlement quantity of the original foundation in the inserted plate area is far greater than those in the non-inserted plate area during the surcharge preloading. The stratified settlement observation results show that in the process of overload preloading, compared with the actual engineering load, the shallow soil layer of the foundation strata is over-consolidated while the deep soil layer is still under-consolidated. Therefore, the residual settlement of each layer after surcharge unloading should be calculated separately. The research results have important reference significance for the design and construction of similar soft soil foundation treatment projects.

Keywords: Soft soil; Settlement deformation; Settlement deformation characteristics; Soil mechanics

1. Introduction

Soft soil has high compressibility, high water content, low strength and poor permeability, in which certain settlements will be generated under the long-term of upper load. Settlement is one of the main research topics of soil mechanics. Therefore, the theoretical development of foundation settlement has made great progress so far and has played a great guiding role in engineering construction [1]. However, as Thai Scholar E.W. Brand pointed out, although the theory of foundation settlement calculation has been greatly improved, the prediction of settlement is more technical than the general geotechnical calculation. Today, in many cases, the error of final settlement prediction is less than 10%–20%, but it is still hard to predict the relationship between settlement and time. Due to the high compressibility of soft soil, the requirements are very strict for settlement deformation and stability of subgrade [2].

Preloading is commonly used for the foundation treatment of large-area soft soil layers. According to the relative size of the applied load and engineering load, it can be divided into insufficient-load preloading, equal-load preloading, and surcharge preloading [3]. Surcharge preloading and joint setting of sand wells or plastic drainage plates in the soil layer can be used to accelerate the drainage consolidation of the foundation [4]. It is proved that surcharge preloading not only solves the problem of large settlement deformation of the soft soil layer, but also significantly improves the physical and mechanical indexes of soft soil. Amin et al. [5] studied the deformation mechanism of soil layer under surcharge preloading and proposed that the magnitude action time of surcharge preloading should be based on the completion of the primary consolidation

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settlement of equal load. Besides, there was regular correspondence between the secondary consolidation coefficient of soft soil and the overload ratio, so the characteristic parameters could be determined by the linear mapping method [6].

The deep soft soil layer of the four runways in an airport is taken as the research object to be conducted on the preloading test. The settlement deformation rule of the foundation soil layer is studied under the two conditions of inserting plastic drainage plates and not inserting plastic drainage plates [7]. The research results provide an important reference for the design and construction of similar soft soil foundation treatment projects.

2. Method

The airport site is a geomorphic type of estuary, spit and sand island, in which the soft soil layer is very thick. In general, the thickness of the soft soil layer in the region is about 30 m, while that in the region with ancient rivers is close to 60 m. The large settlement of soft soil layer and long consolidation time are the problems that need to be solved first in engineering construction [8]. The newly built four runways are adjacent to the seawall. The site is originally a beach land formed by sea reclamation for siltation, most of which has been treated by surcharge preloading for 5 y. The settlement observation data shows that the foundation deformation is stable. Due to the plane adjustment of the airport, the northern end of the four runways is about 400 m beyond the surcharge range [9]. The area is not pretreated causing large settlement, so it is difficult to solve settlement deformation in the area in a short time and to realize the coordinated deformation of the area and the surrounding area [10].

The construction site of four runways is a typical deep multi-layer soft soil foundation with short project construction period and high deformation control requirements [11]. The preloading test is conducted on the site to compare the deformation law of soft soil under the two conditions of inserting plastic drainage plates and not inserting plastic drainage plates to study the deformation characteristics of soft soil. The research results have important reference value and significance for the design and construction of Pudong Airport and similar soft soil foundation treatment.

2.1. Design of surcharge preloading test

The test site is located at the northern end of the four runways, in which the terrain is relatively flat. The original ground elevation is within the range of 2.5–4 m. The soil layer of the site is mainly a soft soil layer within 45 m [12].

The surcharge preloading method is used to accelerate the drainage consolidation rate of the soft soil layer by applying overload. Thus, most of the settlement is completed relative to the engineering load during the stacking period, so that the residual settlement after unloading meets the requirements of the project [6]. The engineering load (filling load and pavement structure load) of the runways on the test site is about 67.5 kPa. Silty fine sand is used as the loading material, forming a pile carrier about 6.5 m of the average height. The weight of silty fine sand is about 16.5 kN/m^2 with an average pressure of about 107.3 kPa.

