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Research on soft ground improved by preloading on expressway

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ABSTRACT: Some significant problems happened in the ground improved by preloading combined with prefabricated vertical drains (PVDs) are discussed in this paper on the basis of field survey results on some expressways and airport runways. The influence of smear and well resistance on consolidation and the influence of the discharge capacity of PVD on well resistance are discussed and the back-analysis results are presented. Analysis is conducted on the relationship between preload and post-construction settlement. Consequently a controlling method is provided which would avoid plastic creep of ground. Based on the discussion of the reasonable installed depth of PVD in thick soft ground, a consolidation calculation method of the subsoil without improvement is proposed.

1 INTRODUCTION

In the past few decades, many expressway and airport runways were built on soft ground in the coast of China, such as Hu-Hang(HH) expressway, HangYong(HY) expressway, Wen-Zhou(WZ) airport and NingBo(NB) airport etc. The soft ground has following features: high water content (w=40~80%), very large void ratio (e>1.2~1.3), very low shear strength (the undrained shear strength Cu=8~15kPa), very high compressibility (compression index Cc=0.3~0.7), very low permeability ($k=(1\sim5)\times10^{-7}$cm/s), and very large thickness of the mucky soil (the thickness of the mucky soil layer H=20~45m). Expressway built on this kind of soft ground generally results in a great deal of settlement, significant difference of settlement, long lasting period of settlement development after construction, and even loss of ground stability. A project on this kind of ground could not be put into normal use unless the ground has been improved.

After field experiment and comparison of many different kinds of ground improvement scheme, it's suggested the above soft ground could be improved by preloading combined with prefabricated vertical drains (PVDs). As shown in Figure 1, the PVDs with certain distance and depth are installed in the ground. Preloading consists of expressway weight and surcharge. Pavement is constructed after the completion of consolidation under the preloading. In order to assure the success of construction, field observations are conducted in the course of preloading on settlement, deep layer displacement, pore water pressure, lateral displacement and foundation pressure through some survey equipments installed under the ground. In current practice of China, the detail info of PVD is as following: the Figure 1. Cross-structure type is complex structure separated and the shape is grillage; the core material is PP or PVC, the filter material is PE or PP series fiber; the width and thickness is 100mm and 3.5~5mm respectively; and discharge ability (q_w) is 40~60 cm^3/s, the equivalent size of filter is less than 75 μm.

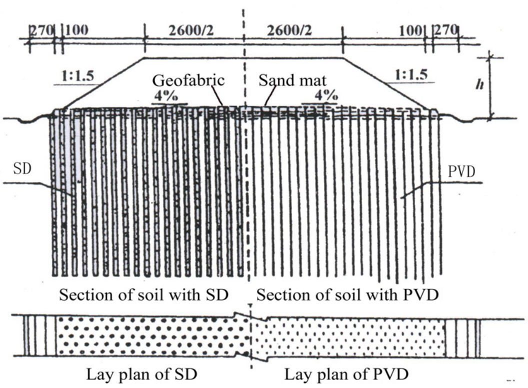


Figure 1. section view of embankment with PVD or SD

Up to now the above embankments of expressway and airport runways have been used well for years, which proves that preloading combined with PVDs is effective. However, with the development of practical application, due to the complicated and changeable properties of soft soil, the soil improvement technique still can be improved to optimize the design and construction and to enhance the preloading effect. Otherwise, in the course of or after construction, a great deal of settlement and lasting settlement development and even creep failure of the ground might happen. Therefore some significant problems are discussed in this paper. The discussions are based on the theoretical analysis and field survey results of settlement, lateral displacement and pore water pressure.

2 THE EFFECT OF WELL RESISTANCE AND SMEAR AND CONSOLIDATION CALCULATION

Vertical drain consolidation theory is guide of design and construction of expressway improved by preloading with PVD and key factor of preloading effect. Based on the past study, the degree of consolidation calculated by Barron's drain theory of idealized well is always much larger than that of the field test. In the test embankment of HY expressway, the consolidation time corresponding to 80% consolidation degree is about 120 days from the theoretical calculation, while the corresponding value is 270 days in the field test. If based the calculated design time, the actual degree of consolidation will not reach the expected value when the pavement is constructed after the remove of surcharge and significant post-construction settlement will happen.

