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Analysis on effective range of plastic vertical drain under vacuum preloading

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Abstract. The effective range of plastic vertical drain (PVD) can reflect the strengthening effect of vacuum preloading. The consolidation degree of the soil at any point is calculated which bases on the conventional consolidation equation for sand-drained ground. The effective range of PVD is deduced through the consolidation degree. The variation of effective range is analyzed. The results show: the effective range of PVD is not always a cylinder but a change process from an inverted cone to an inverted circular truncated cone, to a cylinder. In addition, the thickness of the smear zone, the coefficient of permeability and the ratio of the diameter to the diameter have a certain influence on the effective range. Therefore, the effective range should consider in design and construction.

Key words. Plastic vertical drain, effective range, discharge capacity, vacuum preloading.

1. Introduction

Vacuum preloading has been widely applied to soft ground treatment in recent year. But, the engineering practice shows that reclaimed soil foundation reinforcement effect is not ideal when the plastic vertical drain (PVD) regards as drainage channel[1]˜[3]. The soil strength is higher at the ground surface soil or the soil near the PVD, and it is relatively small between the PVDs. In depth analysis of this phenomenon is mainly due to the nature of the sludge itself, smearing area and plastic drainage plate itself bending, clogging, etc., the actual impact of PVD is not as large as expected, so that the reinforcement effect of the foundation is not ideal.

In this paper, the effective range of plastic drainage plate is introduced, and it is defined as the scope of soil mass whose strength reaches the design requirement after the vacuum preloading is adopted as the center of the PVD. At present, both the consolidation theory[4]˜[6] and the design and construction[7] consider that the effective range of the PVD is the cylinder with the radius of re. Through analysis

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and research, it is considered that the effective range of PVD is constantly changing, and the final range is less than or equal to the cylinder with re radius.

In order to analyze on the effective range of the PVD, the consolidation degree of the soil is calculated based on the analytical theory of sand drain foundation, and the soil range is deduced according to the degree of soil consolidation. Furthermore, the variation of the effective range of PVD in dredger fill silt foundation is analyzed. Finally, the influence of PVD water content, coating area thickness, soil permeability coefficient and well diameter ratio on the effective influence range is discussed.

2. Theoretical basis

Xie Kang-he etc.[4] put forward a new solution for the consolidation of soils with penetrating drain wells under the condition of equal vertical strain bases on Hansbo's classical theory[3]. The analytical solution of sand drain consolidation equation is:

$$\bar{u}_r = \sum_{m=0}^{\infty} \frac{2}{M} \sin\left(\frac{M}{H} Z\right) \cdot e^{-B_r t} \cdot u_0 \tag{1}$$

$$u_r = \sum_{m=0}^{\infty} \frac{2}{M} \sin(\frac{M}{H} Z) \cdot e^{-B_R t} \cdot u_0 \left[\frac{k_h B_r}{k_s F_a \lambda}\left(\ln \frac{r}{r_w} - \frac{r^2 - r_w^2}{2r_e^2}\right) + \frac{\lambda - B_r}{\lambda}\right] \mathrm{r}_w \mathrm{r} \mathrm{r}_s \ (2)$$

$$u_r = \sum_{m=0}^{\infty} \frac{2}{M} \sin(\frac{M}{H} Z) \cdot e^{-B_r t} \cdot u_0 \left\{\frac{B_r}{F_a \lambda}\left[\left(\ln \frac{r}{r_s} - \frac{r^2 - r_s^2}{2r_e^2}\right)\right.\right.$$

$$\left.\left. + \frac{k_h}{k_s}\left(\ln \frac{r_s}{r_w} - \frac{r_s^2 - r_w^2}{2}\right)\right] + \frac{\lambda - B_r}{\lambda}\right\} \mathrm{r}_s \mathrm{r} \mathrm{r}_e \ (3)$$

Formula (1) is the average of excess pore water pressure at any depth in foundation. Formula (2), (3) is expression of excess pore water pressure at any point in foundation.

Where Z is the length of PVD; H is the thickness of the soil (single drainage); r_e is radius of influence of PVD; rw is equivalent radius of PVD; r_s is radius of the smear zone; k_h is the horizontal soil permeability in the undisturbed zone; k_s is the soil permeability in the smear zone; k_w is permeability coefficient of PVD; r is radial coordinate; z is vertical coordinate.