The test area is divided into two zones. Zone One adopts the scheme of inserting a plastic drainage plate (referred to as the "inserting plate" scheme), with an area of about 93,000 m^2. Meanwhile, Zone Two adopts the non-insertion plastic drainage plate scheme (referred to as the "non-insertion" scheme), with an area of about 17,000 m^2. Plastic drainage plates adopt the SPB-C type of 10 cm width and 4.5 mm thickness, which are arranged in a triangle with 1.5 m wide spacing and 25 m length. The surcharge preloading test lasts for 10 months, among which the loading time is about 2 months and the full loading time is about 8 months [13]. The design of the surcharge preloading test is shown in Table 1, and the plane distribution of the test area is shown in Fig. 1.

The final settlement of the foundation is calculated by the stratified summation method, which is expressed as Eq. (1).

$$S = \psi_s \sum_{i=1}^{n} \frac{e_{1i} - e_{2i}}{1 + e_{1i}} h_i \tag{1}$$

where S is a total settlement, while s is the empirical coefficient of settlement calculation. For normal consolidated saturated cohesive soil foundation, s is taken from 1.1 to 1.4. When the load is large and the foundation soil is weak, the larger value is taken, otherwise, the smaller value is taken. e_{1i} is the pore ratio corresponding to self-weight pressure, and e_{2i} is the pore ratio corresponding to the sum of self-weight pressure and additional stress [14].

The improved Takagi Shunsuke method is used to calculate the consolidation degree. When the consolidation time is t, the average consolidation degree of the foundation is expressed as Eqs. (2)–(4).

$$\overline{U}_t = \sum_{i=1}^{n} \frac{q_i}{\sum \Delta p}\left[\left(T_i - T_{i-1}\right) - \frac{\alpha}{\beta} e^{\beta_t}\left(e^{\beta T_i - \beta T_{i-1}}\right)\right] \tag{2}$$

$$\alpha = \frac{8}{\pi^2} \tag{3}$$

$$\beta = \frac{\pi^2 C_v}{4H^2} + \frac{8C_r}{F_n d_e^2} \tag{4}$$

where $\overline{U}_t$ is the average consolidation degree of t, while q_i is the loading rate for the load of the ith level, and $\sum\Delta p$ is the cumulative value of loads at all levels. T_i and T_{i-1} are the end time and start time for the loading of the ith level, respectively. In Eq. (4), C_v is the vertical drainage consolidation coefficient of soil, while C_r is the radial drainage

Table 1
Design of surcharge preloading test

Zone	Foundation treatment method	Note
One	inserting plate	Range of runway surface
Two	Non-inserting plate	Outside the runway surface

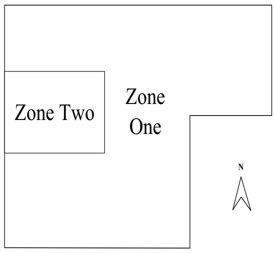

Fig. 1. Diagram of test zones.

consolidation coefficient of soil. d_e is the equivalent conversion diameter for plastic plates.

2.2. Design of deformation observation

The observation is conducted on foundation settlement, stratified settlement, pore water pressure, groundwater level and horizontal displacement of slope toe to understand the deformation characteristics of foundation soil during surcharge preloading. Firstly, the observation plate of the original foundation settlement is set at 0.5 m below the surface, in which the observation rod can be lengthened step by step according to the filling height with the protection of the polyvinyl chloride (PVC) sleeve. Secondly, the one-hole multi-point settlement observation magnetic ring device is adopted to observe the stratified settlement, and the magnetic ring is sleeved outside the PVC observation pipe and buried in the corresponding depth. When the pore water pressure gauge is buried, coarse sand is used as a permeable filler, and the filling thickness of the permeable layer is 0.8 m. For water level observation, a special water level monitoring PVC pipe with a diameter of 53 mm is embedded in the drill hole with a diameter of 89 mm. Finally, a side pile set at slope toe is used to observe the horizontal displacement of slope toe [15].

3. Results and discussion

3.1. Analysis of original foundation settlement

3.1.1. Comparison of the settlement in the inserting plate zone and the non-inserting plate zone

The foundation settlement in the test area is analyzed, and the comparison curve is shown in Fig. 2 of the stuck height, calculative settlement, and time in the inserting plate zone and the non-inserting plate zone. In Fig. 2, there is lots of settlement in both two test zones, and the settlement deformation gradually slows down after the load is stable.

