Study on relationship between static cone penetration strength and shear strength of soil

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ABSTRACT

On basis of the analysis on results of laboratory test, the field vane shear test and the static cone penetration test of different types of soil in Tianjin, it is proposed that there is significant positive linear correlation between the static cone penetration tip resistance and the vane shear strength. Moreover, for clay a more distinct linear correlation exists than that for mucky soil and silty clay. Therefore the results of static cone penetration test can be applied to the stability calculation.

Keywords: static cone penetration test, vane shear test, laboratory test, shear strength, correlation analysis

1 INTRODUCTION

At present, field vane strength index is usually adopted in the stability calculation of slope and pile foundation. Field vane strength test is conducted in situ without disturbance to soil. Thus it can more closely reflect the actual strength of soil so this test is favored by designers. However, the field vane strength test has its own shortcomings. Firstly, its application scope has certain limitations, and it is applicable to saturated soft clay, mainly to sludge, sludge clay, sludge silty clay, or the silty clay and clay with relatively low strength. As for the silty clay and clay with relatively high strength after foundation reinforcement treatment, the vane head is often twisted off during vane shear test, therefore, the actual strength of soil cannot be obtained; secondly, relatively large spacing in depth direction should be adopted. In order to ensure no disturbance to the soil at the previous testing point, it is necessary to press the vane into the hole bottom by 30 ~ 40 cm to conduct vane strength test at the next testing point, and the elevation difference between two consecutive testing points is at least 50cm, i.e. the test results can be obtained from at most two consecutive testing points per 1m in the depth direction; thirdly, if there is thin weak interlayer in the soil layer, the testing point of vane may be not located in the interlayer, so the thin weak interlayer will be neglected. Even though the testing point is located in the weak interlayer, the thickness of this interlayer cannot be judged.

The field static cone penetration test also is directly conducted without any disturbance to soil. It can more closely reflect the actual strength of soil, ascertain the subtle changes in mechanical characteristics that are difficult to be distinguished during drilling and sampling and can test the silty clay and clay with relatively high strength after ground improvement; moreover, during the test, the recording spacing can be set to be recorded once per 10cm so that the test results of 10 testing points can be obtained per 1m in the depth direction, therefore the calculation results will be more reliable through a series of calculations with vane strength instead of static cone penetration strength. In addition, the field static cone penetration test is simple to operate and also costs much less than field vane test. Therefore, it is of great significance to study the relation between field vane strength and static cone penetration strength(Chen and Yu 1991, Liu and Wu 2004, Jian et al. 2005.).

2 STUDY METHOD

2.1 Field test

Tianjin Port is located at the northeast coast of China. The whole port is covered by deep soft clay in a thickness of 20 m approximately, and many areas in the port are formed by dredged soil through hydraulic reclamation. The results of surveys and in-situ tests conducted over years show that these soils are newly-deposited clay with small particles, the deposition history is short and the self-weight consolidation has not yet been finished, so that these soils have very high compressibility, sensitivity and porosity ratio but very low shear strength and coefficient of permeability.

On basis of the results of field static cone penetration test, vane shear test and laboratory test, shear strength, correlation analysis

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penetration test, vane shear test and laboratory test on the soil body before and after soil strength improvement within the depth of about 20 m under the ground of a certain wharf work at Tianjin Port, a statistical analysis is conducted on the correlation among the parameters obtained from tests of five types of soils, i.e., sludge, sludge clay, sludge silty clay, clay and silty clay. To strengthen the comparability of the results obtained by different test methods, each group of field static cone penetration test, vane shear tests and soil sample laboratory tests shall be carried out successively at the same position, with a spacing of the plane positions of three test holes equal to 0.5 m. The test procedures shall be in strict accordance with the relevant specifications. Statistics, analysis and comparison are conducted over a large number of test results to find out the relationship between the field static cone penetration strength and the undrained vane shear strength for five different soil types (sludge, sludge clay, sludge silty clay, clay and silty clay) and to provide a basis for the application of static cone penetration strength in stability checking.

2.2 Data screening principle

During statistical analysis of data, the abnormal values and the lead-lag values of static cone penetration test shall be eliminated. In principle, as for data screening, the vane shear strength shall correspond to the static cone penetration test result obtained at the same depth and the laboratory test results shall correspond to the average value of static cone penetration test results obtained within the same depth range. When the tip resistance curve has sudden change and the thickness of sudden change is small, it can be regarded as the influence of interlayer or the restriction of accidental factors (small stones, shells or a few coarse particles exist in soil), and the data having poor comparability with vane shear strength and laboratory test results, it shall be eliminated; if the vane shear strength is relatively small but the tip resistance is relatively large or the variation of data is stable, their comparability is poor, the vane shear strength is generally regarded as abnormal and shall be eliminated; if the laboratory test results are large or small obviously and have poor comparability with tip resistance value, they also shall be eliminated.

2.3 Correlation analysis of test results

If the independent variable is determined, the dependent variable will be non-determined, but there is a certain relationship between both, i.e. non-determined relationship, which is referred to as correlation. The screened test results will be drawn on the scatter diagram which has the tip resistance at corresponding depth as the abscissa, and the scatter diagram shows the linear variation relationship between most of the parameters and the tip resistance, their linear correlation equation can be obtained according to least square method by using common unitary linear regression analysis, to verify whether their linear correlation is obvious or not.