The calculation of degree of consolidation as follows:

$$U_r = 1 - \frac{u_r}{u_0}$$

$$U_r = 1 - \sum_{m=0}^{\infty} \frac{2}{M} \sin(\frac{M}{H} Z) \cdot e^{-Brt} \left[\frac{k_h B_r}{k_s F_a \lambda}\left(\ln \frac{r}{r_w} - \frac{r^2 - r_w^2}{2r_e^2}\right) + \frac{\lambda - B_r}{\lambda}\right] \ (4)$$

$$U_r = 1 - \sum_{m=0}^{\infty} \frac{2}{M} \sin(\frac{M}{H} Z) \cdot e^{-B_r t} \cdot \left\{\frac{B_r}{F_a \lambda}\left[\left(\ln \frac{r}{r_s} - \frac{r^2 - r_s^2}{2r_e^2}\right)\right.\right.$$

$$\left.\left. + \frac{k_h}{k_s}\left(\ln \frac{r_s}{r_w} - \frac{r_s^2 - r_w^2}{2}\right)\right] + \frac{\lambda - B_r}{\lambda}\right\}\Bigg] \ (5)$$

Formula (4) and (5) are the consolidation degree at any point in foundation.

$$\bar{U}_r = 1 - \sum_{m=0}^{\infty} \frac{2}{M} \sin(\frac{M}{H} Z) \cdot e^{-Brt} \tag{2}$$

Formula (6) is the average of the consolidation degree at any depth in foundation.

$$\bar{U}_{r;} = 1 - \sum_{m=0}^{\infty} \frac{2}{M^2} \cdot e^{-Brt} \tag{3}$$

Formula (7) is average consolidation degree of the whole foundation.

3. Calculation parameters and method

In this paper, the calculation parameters of dredger fill is selected from the dredger fill port headquarters experimental plot project in miaoling district of lianyungang, this project uses negative pressure PVD to strengthen hydraulic mud fill foundation. The value of the parameters of dredger fill is as follows: k_h=6.91e-4m/d, k_z=3.46e-4m/d, k_h/k_z=2, k_{w0}=86.4m/d, H=20m, c_h=1.59e-2m/d. The parameters of PVD are as follow: r_e=0.525m, r_s=0.175m, r_w=0.035m, n=r_e/r_w=15, s=r_s/r_w=5.

This paper will discuss the influence of plastic drainage plate water content, coating area thickness ratio, permeability coefficient and well diameter ratio on the effective range of influence. The numerical value of substitution (4) (5) is used to calculate the consolidation degree of each point in the soil at different time, so as to analyze the change rule of the effective range of plastic drainage plate under different working conditions.

4. Influence of water discharge of PVD

4.1. Analysis of water discharge of PVD

There are many factors strongly influence the discharge capacity, such as PVD type, lateral stress, clogging and deformation. Now, limited theoretical research has focused on these effects. The actual characteristics of the discharge capacity of a PVD are not yet fully understood, but the discharge capacity decreasing with the consolidation process. The decrease of the discharge capacity of PVD is more obvious in earlier stage, and it slows down with the development of consolidation in the late stage, so using exponential function to describe the attenuation process in this paper. In here:

$$k_w = k_{w0} \cdot e^{-\alpha T_h} \tag{4}$$

Where k_{w0} is initial permeability coefficient; α reflects the trend that discharge capacity changes with time; Th is a time factor, calculate according to the following formula:

$$T_h = \frac{c_h}{4r_e^2} \cdot t \tag{5}$$

In this equation, Ch is horizontal consolidation coefficients of soil layer(m2/d),t is consolidation time(d),re is influencing radius of PVD.

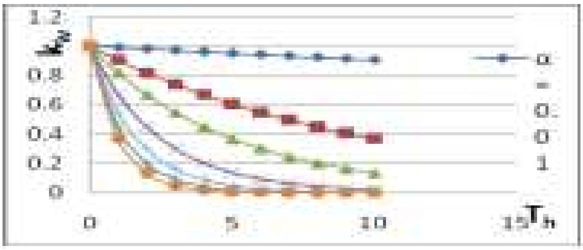

Fig. 1. discharge capacity varies with time for different values of α

Fig.1 plots the variation of kw with exponential change of time for different values of the coefficient α. It can be observed that (1)when α approached 0, kw became constant over time, and (2) as α increased, the decreasing trend of kw with time became more obvious. (3) When α= 1.1, the discharge capacity of the drain became completely interrupted. Based on these conclusions, the value of α was selected to be between 0 and 1.0 in the following analyses.