The settlement of the inserting plate zone during loading is 848.8 mm, accounting for about 64.7% of the total settlement during preloading. The settlement of the non-inserting plate zone is 397.0 mm, accounting for about 59.8% of the total settlement during the preloading period. In this stage, the settlement deformation is mainly instantaneous settlement which is positively correlated with the loading amount [16].

After loading, the settlement deformation rate of the two test zones decreases gradually. The settlement curve tends to be gentle after six months of full load. After 8 months of full load, the settlement of the inserting zone is 1,311.5 mm, while the settlement of the non-inserting zone is 664.3 mm, and the latter is only 50.7% of the former.

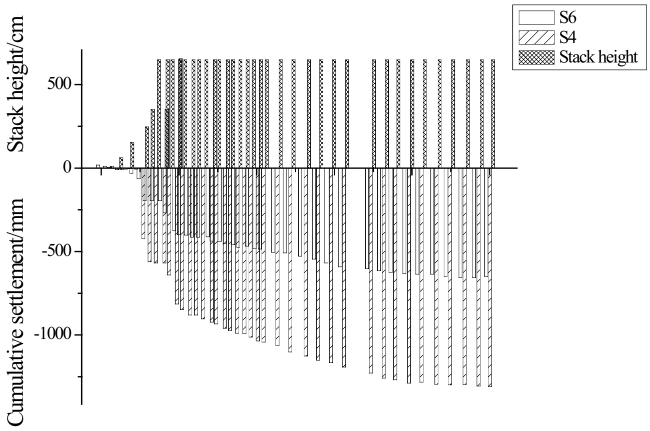

Fig. 2. Stuck height-settlement-time trend.

3.1.2. Analysis of relative settlement

The relative change is analyzed of the foundation settlement S_2 in the non-inserting plate zone and the foundation settlement S_1 in the inserting plate zone after the load is stability, and m is the settlement ratio of the two (the change of the settlement ratio of the two is shown in Fig. 3).

$$m = \frac{S_2}{S_1} \tag{5}$$

From Fig. 3, at the end of the loading (about 2 months), the ratio of the settlement of the non-inserting plate zone to that of the inserting plate zone is m = 46.8%. With the increase in loading time, the settlement ratio m of the two zones increases gradually, and by the tenth month, the settlement ratio m of the two zones increases to 50.7%. Combined with the change relationship of the settlement rate of the two test zones in Fig. 4, the reason for this situation is that when the load is stable, the settlement rate of the inserting plate zone decreases faster than that of the non-inserting plate zone. Besides, with the increase of the preloading time, the settlement rate of the inserting plate zone is smaller than that of the non-inserting plate zone after a certain time point. Therefore, the settlement difference between the inserting plate zone and the non-inserting plate zone increases first and then decreases [17].

3.1.3. Comparative analysis of settlement rate

Fig. 4 shows the change of the foundation settlement rate in the test zones. During the loading period of about 60 d, the settlement rate changes greatly. The larger the loading amount is, the faster the settlement rate is. The average settlement rate of S4 observation point in the inserting plate zone is about 14.4 mm/d in the second month, while the average settlement rate of S6 observation point in the non-inserting plate zone is about 10.6 mm/d. This indicates

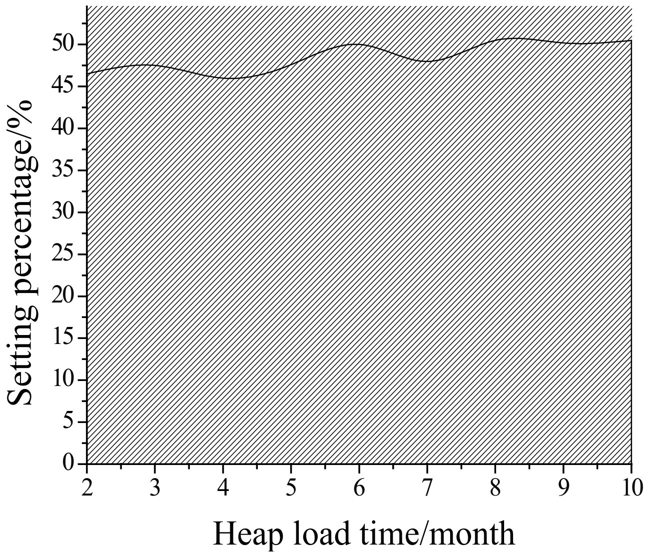

Fig. 3. Change curve of settlement ratio between non-inserting plate zone and inserting plate zone after full load.

