Tests and Analyses on Shear Strength Increment of Soft Soil under Embankment Fill

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ABSTRACT

Shear strength increment of soft soil may affect the stability of soft ground treated with prefabricated vertical drains (PVDs)**,** and it is an active research topic at present. In the study reported in this paper, the *in situ* static cone penetration test and vane shear test were arranged at the center line, the shoulder and the toe of the filling in order to identify the shear strength increment distribution in vertical and horizontal direction of the soft ground treated by PVDs under a fill load. The physical and mechanics tests were carried out with the soil from center line and 22m away from the filling toe. Laboratory and *in situ* tests results are presented in this paper. The results of *in situ* tests demonstrated that the shear strength increased 0.2~0.8 times and the increment is different from the center line to the toe in horizontal direction and within 13m depth. In addition, in order to forecast the shear strength increment with quantification equation, the shear strength polygonal line equation that considering the structure property of soft soil was presented. The polygonal line equation and the linear equation were compared by using the strength parameters acquired from the triaxial consolidated undrained shear (CU) test. The results showed that the outcome of polygonal line equation is closer to *in situ* vane test, therefore the polygonal line equation is superior to the straight line equation in respect of forecasting of shear strength increment. The study results could be referenced in similar projects.

KEYWORDS: soft soil; shear strength increment; polygonal line equation; consolidated undrained shear test; vane shear test; static cone penetration test.

INTRODUCTION

The stability analysis of soft ground is a topic of interest in many engineering problems such as material stack ground, oilcan ground, embankment ground of freeway and large area filling ground of artificial hills which are constructed in stages[1]. The shear strength increment of soft soil improved with PVDs under the fill load is important in stability analysis. Many researchers had provided the theory about shear strength increment, such as Hu (1997), Wei (1987), Shen *et al.* (1998) Kong *et al.* (1999), Lin *et al.* (2000), and Qi *et al.* (2008). They provided some calculation equations based on remolded soft soil and discussed their validity, without considering the structure property of soft soil. The soft soil was formed under the influence of interconnect action of bound water and cement action of particles. The shear strength line of soft soil is not a straight line but a polygonal line under the combined action. The calculation model should be changed if considering the structure property of soft soil. Many scholars such as Qian *et al.* (1996), Burland (1990), Schmertmann (1991), Hoeg *et al.* (2000), Hong *et al.* (2004), Liu *et al.* (2006), Li *et al.* (2006) and Wang *et al.* (2006) had paid attention to this problem but few people used the theory in real project up until now.

In this paper, the *in situ* cone penetration test, vane test were presented and the distribution pattern of shear strength increment in vertical and horizontal direction were analyzed relying on a certain botanical garden project, in Shanghai City. The bores had been arranged at the top center line, shoulder and toe of the fill load. The arrangement made the test results convenient for comparison. The physical and mechanics tests had been done to make clear how much the water content and void ratio changed before and after combined load. The strength growth calculated with polygonal line model adopting the parameter of CU test had been analyzed. Many useful conclusions were got from the analysis.

LAYOUT OF TEST

Site and Soils

The test field is a certain botanical garden project. The soil profile consists of six layers as Fig. 1. 1 and 2 are the main compression layers, and they are of the properties as higher void ratio, water content ratio, compressibility and lower bearing capacity. The soft ground had been treated with 12 to 15m length prefabricated vertical drains (PVDs). The old ground elevation is +3m, and thickness of the back pressures is 1.5m and 2.5m respectively. The filling profile shows as Fig.1. The top width and bottom width is 16m and 39m, the average width (W) is approximately 28m. There were 4 layers geogrid laid in order to maintain the stability of slope. The first layer geogrid located at the elevation 5.5m and others at interval of two meters at vertical direction. The design-elevation was +10.5m. After the filling finished 322 days, its elevation was +10.8m. The top surface of the filling had a settlement about 0.95m, As a result, the filling height could reach 8.8m as expected.

