Research on Field Vane Shear Strength of Marsh Peat Soil in South America

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Abstract: According to high backfilling project in South America, through a large number of laboratory tests data and field vane shear test results, the engineering characteristics of marsh peat soil in this area are analyzed, and the variation of the shear strength of the peat soil along the depth and the sedimentary characteristics are demonstrated. The selection principle of the calculation index of the foundation for the high-filling operation of peat soil foundation is proposed. It has reference significance for similar engineering construction.

1. Introduction

The rivers of South America are widespread and the plants are luxuriant. The tropical rain forests account for 44% of the land area. Most of the areas cover the deep marsh peat soil. The marsh phase peat soil is a special soft soil different from ordinary silt soil. It is due to special climatic environment, dense aquatic vegetation, and a large number of decomposing plant residues under long-term water accumulation and lack of oxygen. The soil was formed by the accumulation of the body [1]. Peat soil is a mixture of organic soil and inorganic soil. Its engineering properties are closely related to the composition and content of local inorganic soil, the characteristics of organic matter and sedimentary environment. The engineering properties of peat soil have strong regional environmental characteristics [2]. Therefore, for the construction project on the marsh peat soil foundation, It is of great significance to the safety of the project construction that fully grasping its engineering characteristics and rationally selecting the soil index.

2. Peat soil engineering characteristics

A total of 244 drilling holes were completed in the geological survey of the project, including 42 vane shear strength test holes, 36 unearthed soil holes, 126 standard penetration test holes, and 40 visual identification holes. From the survey results, the physical, mechanical, and consolidation indicators of marsh peat soil are counted. The statistical results are shown in table 1 ~ table3.
Table 1. Physical indicators statistics of peat soil

| Statistical item | Natural moisture content w(%) | Gravity density γ (kN/m³) | Void ratio e | Specific gravity Gs | Organic matter content (%) | Liquid limit wL(%) | Plastic limit wP(%) | Plastic index Ip | Liquidity index IL |
|------------------|-------------------------------|----------------------------|---------------|---------------------|---------------------------|------------------|-------------------|----------------|------------------|
| Max.             | 202.0                         | 16.0                       | 4.039         | 2.54                | 16.8                      | 134.0            | 80.0              | 54.0           | 1.54             |
| Min.             | 84.5                          | 13.5                       | 2.523         | 2.45                | 14.8                      | 84.0             | 35.2              | 48.7           | 0.98             |
| Mean             | 149.5                         | 14.5                       | 3.361         | 2.47                | 15.7                      | 104.3            | 66.5              | 41.7           | 1.44             |

Table 2. Mechanical indexes statistics of peat soil

| Statistical item | Direct shear test Cohesion c (kPa) | Internal friction angle φ (°) | Consolidated quick direct shear test Cohesion c (kPa) | Internal friction angle φ (°) | Triaxial test [UU] Cohesion c (kPa) | Internal friction angle φ (°) | Field vane shear test Undisturbed soil C_u (kPa) | Disturbed soil C_u (kPa) | Sensitivity S_t |
|------------------|-----------------------------------|-------------------------------|------------------------------------------------------|-------------------------------|-------------------------------------|-------------------------------|-----------------------------|----------------------|----------------|
| Max.             | 12.6                              | 3.8                           | 20.1                                                  | 7.1                           | 30.9                                | 21                           | 23.6                        | 4.9                  | 10.5            |
| Min.             | 9.1                               | 2.0                           | 8.3                                                   | 0.6                           | 3.6                                 | 0.3                          | 5.9                         | 1.4                  | 4.2              |
| Mean             | 10.8                              | 2.6                           | 13.7                                                  | 3.8                           | 11.0                                | 1.2                          | 10.1                        | 2.7                  | 7.1              |

Table 3. Consolidation index statistics of peat soil

| Statistical item | Compression factor a_{0.1-0.2} (MPa) | Compression modulus E_{50.1-0.2} (MPa) | Consolidation coefficient C_v (*10^3/cm²/s) | Consolidation coefficient C_h (*10^3/cm²/s) |
|------------------|----------------------------------------|----------------------------------------|---------------------------------------------|---------------------------------------------|
| Max.             | 3.25                                   | 1.35                                   | 0.87                                        | 0.50                                        | 0.48                                      | 0.75                          | 0.35                        | 0.3                |
| Min.             | 2.45                                   | 1.10                                   | 0.82                                        | 0.35                                        | 0.15                                      | 0.65                          | 0.28                        | 0.25               |
| Mean             | 2.88                                   | 1.29                                   | 0.85                                        | 0.45                                        | 0.32                                      | 0.70                          | 0.32                        | 0.27               |

From the statistical results of table 1 ~ table 3, the engineering characteristics of the marsh peat soil in the project area are as follows.