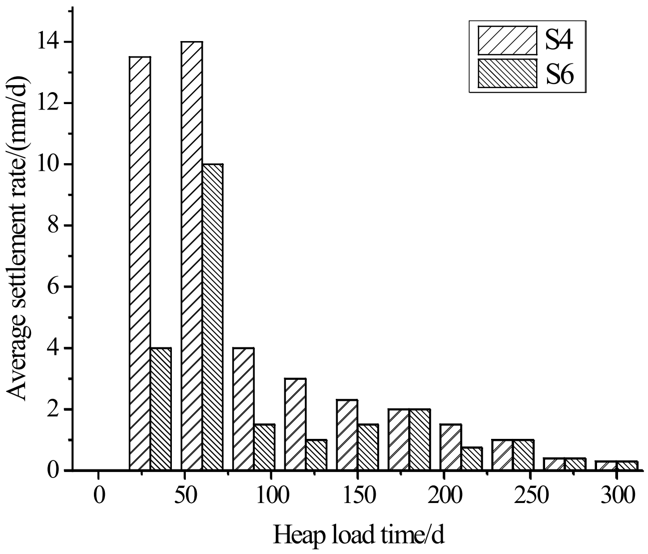

Fig. 4. Average settlement rate during preloading.

that the settlement rate of the inserting plate zone is far greater than that of the non-inserting plate zone.

During the placement period after loading, the settlement rate of the two test zones decreases gradually. In detail, the settlement rate of the inserting plate zone decreases rapidly from 3.54 mm/d in the third month to 0.32 mm/d in the tenth month. However, the settlement rate of the non-inserting plate zone changes relatively slowly from 1.87 mm/d in the third month to 0.33 mm/d in the tenth month. The settlement rate of the two test zones is both less than 0.4 mm/d in the tenth month. Meanwhile, the change trend of the settlement deformation rate of the two test zones begins to appear the scissors difference in the tenth month. It is predicted that the settlement rate of the non-inserting plate zone will be greater than that of the inserting plate zone from the eleventh month [18].

3.2. Analysis of stratified settlement

3.2.1. Observation results of the inserting plate zone

The study of stratified settlement is also crucial besides the foundation settlement deformation analysis. Through stratified research, the main soil layer and its deformation law of settlement deformation are found to formulate targeted treatment measures. In this experiment, the stratified settlement is observed of the soil layer in the inserting plate zone. The buried depth of the observation magnetic ring of stratified settlement is two meters to 38 m, and 10 observation points are set up. The detail of stratified settlement deformation is shown in Fig. 5.

In Fig. 5, the deformation rule is basically the same observed by the magnetic ring at each depth. The settlement is large measured by the magnetic ring at the shallow depth, while the settlement is small measured by the magnetic ring at the deep depth. The settlement measured by the magnetic ring at the depth of 22 m is about 280.7 mm. Meanwhile, the settlement measured by the magnetic ring at the depth is 38 m. These indicate that large-area loading can influence the settlement of a very deep soil layer.

3.2.2. Analysis of the main layer settlement in the inserting plate zone

Combined with the observation data of ST1 observation point of stratified settlement and adjacent S4 observation point of foundation settlement, the stratified settlement deformation is analyzed in the inserting plate zone.

The ground soil layer is divided into four main layers, in which the first layer is the shallow layer within the depth from 0 to 10 m. The second layer is the middle layer within the depth interval from ten meters to 22 m. The middle layer is mainly ④ layer of the muddy clay, which is the main soil layer for settlement deformation according to experience. The third layer is within the depth from 22 to 38 m, which is ⑤ layer (⑤ 1–1 is clay, and ⑤ 1–2 is silty clay). The fourth layer is below 38 m mainly with silty sand. The settlement deformation of these four main layers during the loading process is compared and analyzed, and the comparison results are shown in Fig. 6.

In Fig. 6, when the loading is just completed, the settlement of the second layer is the largest, about 339.0 mm, and the settlement of the first layer is 279.2 mm. When the stacking time reaches 6 months, the deformation of the first layer is larger, of which the total deformation exceeds the second layer. After 6 months, the deformation of each group is relatively small.