Layout Of Boreholes

The static cone penetration test (SCPT), vane shear test (VST) had been done, and the test positions is shown as Fig. 2. The control boreholes of SCPT, VST and soil sample bores laid out at 22m far from the filling toe to avoid the effect of the filling, and the physical and mechanics properties of this tube sample boring were tested for nature soil. In order to compare the strength increment in horizontal direction, the SCPT and VST boreholes were laid at the top center line, shoulder and toe of the filling. The space between test positions was determined as about 2~3m in order to reduce the influence of SCPT, VST and tube sample boring. JK denotes SCPT borehole, and SK denotes VST borehole. At the same location, the tube sample boring was not labeled in Fig. 2. The diameter of thin-wall soil sampler was 100mm. In order to reduce disturbing to soil sample, manual static press way was taken when getting soil samples in soft clay layer and the indoor test was done in time.

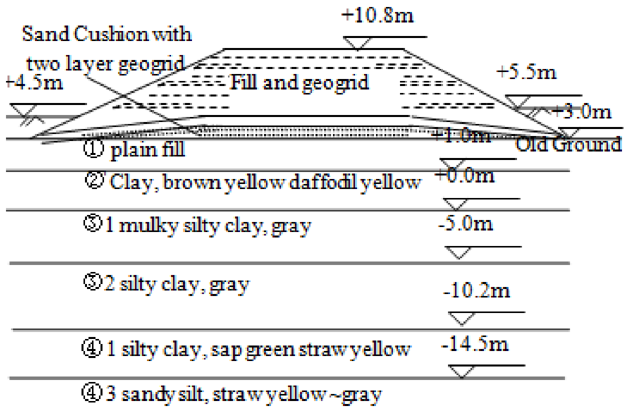

Figure 1: Geology profile of ground and fill

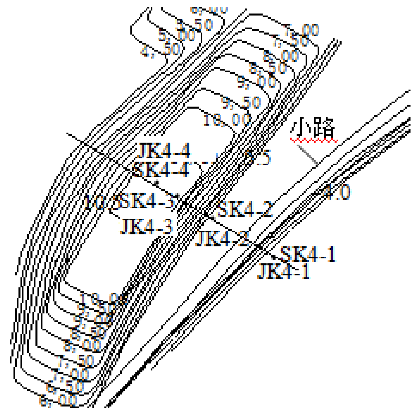

Figure 2: Boreholes layout of vane shear test and static cone penetration Test

TEST RESULTS

Moisture Content Results

The liquid limit (I_L or LL), plastic limit (I_P or PL) and moisture content (*w*) before and after surcharge loading were shown in Fig. 3. The bigger legends denoted of moisture content (*w*), liquid limit and plastic limit of soil under filling and the smaller ones denoted the nature soil in Fig. 3.

Fig. 3 shows that the water moisture content (*w*), liquid limit and plastic limit of soil under surcharge preloading are lower than that of nature soil. The *w* decreases about 10~20% as soft clay consolidated under the preloading. The *w* decreased more within the depth of 4m than that of deeper position, because of the effect of sandy cushion. The I_L and I_L decreased resulting from the structure of soft clay had been destroyed by the surcharge load. With the water drained from soft clay, the *w* decreased and that lead the soil's shear strength to increase.

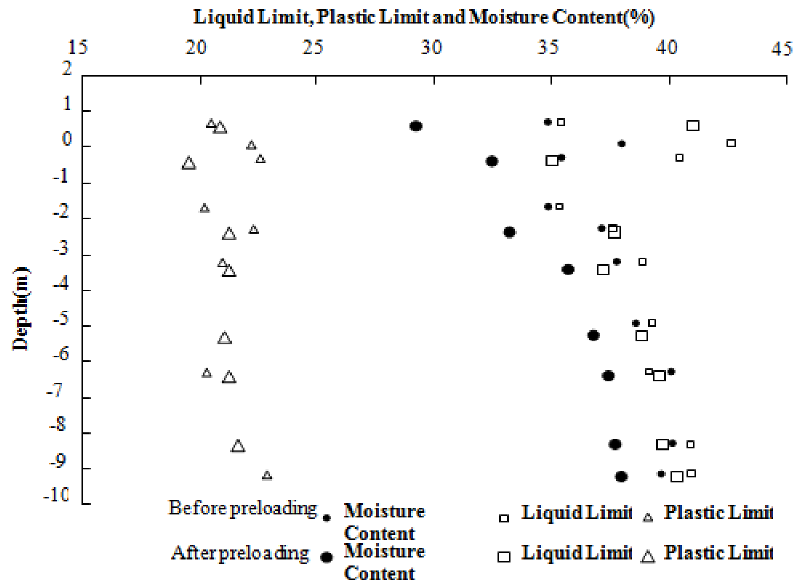

Figure 3: Liquid limit plastic limit and water content ratio before and after surcharge preloading