(1) Physical property index

The organic matter content of the soil is 14.8%~16.8%, with an average of 15.7%, which is peat soil. The natural water content is 84.5%~202.0%, and the average value is 149.5%. The void ratio is 2.523~4.039, and the average value is 3.361, which is close to the floating mud category.

(2) Strength index

The cohesive is 12.2 kPa~14.4 kPa, the internal friction angle is 2.8°~5.6°, and the shear strength index is small.

(3) Deformation index

The compression coefficient is 2.45 MPa^{-1}~3.25 MPa^{-1}, which is a high compressibility soil. The average value of the consolidation coefficient is 3.2×10^{-4}cm²/s ~8.5×10^{-4}cm²/s, and the consolidation coefficient decreases significantly with the increase of the overburden pressure. When the drainage consolidation method is used, the soil consolidation is slow.

(4) Soil consolidation strength growth index

The fast internal friction angle of the consolidation is 3.6°~7.1°, and the average value is 5.6°. The foundation is consolidated by the drainage consolidation method, the strength of the foundation soil increases slowly.

(5) Sensitivity index
The sensitivity of the soil is 4.2~10.5, with an average of 7.1, which is a high sensitivity soil. After the soil is disturbed and destroyed, the strength of the soil is significantly reduced.

The peat soil of this project belongs to the category of muddy mud, which has the engineering characteristics of high sensitivity, high compressibility, slow drainage consolidation and slow growth. Non-organic slime is generally considered to have no structural strength. The strength of peat floating mud is mainly derived from the interaction between organic matter and soil particles, and this effect is fragile, and the intensity is reduced after disturbance.

3. Separation characteristics of shear strength along the depth of peat soil cross

3.1. Field vane shear test specification requirements

The standard used in the field vane shear test of this project is ASTM D2573/D2573M-15 [3]. In order to facilitate the use of domestic analytical procedures for the stability analysis of high-filled foundations, it is necessary to demonstrate the effectiveness of the strength obtained by the field vane shear test using American Standard. The comparison between Chinese and American standards is now carried out.

3.1.1. Field vane shearing equipment

The comparison of Chinese and American standard field vane shearing equipment parameters are shown in Table 4.

| Standard        | Diameter D (mm) | High H (mm) | Thickness t (mm) | Shaft diameter (mm) | Lower edge angle α(°) | Height to diameter ratio H/D | Area ratio (%) |
|-----------------|-----------------|-------------|------------------|---------------------|-----------------------|------------------------------|----------------|
| ASTM D2573M-15  | 35~100          | 70~250      | 0.8~3.0          | 14~20               | 0 or 45               | 1~2.5                        | ≤10            |
| GB50021-2001    | 50              | 100         |                  |                     |                       |                              |                |
|                 | 75              | 150         |                  |                     |                       |                              |                |
|                 | 100             | 200         |                  |                     |                       |                              |                |

As can be seen from Table 4, the US standard gives a wider range of vane diameters and heights. The Chinese standard vane equipment also meets American standards.

3.1.2. Field vane shear test shear rate

ASTM D2573/D2573M-15 requires: the shear rate is controlled from 3°/min to 7°/min, the shear failure time is about 2 min ~ 4 min, and the soft soil can be used for 10 min ~ 15 min. The vane plate was rotated 5 ~ 10 loops to test the shear strength of the remolded soil.

“Code of Geotechnical Investigation on Port and Waterway Engineering” [4] (JTS 133-2013): The shear rate is 1°/10s, which is equivalent to 6°/min, and the shear failure time is about 3min~10min. The vane plate was rotated 6 loops to test the shear strength of the remolded soil.