4.2. The analysis of the effective range without considering the discharge capacity

Fig2. is the schematic diagram of the effective range with consolidation time. The shaded is the soil consolidation degree of greater than 80%. The curves represent the depth of the consolidation degree of 80%.

As shown in Fig.2, the shaded appears near the PVD at first, and then gradually spreads to the surface soil and the depth of soil near the PVD, finally extends to other locations soil. Therefore, the effective range of the PVD is not always a cylinder but a change process from an inverted cone to an inverted circular truncated cone, to a cylinder.

When the consolidation time is 90days, the average consolidation degree throughout the soil is 86%, but the soil consolidation degree has not reached 80% in some soil between the PVD. Therefore, the effective range of the PVD is not a cylinder but an inverted circular truncated cone within certain time.

When the consolidation time is 120days, the average consolidation degree throughout the soil is 93%, and the soil consolidation degree has reached 80% in the soil between the PVD. The effective range of the PVD is a cylinder. Thus, it can improve the effective range of the PVD with the increase of time.

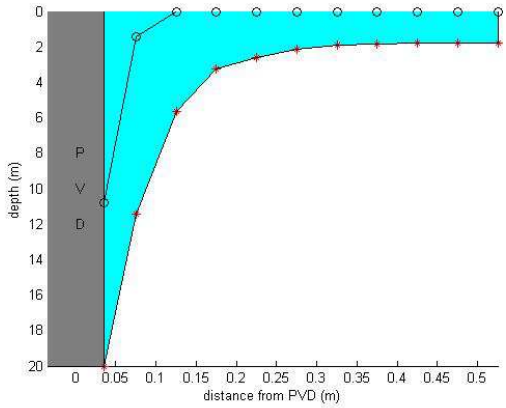

Fig. 2. Change of the effective range with consolidation time

4.3. The analysis of the effective range considering the discharge capacity

Figure 3 is the variation curve of the effective range of the PVD under the condition of vacuum preloading for 90 days. It can be seen from Figure 3 that in the vacuum preloading for 90 days, with the increase of α, the consolidation degree of 80% decreases, and the effective influence range of PVD changes obviously. This is mainly because with the decrease of the discharge capacity of the PVD, free water deep in the soil are unable to drain out of the foundation, it is not up to the expected effect of reinforcement, and the shallow soil in the PVD discharge capacity does not decrease a lot, has been strengthening.

Fig. 4 is the variation curve of the effective influence depth of the PVD with the consolidation time when re=0.525m. We can see from Figure 4, when α0.4, the curve is still relatively steep, prolonged consolidation time can increase the degree of consolidation at 80% depth, effective range improvement of PVD. The effective range of PVD is almost unchanged when the consolidation time is increased with the addition of α>0.4. At the same time, it can be seen that in the general vacuum preloading time (90 days), the consolidation degree of soil is less than 80% at r_e=0.525m. This shows that there is always a part of the soil consolidation degree is less than 80% between the PVDs in the vacuum preloading treatment foundation, and the reinforcement effect of this part of the soil is not ideal.

5. Influence of smear area thickness

5.1. Smear area thickness

The smear area will appear when the PVD is set up. The permeability of the soil in the smear area is smaller than that of the disturbed zone, which makes the consolidation rate of the foundation slow down. This effect is called smearing effect.

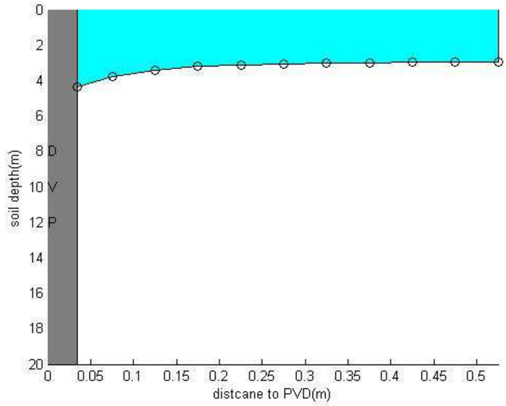

Fig. 3. Change of the effective range at different α

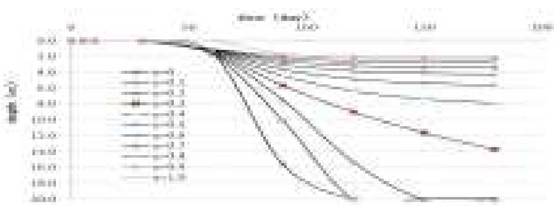

Fig. 4. Change of the effective range when r_e=0.525m

The smear effect is related to the sensitivity of the soil around the drainage plate and the setting method of the PVD.