The degree of consolidation is overestimated due to many kinds of different reasons such as non-perfect consolidation theories, inaccurate calculation parameters, underestimated effect of well resistance and smear. Discussions in the following section are based on the study on the test embankment of HY expressway. And the consolidation method is improved to follow actual field condition more closely.

2.1 *Consolidation theory*

The theoretical solution for vertical drain consolidation was first proposed by Barron. Further studies were made by Hansbo, Yoshikuni and XieKanghe and they all suggest that the Barron's theory of idealized drain results in large error because of small discharge section of PVD, large installed depth and large disturbance in construction. They proposed both the effect of well resistance and smear should be considerd. On account of that XieKanghe's theory, with clear concept and simple calculation, his simplified solution is adopted here to analyze the influence of well resistance and smear on consolidation behavior.

Corresponding to the situation of immediate and staged loading, the degree of consolidation is given respectively by:

$$U_t = 1 - \alpha e^{-\beta t} \tag{1}$$

$$U_t = \sum_{i=1}^{n} \frac{q_i}{P_n} [(T_i - T_{i-1}) - \frac{\alpha}{\beta} e^{-\beta t} (e^{\beta T_i} - e^{\beta t_{i-1}})] \tag{2}$$

And the definition of the parameter is shown in table 1.

Table 1. Definition of Parameter

Parameter	Definition
α	$8/\pi^2$
β	index of consolidation, $\beta=\beta_r+\beta_z$
β_r	$\beta_r = (8C_H)/[(F_n+J+\pi G)d_e^2]$
β_z	$\beta_z = (C_V)/(4H^2)$
C_H	coefficient of consolidation for horizontal drainage
C_V	coefficient of consolidation for vertical drainage
H	depth of vertical drain
F_n	$F_n=\ln(n)-3/4, n=d_e/d_w$;
J	smear factor, $J=\ln(\lambda)(k_n/k_s-1)$, $\lambda=d_s/d_w$
G	factor of well resistance, $G=(k_n \pi L^2)/(4q_w)$,
d_w, d_s, d_e	diameter of the vertical drain, the smear zone and the influence zone respectively
q_w	discharge capacity of vertical drain
k_n, k_s	permeability of natural soil and smear zone
T_{i-1}	start time corresponding to the i[th] stage loading
T_i	end time corresponding to the i[th] stage loading
q_i	loading rate corresponding to the i[th] stage loading
P_n	sum of every stage load

2.2 *The influence of well resistance on consolidation*

From the point of view of theory, the influence of well resistance on consolidation is determined by the factor of well resistance (G). The degree of consolidation will decrease with increase of G. According to the above described non-idealized sand drain consolidation theory, the relationship between the degree of consolidation and G can be figured out as Figure 2.

When G≤0.1, the influence of well resistance on consolidation could be ignored and the result is close to that of idealized drain. When G>10, the degree of consolidation decreases significantly, which indicates that vertical drain is invalid. The amount of G is related with the discharge ability and the installed depth (l) of PVD. In current practice of China, G is as following: G=0.0062-0.0034 when l is 10m and G=0.056-0.078 when l is 30m.Therefore, G of the common PVD with less than 30m installed depth is less than 0.1. It indicates the

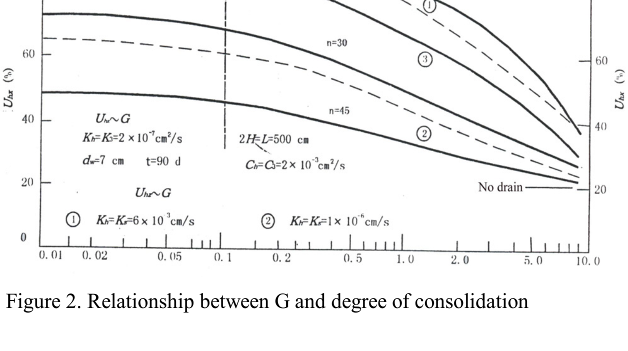


Figure 2. Relationship between G and degree of consolidation

influence of well resistance on consolidation could be ignored. The above is the same as Hansbo's suggestion in 1981.