3.2.3. Analysis of soil state under engineering load

Due to the surcharge preloading, the settlement rate of foundation soil is fast, and the settlement is large in a short time. For the state of foundation soil at this time, the analysis should be carried out relative to the actual engineering load [19].

The settlement under the engineering load of the runways in the test site is calculated by the stratified summation method. The engineering load of the runway is about 67.5 kPa. The calculated settlement under the engineering

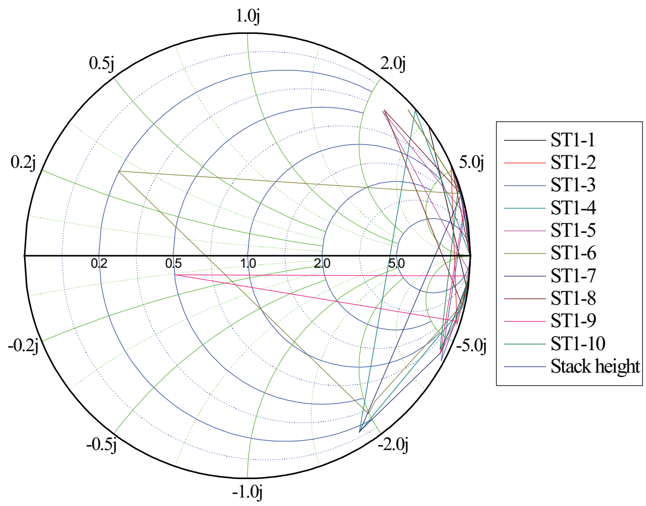

Fig. 5. The curve of stratified settlement deformation.

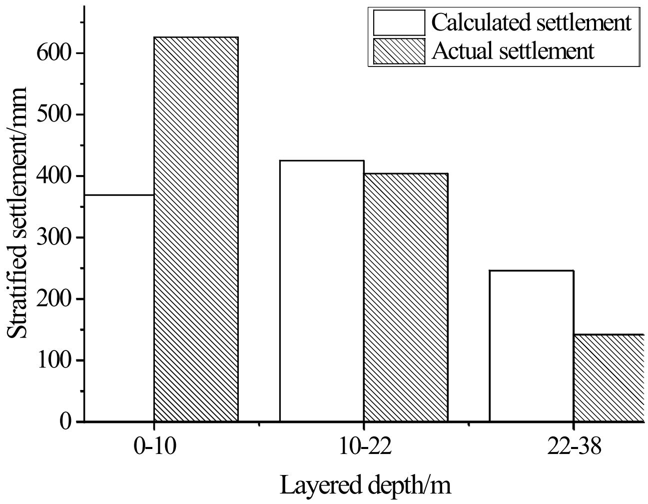

Fig. 7. Comparison between the calculated settlement and actual settlement.

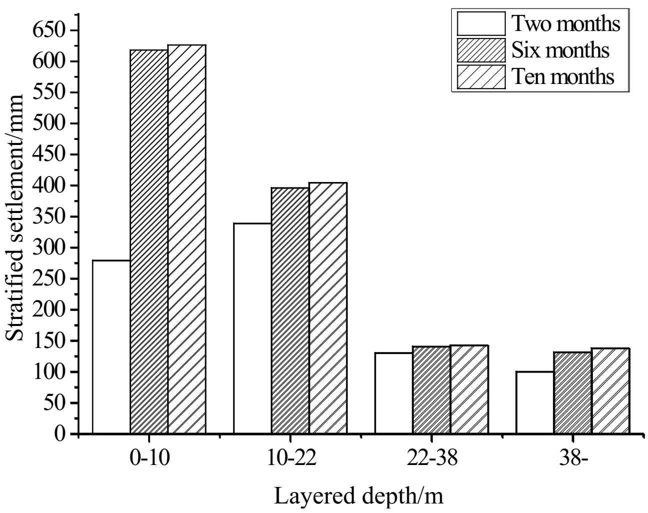

Fig. 6. Comparison of the settlement of each layer.

load is compared with the measured stratified settlement after ten months of surcharge preloading. The comparison results are shown in Fig. 7.

In Fig. 7, the measured deformation of the shallow soil layer is far greater than the calculated settlement under the engineering load when the surcharge preloading is up to the tenth month. This denotes that the shallow soil layer at this time is in a state of over-consolidation relative to the engineering load. The soil layer below ten meters is still under consolidation, and settlement deformation still occurs after overload removal and engineering load application.