The scope of the smear area is usually obtained by establishing the relationship between the diameter of smear area and the equivalent diameter of PVD. The study of smear area shows that the diameter of smear area is d_s=(1.6˜7) dw. Therefore, s=r_s/r_w=2, 3, 4, 5 and 6 are used to analyze and compare, and other parameters are derived from the example parameters.

6. Discussion

As shown in Fig. 5, when the consolidation time is 90 days, the range of effective influence varies with s. The curve shows the depth of the soil with consolidation degree of 80%, and the consolidation degree of the soil above the depth is more than 80%. It can be seen from the diagram that with the decrease of s, the effective influence scope of drainage plate is more and more big. This shows that with the decrease of s, the thickness of the smear area is smaller and smaller, which is more conducive to the free water discharge in the soil, and the effective range of the PVD is also greater. At the same time, with the increase of s, the range of effective influence change is getting smaller and smaller. This shows that the thickness of the smear area to a certain extent, the effect of thickness on the effective range of influence tends to be reduced.

As shown in Fig. 6, the variation curve of the effective influence range at different s is obtained when r_e=0.525m. With the increase of s, the depth of effective influence depth reaches 20m (that is, the bottom of PVD), and the consolidation time is more and more.

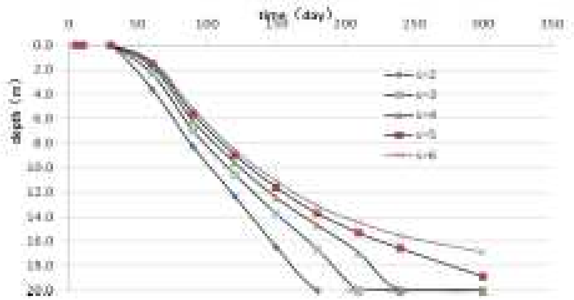

Fig. 5. Change of the effective range

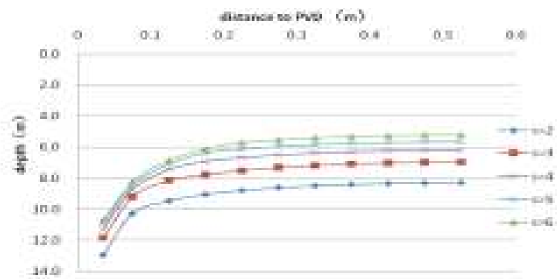

Fig. 6. Change of the effective range

7. Influence of permeability coefficient ratio

7.1. permeability coefficient ratio

Another parameter that reflects the smear area is the permeability coefficient kh/ks. At present, the results of the permeability coefficient ratio are inconsistent, mainly because the kh and ks test results are affected by many factors. Many scholars have shown that the range of k_h/k_s is between 1.0˜5. Therefore, this paper takes k_h/k_s =1, 2, 3 and 4 for analysis, and other parameters are taken as example parameters.

7.2. Discussion

As shown in Fig. 7, the curve of the effective range of PVD varies with kh/ks when the consolidation time is 90 days. The curve shows the depth of consolidation of the soil is 80%, and the consolidation degree of the soil above the curve is greater than 80%. It can be seen from the diagram that when the smear effect is not considered (kh/ks =1), the effective range of the plastic drainage plate is the largest. With the increasing of kh/ks, the permeability coefficient of the soil in the smear area is getting smaller and smaller, and the influence scope of the PVD is getting smaller and smaller. When kh/ks =4, the effective range of PVD only reaches the distance from the drain plate 0.175m. All these indicate that smearing effect has a great influence on the effective range of PVD.

Figure 8 is the curve of the effective range of the PVD along with the consolidation time at re=0.525m. According to the diagram, with the increase of consolidation time, the depth of the effective range of PVD is also increasing. When the smear effect is not considered (kh/ks=1) , the effective range of the soil reaches 20M (the bottom of the plastic drain plate) when the consolidation time is 130 days. With the increase of kh/ks value, more and more consolidation time is needed to reach the effective range of 20m. When the kh/ks is greater than 3, the curve tends to be gentle. This shows that increasing the consolidation time cannot improve the effective range of the PVD.