Results of static cone penetration test (SCPT)

The results of SCPT were shown as the curve of specific penetration resistance (*P*s) in Fig.4.

Fig.4 shows that the influence depth at the center of the combined load was 1/3~1/2W (W was average value of top and bottom width of fill) and the *P*s increased 0.4~0.8 times within the 1/3W, and 0.2~0.4 times within the 1/3~1/2W. At the shoulder of the slope, the *P*s increment was similar as at the center within the 3/14W and 0.1~0.3 times within 3/14~1/2W. At the toe of the slope, the *P*s was near to nature soil within 1/4W, and increased 0.1~0.3 times within 1/4~1/2W, the *P*s changed very little below the elevation -10.5m, where it was layer 4. The main influence depth of fill was the soft clay layer when there was a hard underlying stratum.

The result that the *P*s was near to nature soil within 1/4W at the toe of the slope should attract more attention. It is one of unfavorable factors that might cause instability if designer overvalued the strength increment at toe of slope. At the toe and outside of the filling, shear strength parameters of nature soil should be used. From shoulder to toe of slope, shear strength increment should multiply a reduction factor ξ. The factor ξ is a function of the distance from toe to shoulder of the filling, and its expression is as follows:

$$\xi = \Delta\tau \cdot x / d \qquad (1)$$

where $\Delta\tau$ is the shear stress increment of middle of the fill, x is the distance from toe to shoulder, d is the distance between toe and shoulder.

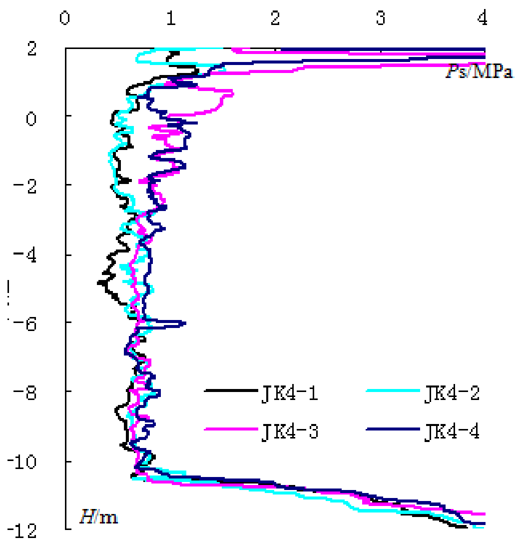

Figure 4: Curves of static cone penetration test

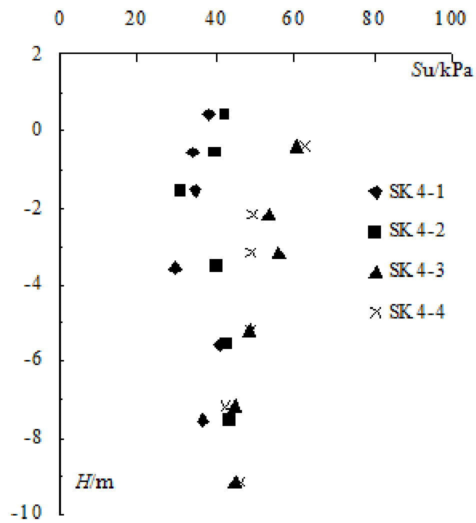

Figure 5: Plot of vane shear test

Results of vane shear test (VST)

The results of VST were shown as Fig.6. The locations of SK were shown in Fig.2. The shear strength increased less and less as the depth increased. It was clear that at middle and shoulder of the slope, it improved 0.4~0.8 times above elevation -4m(7m depth), and 0.2 times between elevation -4m and -7m(about 7~10m depth). The results coincided with the SCPT. The influence depth of the filling was about 1/3W.