However in the test embankment, it's observed that the actual discharge ability of PVD decreases significantly because of it's crimpy or bend due to the pull and friction action during the installing, the settlement of ground and the lateral extrusion. The actual discharge ability of PVD (q_w') obtained in field is equal to 1/4~1/9 of the measured discharge ability of PVD (q_w) obtained in the lab, even 1/21 in some cases. This accords with the back-analysis results (Miura, Koernet et al. 1991) of projects that q_w' is the only (1/4~1/9) of q_w. According to the actual PVD discharge capacity q'_w, well resistance factor is still less than 0.1 to the PVD with discharge capacity q_w= 45cm³/s and drainage length less than 20m. Therefore, well resistance can be ignored in practice. However when drainage length is larger than 20m, well resistance factor increases to 0.16~0.23, which will make the consolidation degree decrease by 10%~20% so that well resistance must be considered. As the above principle, well resistance can be ignored to the PVD with well resistance factor less than or equal 0.1. Then the PVD discharge capacity can be determined as following:

$$q_{wa} = 7.85 \times F_s K_n L^2 \tag{3}$$

where L=drainage length(cm); q_{wa} =discharge capacity with ignored well resistance (cm³/s); k_n = subsoil permeability; F_s= the reduced factor of PVD, which equals 4 ,5, 6 when L is less than 20m, among 20~30m and more than 30m respectively.

Therefore in practice, if the PVD discharge capacity satisfies equation(3), that is q_w>q_{wa}, well resistance could be ignored during the consolidation degree calculation. Otherwise, the effect of the well resistance must be taken into consideration.

2.3 *The influence of smear on consolidation*

The field measurement results, proposed by D.T. Bergado(1990) and S. Hansbo(1991), indicate that smear effect exists during the consolidation. But the diameter of the smear zone is quite difficult to determine. The disturbance zone and the hydraulic conductivity in the smear zone have no field measurement yet. In this paper, the value of the disturbance zone and the corresponding hydraulic conductivity is estimated, by using the back-analysis method, according to the field settlement-time curves or pore pressure-time curves of the test highway section. On the settlement-time relation curves, three points during the certain lasting load section is taken. These points must satisfy the equation $t_2-t_1=t_3-t_2=\Delta t$. The pertinent settlement is S_{t1}, S_{t2}, S_{t3}, respectively. According to the consolidation theory,

$$\beta = \frac{1}{\Delta t} \ln \frac{s_{t2} - s_{t1}}{s_{t3} - s_{t2}} \tag{4}$$

$$\beta = \frac{8C_H}{(F_n + J + \pi G) d_e^2} \tag{5}$$

then

$$J = \frac{8C_H}{\beta d_e^2} - (F_n + \pi G) \tag{6}$$

Six section planes are selected in the HY highway embankment. Using the above back-analysis method, the results are listed in Table 1. In the back computing, the consolidation parameter C_H is determined from the statistical average value of laboratory test results. The value of β is estimated from the statistical average value of many points. And well resistance is ignored because of the drainage length less than 20m and the PVD discharge capacity larger than 45cm³/s, i.e. G = 0.The results is shown in Table 2.

The smear effect factor is about 2.26~3.26 in clay soils and some is as high as 6.98. Thus the degree of consolidation reduced 25%~30%. It is suggested that the smear zone size is 2.5~3.5 times of the PVDs' equivalent diameter and the hydraulic conductivity ratio (k_h/k_s) is 3~5. Therefore the smear effect can not be ignored. Figure 3 gives the comparison between

Table2. Analysis results of smear effect factor

Test highway section No.	Drainage length &Space of PVDs	Average seepage co-efficient (10^{-7}cm/s)	Back-calculated value β (1/d)	Back-calculated value J
4	15; 1.5	1.67	0.0083	3.26
5	15; 2.0	1.62	0.0091	2.35
6	15; 2.0	2.10	0.0093	2.70
7	20; 1.5	1.82	0.0093	3.10
8	20; 1.5	1.86	0.0102	2.71
9	18; 1.5	1.82	0.0049	6.98
10	18; 1.5	1.82	0.0110	2.26

the calculated and measured settlements. The settlement shown in Figure 3 is calculated based on the consolidation theory mentioned previously, respectively with or without smear effect and well resistance. It is obvious that the calculated settlement curves with smear effect fit well with the field-measured curves.