The field vane shear test is an in-situ test method for saturated soft clay. The shear rate of soft clay has a great influence on the obtained shear strength value. For the above two standards, the shear rate is basically the same, and the shear rate using the national standard can meet the requirements of the American standard.

3.1.3. Correction of measured value of field vane shear strength

Both Chinese and American standards believe that the measured field vane shear strength needs to be corrected. The modified expression is as shown in equation (1):

\[ c_u = \mu S_u \]  \hspace{1cm} (1)

Equation: \( c_u \) = Shear strength, kPa. \( \mu \) = Correction factor. \( S_u \) = Field vane shear strength measured value, kPa.
The Chinese standard first defines the applicable soil range of the field vane shear test, which is generally used for saturated soft clay. For the revision of $S_u$, “Geotechnical Investigation Specification” [5] (GB 50021-2001) (2009 edition) stipulate: “Revised the undraind shear strength of the measured in-situ field vane shear test according to soil conditions and regional experience.” The revised method gives the “regional experience method” and “the plasticity index method recommended by Daccal et al.” in the description of the article. The revised principle of the shear strength of the measured vane shear strength is the same as the “Code of Geotechnical Investigation on Port and Waterway Engineering” (JTS 133-2013) and “Geotechnical Investigation Specification” (GB 50021-2001) (2009 edition). “In-situ test procedures for railway engineering geology” [6] (TB10018-2003) stipulates: “When $I_p \leq 5$, the correction coefficient $\mu=1$. When $20<I_p \leq 40,$ $\mu=0.9$.”

According to the appendix of ASTM D2573/D2573M-15, by analyzing and comparing the factors affecting the field vane shear test, for clay and silt [7], when $I_p > 5$, the field vane shear strength correction method is as follows:

$$\mu = \mu_A \mu_R$$  \hspace{1cm} (2)

$$\mu_R = 1.05 - b \cdot I_p^{0.5}$$  \hspace{1cm} (3)

$$b = 0.015 + 0.0075 \log t_f$$  \hspace{1cm} (4)

Equation: $\mu =$ Correction factor, $\mu_A =$ Soil anisotropy correction factor. $\mu_A =$ decreases with the increase of the plasticity index $I_p$ of soil, ranging from 1.05 to 1.10. $\mu_R =$ is the correction coefficient of shear failure time. For the soft soil foundation using the standard method for field vane shear test, usually $t_f$ takes $10^4$. It can be seen that the revision of $S_u$ by the standards of Chinese and the United States are basically adjusted based on the change of the plasticity index $I_p$, and the processing principle of the correction coefficient is the same.

### 3.2. Field vane shear strength along the depth distribution

It is known from Table 1 that the plasticity index of the marsh phase peat soil is 41.7 and the correction factor is 0.762. After the abnormal value of the shearing index of the measured field vane shear is removed, the peak strength is corrected to obtain the shear strength index of the cross plate. The statistical results of the field vane shear strength are shown in Fig. 1.

It is known from Fig. 1 that the field vane shear strength of the marsh peat soil crucible increases linearly with depth.
4. Analysis of sedimentary uniformity of marsh phase peat soil

4.1. The significance of two strength indexes of vane shear index and direct shear fast shear index

Both indicators forcefully control the location of the fracture surface when the soil is damaged.

The direct shear fast shear index is the soil unconsolidated undrained strength index of the soil plane shear condition, and the corresponding sliding surface is the horizontal plane.

The field vane shear test reflects the unconsolidated undrained strength index of the soil combined with the horizontal and vertical planes. Specifically, the field vane equipment used in this project has a diameter of 50mm and a height of 100mm. The upper and lower horizontal planes are about 3925mm², the vertical plane area is 15700mm², the total shear area is 19625mm², and the horizontal plane is 20%. Vertical plane Accounted for 80%.

Due to the complexity of sedimentary history, foundation soils generally do not have isotropic properties, so the two indices give different shear strengths for the same foundation.

When the foundation soil is subjected to the arc sliding stability analysis, it is characterized by the sliding of the circular arc, and only one point directly below the center of the sliding arc is consistent with the direct shearing rupture surface, and the other sliding arc positions are all with the direct shearing rupture. Therefore, for the stability analysis of the arc sliding of the anisotropic soil, the field vane strength index is closer to the ground damage.