CACULATION WITH POLYGONAL LINE EQUATION

The SCPT and VST results show that shear strength increment could reach 0.4~0.8 times within the depth 1~7m. The next target is to calculate the shear strength increment with polygonal line equation adopting the parameters got from CU test and compare the calculation results with *in situ* test results to prove the validity of the equation.

Polygonal Line Shear Strength Equation

Fig. 6 shows the strength envelope of polygonal line and straight line. The black bold straight line stands for the model not considering the structure property of soft soil, and the polygonal line for the model considering the structure property of soft soil. The latter is divided into two sections, the first section is to fit low stress level test data and the second one high stress level data. The turning point corresponds to the yield stress σ_{vc}. The equation considering structure property of soft soil was as follows:

When $\sigma'_{v0}<\sigma'_{v}<\sigma_{vc}$

$$\tau_f=c_1+\sigma'_{v}\tan\varphi_1 \qquad (2)$$

Where σ'_{v0} is called effective vertical geostatic stress; σ'_{v} is the vertical effective stress, which is total of effective vertical geostatic stress and effective stress induced by applied loads; τ_f is shear strength ; c_1 is the cohesion before σ_{vc} ; φ_1 is fictional angle before σ_{vc}.

The strength increment can be deduced as follow:

$$\triangle\tau=\tau_f-\tau_{f0}=(\sigma'_v-\sigma'_{v0})\tan\varphi_1 \tag{3}$$

Whereτ_{f0} is called shear strength of nature soft clay.

When $\sigma'_v > \sigma_{vc}$,

$$\tau_f=c_2+\sigma'_v\tan\varphi_2 \tag{4}$$

$$\triangle\tau=\tau_f-\tau_{f0}=c_2-c_1+\sigma'_v\tan\varphi_2-\sigma'_{v0}\tan\varphi_1 \tag{5}$$

Wherec_2 is the cohesion after σ_{vc}, which is very near to zero; φ_1 is fiction angle after σ_{vc}.

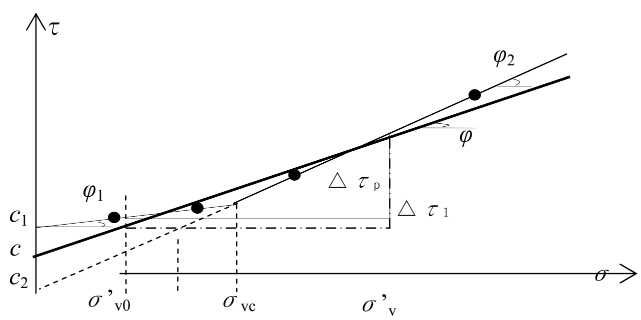

Figure 6: Calculation model of strength increase

Parameters acquired from the CU test

The data, fitting polygonal line and straight line were shown in Fig.7. The yield stress σ_{vc}, it was about 150kPa. Before and after the σ_{vc}, the parameters were shown in Fig.8. The shear strength changed very little before σ_{vc}, and it denoted the nature shear strength of soft soil.

Calculation of shear strength increment

The calculated results with the polygonal line equation and parameters got from CU test were shown in Table 2. The stress induced by filling was calculated using the Lu's design chart (2002) and Li *et al.* (2001) method.

Table 2 shows that, the result calculated with polygonal line equation are higher than the straight line equation, and polygonal line equation result is closed to the outcome of SVT at depth of 3.5m but the straight line equation result is closed to the SVT outcome at 6.5m depth. Under the filling, the calculation results of polygonal line and straight line equation are all higher than SVT outcomes, but the polygonal line equation results are lower than that of straight line and closer to SVT results. So it can be deduced that the polygonal line equation has advantages on calculating the nature shear strength at shallow depth, and it is suitable to calculate the shear strength under combined load and shear strength increment. In addition, the straight line equation may underestimate the nature shear strength and overrate the increment of shear strength. It may lead to underestimate the limit high of filling at prophase of project and postpone the days of construction consequently, and overrate the increment at anaphase, which may bring on instability of the soft soil ground. All these risks can reduce with polygonal line equation.