In conclusion, for consolidation calculation with PVD, it is recommended that non-idealized sand drain consolidation theory should be selected. Well resistance can be ignored if the PVD discharge capacity is quite large ($q_w>q_{wa}$). Smear effects should be considered and smear effect factor is about 2.5~3.5 for general clay soils. Thus the accuracy of calculation is improved in comparison with the field measurements.

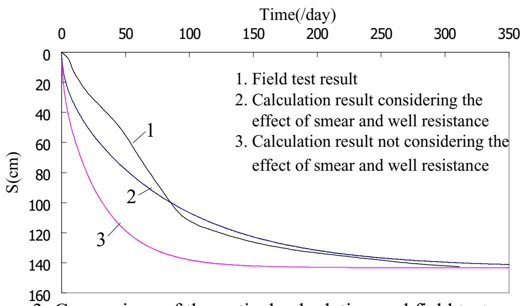


Figure 3. Comparison of theoretical calculation and field test result

3 PRELOAD AND SETTLEMENT POST-CONSTRUCTION

How to determine the reasonable amount of preload is a key issue influencing on the effect of preloading, especially when surcharge is applied. From the point of view of theory, the larger the preload is, the more the amount of the removed settlement and the quicker the rate of settlement. However too large surcharge might induce the plastic creep of the ground or even cause loss of stability. If the surcharge is too small, the expected amount of removed settlement will not be achieved, which will result in a great deal of post-construction settlement. It's difficult to determine the required preload accurately. Analysis is conducted on the field test result of runways of two airports improved by preloading with PVD to study the above issues.

3.1 *Basic situation of WZ airport and NB airport*

The thickness of the soft ground of WZ airport is about 35~40m, while that of NB airport is 25~35m. The parameters of adopted sand drain are same and shown as the following: the diameter is 0.07m, the distance is 1.4m, and the installed depth is 20m. And the basic information of preloading is shown in Table 3.

As stated above, the situation of these two airports is similar, except that the thickness of ground and the amount of surcharge of WZ airport is larger. After removing the surcharge, ground rebounded little in both airports. Consequently after pavement, no considerable settlement took place. But with the elapsing of time, the post-construction settlement develops continually, reaching 60~70mm in WZ airport. While in NB airport the post-construction settlement is less and reached a stable value finally. However the post-construction settlement in the two airports estimated by the current design is small. It seems contradictive

Table 3. Basic information of preloading in WZ airport and NB airport

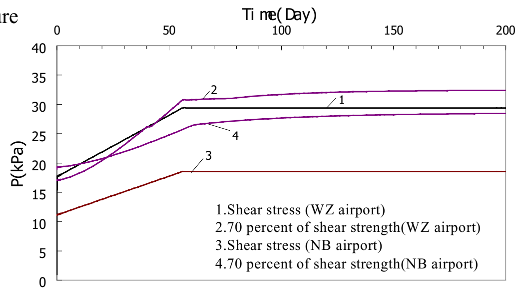
Airport name	Height of pavement (m)	Height of surcharge fill (m)	Maximum preload fill (m)	Loading time (Day)	Dead loading time (Day)
WZ	1.9	2.6	4.5	55	240
NB	1.8	2.15	3.95	61	280~320

between the field test result and the current design method. Therefore more attention should be paid to this problem.