4.2. Estimating the φ and c values of the soil from the field vane shear strength

The vane head is subjected to the torsional moment as follows:

\[ M = \pi DH \cdot \frac{D}{2} \cdot \tau_{fv} + 2 \cdot \frac{nD^2}{4} \cdot \tau_{fh} = \frac{1}{2} \pi D^2 H \tau_{fv} + \frac{1}{6} \pi D^3 \tau_{th} \]  \hspace{1cm} (5)

Equation: \( M \) = Torque for shear failure, \( \tau_{fv} \), \( \tau_{th} \)=The shear strength of the cylindrical soil side surface and the upper and lower bottom surfaces respectively during shear failure.\( H \)=Vane high, \( D \)=Vane Diameter.

When calculating the field vane shear strength \( c_u \), it is often simplified \( \tau_{fv} = \tau_{th} = c_u \). Substitute equation (5) can deduced:

\[ c_u = \frac{2M}{\pi D^2 (H + \frac{D}{2})} \]  \hspace{1cm} (6)

In fact, the soil is anisotropic, and the shear strength of the upper and lower surfaces and sides of the soil column are different during the shearing process. A large number of studies have found that since the lateral area of the soil column is much larger than the upper and lower bottom areas, the shear strength of the side is about 85% [8]. According to equation (5), the shear strength of the cross plate mainly reflects the field vane shear strength of the soil, while the strength of the vertical plane is the effective consolidation pressure or the small principal stress, then the field vane shear strength is the soil damage. The stability calculation of the foundation is directly carried out by using the field vane shear strength index. The result will be conservative and the stability of the foundation cannot be reasonably evaluated. Therefore, it is particularly important to estimate the two index of cohesion and internal friction angles required for the calculation of foundation soil pressure and bearing capacity by the field vane shear strength index.

According to the Mohr-Coulomb shear strength formula, \( \tau_f = \sigma \cdot \tan \varphi + c \), the shear strength of soft clay consists of friction strength \( \sigma \cdot \tan \varphi \) and cohesive strength \( c \)[9]. The frictional strength is determined by the effective normal stress \( \sigma \) and the friction coefficient \( \tan \varphi \) on the shear plane. \( \varphi \) is the internal friction angle of the soil, which is mainly related to the mineral composition of the soil, the shape and size of the particles and other factors. \( c \) is the cohesion of the soil, mainly related to various physical and chemical forces between the soil particles. The frictional strength is related to the normal stress on the shear plane. The larger normal stress will produce a larger frictional strength, and the cohesive force is independent of the normal stress. The frictional strength and the cohesive
strength work together to make the different shear planes of the soil have different shear strengths.

The vane plate forms a cylinder slightly larger than the diameter and height of the vane plate during the shearing process. Under different consolidation degrees, the strength of the vertical plane and the horizontal plane of the soil column are different, respectively:

\[
\tau_{fv} = k_0 U_t \gamma' z \tan \varphi + c \tag{7}
\]

\[
\tau_{th} = U_t \gamma' z \tan \varphi + c \tag{8}
\]

Equation: \(\tau_{fv}\)=Shear strength on vertical surface, \(\tau_{th}\)=Shear strength on a horizontal surface, \(k_0\)=Lateral pressure coefficient of soil, \(U_t\)=Average consolidation degree of soil, \(\gamma'\)=Effective gravity of soil, \(z\)=Calculate point depth.

Bringing equations (7) and (8) into equation (5):

\[
M = \frac{1}{2} \pi D^2 H \left( k_0 U_t \gamma' z \tan \varphi + c \right) + \frac{1}{6} \pi D^3 (U_t \gamma' z \tan \varphi + c) \tag{9}
\]

Simultaneous (3) and (6) simplified calculations:

\[
c_u = \frac{k_0 H \gamma' + D}{H + \frac{D}{2}} U_t \gamma' z \tan \varphi + c \tag{10}
\]

For statistical regression analysis, then \(\bar{Y} = c_u\), \(\bar{X} = z\),

\[
a = \frac{k_0 H \gamma' + D}{H + \frac{D}{2}} U_t \gamma' z \tan \varphi, \quad b = c \tag{11}
\]

Then the standard form of the linear regression equation of equation (10) is obtained.

\[
\bar{Y} = a \bar{X} + b \tag{12}
\]

In equation (10) \(D, H\) and \(\gamma'\) are all known, and for marsh peat soil \(k_0\), it is generally about 0.6 [10]. By linearly calculating the strength of the field vane strength measured, a linear equation of the field vane strength \(c_u\) and the depth \(Z\) is established. The intercept \(B\) of the linear equation is the cohesion \(C\), and the slope can calculate the internal friction angle \(\varphi\).