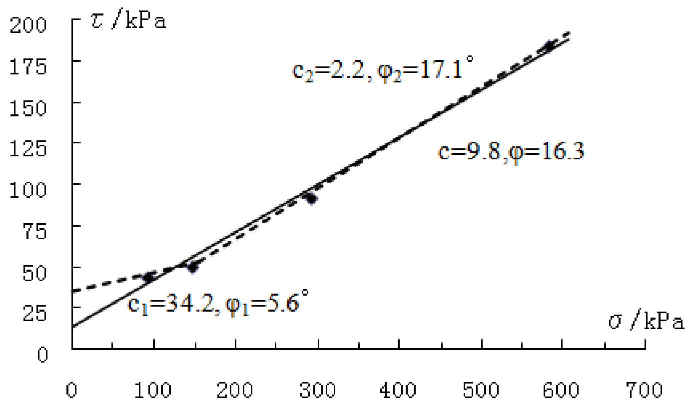

Figure 7: Consolidated-undrained shear test and the strength parameters

Table 2: The Calculation Results Comparative used Parameters from Consolidated-Undrained Shear Test with vane test

Location	Depth /m	Nature shear strength (kPa)			Strength under filling (kPa)			Increment (kPa)		
		PLE	SLE	Vane test	PLE	SLE	Vane test	PLE	SLE	Vane test
Middle SK4-4	3.5	37.6	20	34.1	66.5	70.9	62.6	28.9	50.9	28.5
	6.5	40.6	29	29.5	73.3	77.3	48.5	32.7	48.5	19.0
Shoulder SK4-3	3.5	37.6	20.6	34.1	62.2	69.8	60.3	24.6	49.2	26.2
	6.5	40.6	29.8	29.5	67.4	75.0	55.9	26.8	45.2	26.4
Toe SK4-2	3.5	37.6	20.6	34.1	46.2	32.9	42.1	8.6	12.3	8.0
	6.5	40.6	29.8	29.5	43.7	44.9	40.0	3.1	15.1	10.5

CONCLUSIONS

In this paper the water content, void ratio, static cone penetration test, and vane shear test have been analyzed to make the influence of combined load in vertical and horizontal direction clear. In addition, the polygonal line equation of shear strength increment has been used to calculate and compare with straight line equation. All of the calculated results have been compared with the *in situ* vane shear test results. The following conclusions have been reached:

(1) The water content, liquid limit and plastic limit of soil under filling are lower than that of nature soil. The *w* and *e* decreases about 10~20%. The L_L and P_L decreased resulting from the structure of soft clay destroyed by the surcharge load.

(2) The test results demonstrated that the influence depth at the center of the combined load was (1/3~1/2)W, and the strength increased (0.4~0.8) times within the 1/3W, and (0.2~0.4) times within the (1/3~1/2)W. At the shoulder of the slope, the increment was similar to that at the center within the 3/14W and (0.1~0.3) times within (3/14~1/2) W. At the toe of the slope, the strength was close to nature strength, and increased (0.1~0.3) times within (1/4~1/2) W.

(3) The polygonal line model was verified to be effective and superior based on the results of *in situ* vane test. In calculation of the nature strength of soft clay, the result of polygonal line model adopting the CU test, is closer to that of *in situ* vane test. Moreover, in calculation of the strength growth after surcharge, the soft soil strength got from the polygonal line model adopting the parameter of CU test was closer to *in situ* vane test.

(4) The yield stress is different to preconsolidated stress. Preconsolidated stress is the maximum stress that the soil had been exposed to but the yield stress is a general concept that reflects the preconsolidated stress and structure property of soft soil. In order to get better polygonal line and yield stress, more soil samples at lower vertical stress level in CU test should be used.

(5) The creep properties of soft soil that may decrease the shear strength had not been considered in this paper. The shear strength increment of soft soil is a complex topic in geotechnical engineering, and more factors need to be studied and discussed in next step.

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