3.2 *Analysis and controlling of continuous post-construction settlement*

As say to runways of the two airports, the continuous post-construction settlement could not be induced by unfinished primary consolidation settlement due to smaller preload or shorter preloading time, for the preload is larger and the preloading time is longer and the pore water pressure had been dissipated before removing the load. Maybe the reason is the shear failure of the ground due to that the applied surcharge is too large. It's proposed by ChuangShanShuoLang in 1956 that when the shear stress due to the applied load is less than the corresponding yielding shear strength of ground, the creep of the soil will decrease gradually and cease with the elapse of time; otherwise the creep of the soil will increase with the elapse of time and results in the failure of ground finally. The corresponding yield shear strength of soil is equal to 71 percent of the shear strength of ground. According to this theory, analysis is conducted. A point beneath the ground 8 m is selected as the calculation point, and the corresponding change of the maximum shear stress τ_{max} ($\tau_{max}=1/2(\sigma_1 - \sigma_3)$) and the increased shear strength due to consolidation with the time is shown in Figure 4.

Figure 4.



Calculation results of shear stress and shear strength

It can be seen that as say to WZ airport, after an elapsing time of about 40 days, the shear stress exceed 70 percent of the shear strength of ground. It indicates that the rate of loading isn't controlled well in the phase of preloading. The increment of the shear strength due to consolidation is less than the increment of the shear stress due to the applied load, which results in the shear stress exceeding the yielding shear strength of ground. And the post-construction settlement develops continually and reaches a bigger value finally. While in NB airport, the shear stress is always less than 70 percent of the shear strength of ground. And the post-construction settlement is little and reaches a stable value quickly.

Based on the above analyses, the different post-construction settlement is caused by the different ratio η ($\eta = \tau / \tau_f$) of the shear stress τ due to the applied load and the shear strength of ground τ_f. η is less than 0.7 in NB airport, and the post-construction settlement is little and reaches a stable value quickly. η is larger than 0.7 in WZ airport, and the post-construction settlement develops continually and reaches a larger value. It's suggested the amount and the rate of preloading be controlled strictly and the shear stress due to the applied load be less than 70 percent of shear strength of the ground in order to avoid larger continual post-construction settlement. Whether the proposed method is reasonable still need further research due to that only two airports are included in the analysis. However, larger post-construction settlement is also found in preloading of other embankments with high shear stress, which indicates the above suggestion should be paid more attention to.

4 SETTLEMENT OF SUBSOIL

The installed depth of PVDs should be taken into consideration in the thick soft soil. For HY test expressway section where the thickness of soft clay is 41m, PVDs with the length of 15~20m meets the principle that post-construction settlements must be less than 30mm, if computed based on ordinary design theory. However, in practice, post-construction settlements are much larger. Figure 5 and 6 respectively refer to measured results of settlement and excess pore-water pressure of section Ⅳ and Ⅷ.

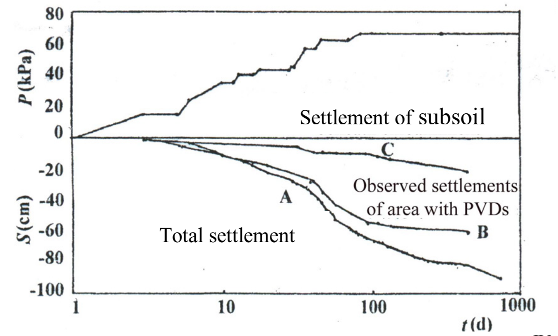


Figure 5. Observed settlements profiles of test expressway section Ⅳ

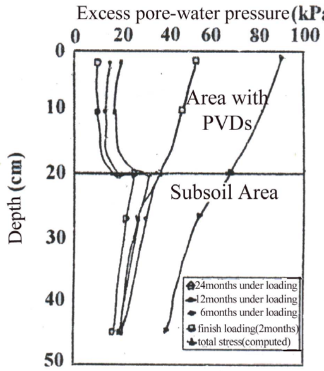


Figure6. Observed excess pore-water pressure of section Ⅷ

It is apparent that settlement of preloading areas remains constant after 100 days and degree of consolidation corresponding to the time reaches to 80 percent or so. Meanwhile, degree of consolidation of the other area subsoil is only 10~25 percent. The degree of consolidation based on field measured results(section Ⅷ) is shown in Table 4.