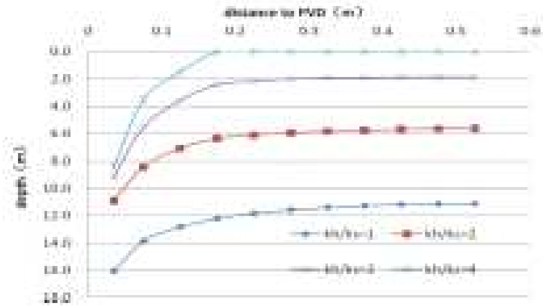

Fig. 7. Change of the effective range

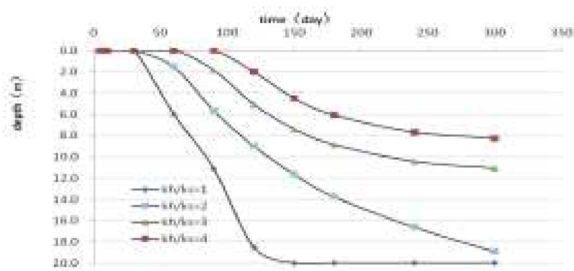

Fig. 8. Change of the effective range

8. Influence of well diameter ratio

8.1. Well diameter ratio thickness

The effect of the spacing of the plastic drains on the consolidation of the foundation by vacuum preloading has a great influence. According to the specification [6], the spacing of the drainage shaft can be determined according to the consolidation characteristics of the foundation soil and the degree of consolidation required in the predetermined time. When designing, the spacing of shafts can be chosen according to the ratio of well diameter. The spacing of plastic drain plates can be chosen according to n=15˜22. Therefore, this paper selects n=12, 15, 18, 21, 24 for analysis. Other parameters are taken as example parameters.

8.2. Discussion

As shown in Fig. 9, when the consolidation time is 90 days, the effective influence range of the PVD varies with the ratio of the borehole diameter ratio. The curve shows the depth of consolidation of the soil is 80%, and the consolidation degree of the soil above the curve is greater than 80%. According to the diagram, with the increase of well diameter ratio, the effective influence scope of PVD is getting smaller and smaller. When the n is greater than 18, the effective depth of the PVD is limited to 2m below the ground.

Fig. 10 is the change curve of the effective influence range of PVD with the consolidation time when r_e=0.375m. According to the diagram, with the increase of well diameter ratio (n), the effective time of consolidation (20m) at the bottom of the drainage plate is more and more. At r_e=0.375m, the influence range of the PVD is likely to reach the bottom of the drainage plate with the increase of consolidation time.

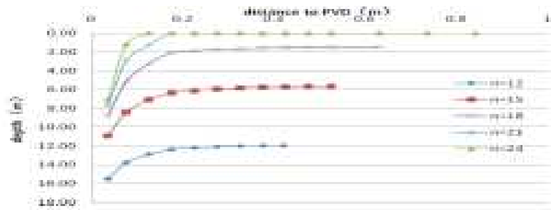

Fig. 9. change of the effective range

9. Conclusions

Based on the analytical solution of the traditional consolidation equation, the consolidation degree of soil in different position and time is calculated, and the change rule of the effective range of PVD is analyzed theoretically. Conclusions are as follows:

(1) The effective range of the plastic drainage plate is not constant, but is a

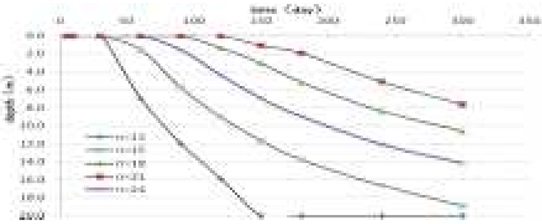

Fig. 10. Change of the effective range

change from the reversed cone to the reversed frustum of the cone, and eventually becomes a cylindrical change process. In the ordinary vacuum preloading time (90 days), the effective range of PVD is not a cylindrical shape, which indicates that the soil between the drainage plates is not all able to meet the design requirements of the degree of consolidation.

(2) When the influence of discharge capacity is not taken into account, the effective range of PVD will eventually reach a cylindrical shape with the increase of consolidation time. This shows that the strength of the soil between the PVDs can meet the design requirements.

(3) The discharge capacity of PVD has a great influence on the effective influence range. With the gradual decrease of discharge capacity, the effective influence range of PVD is obviously reduced.

(4) The effective thickness of smear zone, permeability coefficient ratio and well diameter ratio also have obvious influence. With the increase of smear area thickness, the effective range of PVD decreases gradually. With the permeability ratio increasing, the effective influence area is getting smaller and smaller. With the increase of well diameter ratio, the effective influence area also tends to be smaller.

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