Suppose that the unitary linear regression equation is \( y = a + bx \).

According to least square method, the coefficients are taken as:

\[
b = \frac{\sum X_i Y_i - \frac{1}{n} (\sum X_i)(\sum Y_i)}{\sum X_i^2 - \frac{1}{n} (\sum X_i)^2}
\]

(1)

\[
a = y - bx
\]

(2)

Thus the correlation coefficient is obtained:

\[
R = \frac{\sum (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum (X_i - \bar{X})^2 \sum (Y_i - \bar{Y})^2}}
\]

(3)

where \( 0 \leq |R| \leq 1 \). The more the correlation coefficient approximates to 1, the better the fitting degree of regression equation is; contrarily, the more the correlation coefficient is approximate to 0, the worse the fitting degree of regression equation is. If the correlation coefficient is greater than 0, a positive correlation exists; otherwise, a negative correlation exists.

The significance test for unitary linear regression effect adopts correlation coefficient test method, the significant level \( \alpha \) is given, and the critical value \( R_a(n-2) \) can be looked up from the table of correlation coefficient critical value. For \( |R| > R_a(n-2) \), the linear regression is deemed to be significant; for \( |R| \leq R_a(n-2) \), the linear regression is deemed to be non-significant or not exist.

3 TEST RESULTS

In Tianjin, the soft soil at the depth of 20 m mainly is sludge, sludge clay, sludge silty clay, or silty clay and clay with low strength. Sludge and muddy soil occupy a considerable proportion before reinforcement, while after ground improvement, part of sludge clay is transformed to clay and part of sludge silty clay is transformed to silty clay. The correlation between the tip resistance \( qc \) of double-bridge static cone penetration test and the undrained shear strength of vane for different soil types can be obtained through mathematical statistics and analysis on the comparison test results of field static cone penetration test, vane shear test and soil sample laboratory test, as shown in Table 1 and Fig. 1 to Fig. 5.
Table 1  Correlation between static cone penetration tip resistance $q_c$ and vane shear strength $c_u$ for different soil types

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Sludge</th>
<th>Sludge clay</th>
<th>Sludge silty clay</th>
<th>Clay</th>
<th>Silty clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression equation</td>
<td>$q_c = 61.65$</td>
<td>$q_c = 68.91$</td>
<td>$q_c = 63.55$</td>
<td>$q_c = 49.17$</td>
<td>$q_c = 20.56$</td>
</tr>
<tr>
<td>$q_c + 10.75$</td>
<td>$q_c + 10.44$</td>
<td>$q_c + 18.25$</td>
<td>$q_c + 27.75$</td>
<td>$q_c + 50.06$</td>
<td></td>
</tr>
<tr>
<td>Statistical sample $n$</td>
<td>140</td>
<td>145</td>
<td>70</td>
<td>102</td>
<td>50</td>
</tr>
<tr>
<td>Correlation coefficient $R$</td>
<td>0.69</td>
<td>0.74</td>
<td>0.71</td>
<td>0.79</td>
<td>0.73</td>
</tr>
<tr>
<td>$R_{(n-2)}$ (α=0.01)</td>
<td>0.218</td>
<td>0.214</td>
<td>0.307</td>
<td>0.254</td>
<td>0.361</td>
</tr>
<tr>
<td>Scope of application</td>
<td>$10.0 \leq c_u \leq 42.4$</td>
<td>$18.9 \leq c_u \leq 72.6$</td>
<td>$23.1 \leq c_u \leq 72.4$</td>
<td>$56.5 \leq c_u \leq 75.8$</td>
<td>$50.7 \leq c_u \leq 112.6$</td>
</tr>
</tbody>
</table>

Fig. 1. Correlation between static cone penetration tip resistance and vane shear strength of sludge.

Fig. 2. Correlation between static cone penetration tip resistance and vane shear strength of sludge clay.

Fig. 3. Correlation between static cone penetration tip resistance and vane shear strength of sludge silty clay.

Fig. 4. Correlation between static cone penetration tip resistance and vane shear strength of clay.

Fig. 5. Correlation between static cone penetration tip resistance and vane shear strength of silty clay.

The test results show that there is better linear correlation between the static cone penetration tip resistance and vane shear strength, i.e. the vane shear strength increases along with an increase of static cone penetration tip resistance, the correlation coefficient is larger than the critical correlative value and the linear regression is significant. Clay has relatively uniform nature so that its test results are relatively stable, and compared to other mucky soil and silty clay, it is a more distinct linear correlation between the static cone penetration tip resistance and undrained vane shear strength.
4 CONCLUSIONS

The correlation between static cone penetration strength and vane shear strength for different soil types are obtained through result analysis between a large number of field tests and laboratory tests in Tianjin, and the conclusions are drawn as follows:

(1) There is obvious linear positive correlation between static cone penetration tip resistance and undrained vane shear strength for sludge, sludge clay, sludge silty clay, clay and silty clay, so the results of static cone penetration test can be applied to stability calculation.

(2) Clay has relatively uniform nature, compared to other mucky soil and silty clay, it has more distinct linear correlation between the static cone penetration tip resistance and undrained vane shear strength.

REFERENCES