Table 4. Degree of consolidation based on excess pore-water pressure

Subarea	Degree of consolidation (%) Field measurements / theory results		
	Half year	One year	2 years
Ares with PVDs	45/70.5	75/79.5	86/88.5
Subsoil	3.2/33.8	11.7/35.97	23.5/44.63

The significance feature of Table 3 implicates that large post-construction settlements results from deficient installed depth of PVDs. Based on field measurements, at the time of 2 years' preloading, it is obvious that degree of consolidation of area with PVDs reaches about 86 percent, closely to calculated results. While degree of consolidation of the other area subsoil is only 23.5 percent, which is less than the calculated results. That is to say, most of the primary consolidation of the subsoil is not complete yet. Thus post-construction settlements still develops considerable quickly. In calculation, according to general one dimension consolidation theory, boundary of the subsoil is deemed to be permeable thoroughly, which results in overestimated values of consolidation settlements. Then the designed installed depth of PVDs is underestimated correspondently. Therefore, depth of PVDs should be increased to 25m to avoid great post-construction settlements.

As say to estimate the reasonable consolidation of subsoil, it is proposed that the interaction between the layer with PVDs and the subsoil without improvement be adequately considered. That is, on the basis of one dimensional consolidation theory, equivalent relationship is built to obtain the degree of consolidation accurately.According one dimension consolidation theory, the thickness of layer is the length of drainage path in the expression of consolidation degree. Thus when three-dimensional consolidation of sand drain area is equalized to one-dimensional consolidation of single layer, the equivalent thickness of the layer is determined by drainage path. That is, the distance between PVDs determines the equivalent thickness of the stratum. And the equivalent consolidation coefficient of equivalent stratum with PVDs is determined as following.

The consolidation degree of areas with PVDs is calculated by equation (1). And the consolidation degree of one dimension layer with equivalent consolidation parameter $\bar{C}_v$ is determined as follows:

$$\bar{U}_z = 1 - \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 \bar{C}_v t}{4{h_2}^2}\right) \tag{7}$$

where, h_2 equals to d_e, the space of PVDs.

$$\bar{U}_z = U_{rz} \tag{8}$$

Substituting (1) and (7) into (8), the equivalent one dimensional consolidation parameter of the areas with PVDs is determined as follows:

$$\bar{C}_v = C_v \times \left(\frac{d_e}{H}\right)^2 + \frac{32C_h}{\pi^2 F(n)} \tag{9}$$

Therefore, to determine reasonable depth of PVDs, consolidation of HY test embankments should be estimated using the above-discussed method.

5 CONCLUSION

For consolidation calculation of soft ground improved by preloading combined with PVDs, it 's recommended that non-idealized sand drain consolidation theory should be selected. Well resistance could be ignored if the PVD discharge capacity is quite large and smear effects should be considered. Thus the accuracy of calculation is improved in comparison with the field measurements. In order to avoid bigger continual post-construction settlement, it's suggested the amount and the rate of preloading be controlled strictly and the shear stress due to the applied load be less than 70 percent of shear strength of the ground. And it's proposed the interaction between the layer with PVDs and the subsoil without improvement should be necessarily adequately considered. An equalized relationship is built to obtain the degree of consolidation of the subsoil accurately on the basis of one dimensional consolidation theory.

REFERENCE

Chai Tiren. 1998. Ground improvement of HangYong expresway built on soft soil.

Geotechnical engineering institute of zhejiang University.1988. Research report on NingBo airport improved by sand drain.

Geotechnical engineering institute of zhejiang University.1989. Research report on WenZhou airport improved by sand drain.

Hansbo.1981.Consolidation of fine-grained soils by prefabricated drains, proc.10th Int. Con. Soil mech., Stockholm, Vol.3.

Xie Kanghe. 1994. Theory of one dimensional consolidation of double-clayed ground and its applications. Journal of geotechnical engineering 16(5):24-35