Through the above analysis of stratified settlement of foundation soil during surcharge preloading, the plastic drainage plate installed in the soil layer changes the original drainage channel of the foundation, so the drainage consolidation rate of the inserting plate zone is faster than that of the non-inserting plate zone. In the range of the plate, considering that with the increase of buried depth and time, the drainage effect of the drainage plate gradually decreases, the drainage consolidation rate of the shallow layer is faster than that of the deep layer.

Under the surcharge preloading, the calculated settlement and settlement rate during the stacking period increase with the growth of the overload. Therefore, for the deep and multi-layer soft soil foundation, as the preloading time increases, the shallow soil layer will be the first to reach 100% consolidation relative to the engineering load, while the deep soil layer is still under-developed. Besides, as the stacking time continues to increase thereafter, the shallow soil layer will appear over-consolidated while the deep soil layer is still in a state of coexistence of under-consolidation. Thus, the analysis of the remaining settlement relative to the engineering load after the unload should be calculated separately in layers rather than a simple comparison from the perspective of the original foundation settlement.

3.3. Evaluation of the loading effect on the test area

After the completion of the four runways project in an airport, the settlement observation points are set on the runway surface to observe the settlement of the runway during the operation period. Four times of settlement observations are carried out on the four runways. At this time, the settlement rate of the test section pavement area (the inserting plate zone) is compared with the settlement rate of the pre-loading area of the four runways. The comparison results are shown in Fig. 8.

From the comparison of settlement rate in Fig. 8, the settlement rate of the test area (the inserting plate zone) is slightly larger than that of the pre-loading area, but the settlement rate is relatively close. The surcharge preloading integrated with inserting plate adopted in the test pavement area solves the problem of large settlement deformation and realizes the uniform settlement of the whole four runways.

4. Conclusions

Through the surcharge preloading test, the following conclusions can be drawn. (1) The settlement deformation

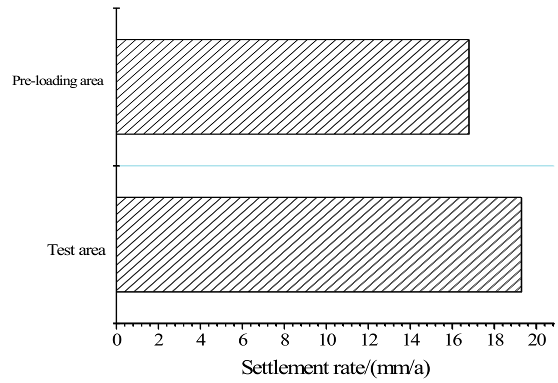

Fig. 8. Comparison of the settlement rate of the test area and pre-loading area.

of the inserting plate zone is much larger than that of the non-inserting plate zone. When the load is completed, the settlement of the non-inserting plate zone is only 46.8% of that of the inserting plate zone. After ten months of surcharge preloading, the settlement of the non-inserting plate zone is only 50.6% of that of the inserting plate zone. (2) The instantaneous settlement is relatively large. The instantaneous settlement of the inserting plate zone accounts for about 64.7% of the total settlement during the stacking. The instantaneous settlement of the non-inserting plate zone accounts for about 59.8% of the total settlement during the stacking. Besides, the instantaneous settlement is positively correlated with loading within the allowable range of foundation strength. (3) The settlement rate of the inserting plate zone is fast first and then slow, which is much larger than that of the non-inserting plate zone in the early stage of the heap load. When the heap load time reaches eight to nine months, the settlement rate of the inserting plate zone is close to that of the non-inserting plate zone. After ten months of heap load, the settlement rate of the two zones appears scissors difference. The drainage consolidation rate of the non-inserting plate zone is small, but the time to maintain a certain drainage rate is long. (4) Through the investigation of the stratified settlement of the inserting plate zone, with the stacking time increasing, compared with the engineering load, the shallow soil layer will be over-consolidated and the deep soil layer is still under-consolidated. Therefore, the residual settlement after unloading should be analyzed separately.

There may be result deviations caused by data errors in the research, so future research will be more rigorous to reduce errors. Although some progress has been achieved in the settlement and deformation control of soft soils, due to the constraints of time and actual working conditions, the above conclusions are only preliminary results. With the further deepening of the research work and the continuous expansion of the actual scope, a series of new problems will inevitably appear. Thus, more deep research is expected to be conducted in the future.

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