Regression analysis is carried out on the field vane shear strength index and depth of the peat soil. See Fig.2, the standard form of the statistical equation is \(\bar{Y} = 0.2656 \bar{X} + 4.2315\), and the correlation coefficient \(r=0.9037\), from the formula (10), the calculated strength index: cohesion \(c=4.2\) kPa, internal friction angle \(\varphi=3.2^\circ\).

4.3. Sediment uniformity of marsh-phase peat soil

The strength index of the marsh phase peat soil calculated from the field vane shear strength index is \(\varphi=3.2^\circ\), \(c=4.2\)kPa, from Table 3, the direct shear fast shear index of the layer is \(\varphi=3.8^\circ\), \(c=12.6\)kPa.Therefore, it is determined that the marsh-phase peat soil of this project has obvious anisotropy.

5. Selection and evaluation of shear index for calculation of circular slip of peat soil

The marsh peat foundation treatment of this project adopts the preloading method of stacking, specific steps:①Remove the upper surface trees and humus soil (cleared to ±0.0m);②Backfilling sand to +2.5m.③Plastic drainage board is set into the foundation below the airport runway safety zone with a spacing of 0.9m and a depth of 1.0m into the clay. The slope area is treated with drainage board + 10% replacement rate sand pile (the spacing of the sand piles are 2.24m, the center of the four sand piles are plastic drainage board).④The medium-fine sand piled load construction is divided into 4 layers (the load loading period of each stage is one month, the intermittent period is three months, and then the next stage loading). A typical cross-section is shown in Fig. 2.
The port engineering foundation calculation system (2008 version) was developed by the CCCC Tianjin Port Engineering Institute Co., Ltd. It is applicable to all kinds of docks, revetments, various types of dikes, dams, soft soil foundation reinforcement and other projects for analysis and calculation. This example is the stability calculation of the slope during construction, and the sliding surface is assumed to be the circular sliding of the composite sliding surface. Three kinds of shear strength parameters are used in the slope stability calculation during construction, which are the direct shear fast shear index, the unconsolidated-undrained triaxial UU index and the field vane shear strength calculated soil shear strength index. The selected parameters are shown in Table 5. According to the groundwater level monitoring data before the landslide, the groundwater level is +4.0m.

Table 5. Selection of parameters

| Soil name    | Gravity density γ(kN/m³) | Effective bulk density γ’(kN/m³) | experiment method       | Cohesion c (kPa) | Internal friction angle φ(°) |
|--------------|--------------------------|----------------------------------|-------------------------|------------------|----------------------------|
| Backfilling sand | 18.8                     | 8.0                              | Direct shear test       | 10.8             | 2.6                        |
| Peat soil    | 14.5                     | 4.5                              | Triaxial test [UU]     | 11.0             | 1.2                        |
| Clay         | 18.5                     | 8.5                              | Field vane shear test  | 4.2              | 3.2                        |

According to the provisions of "Technical Specifications for Building Slope Engineering" [11] (GB50330-2013), the soil slope 10m<H≤15m is a slope with safety level 1. The safety factor of the slope is: 1.0<F≤1.0 is unstable, 1.0<F≤1.05 is lack stable, 1.05<F≤1.35 is basically stable, 1.35<F is stable. According to the calculation results of the port ground engineering calculation system, the calculation results of the shear strength index of the field vane shear strength after the second stage loading show a lack steady state. The statistical results of the safety factors calculated by the different shear indicators are shown in Table 6.

Table 6. Slope safety factor obtained from different shear indicators

| Item             | Cohesion c (kPa) | Internal friction angle φ(°) | Safety factor | stability   |
|------------------|------------------|-----------------------------|---------------|-------------|
| Direct shear test| 10.8             | 2.6                         | 1.649         | Stable      |
| Triaxial test [UU]| 11.0           | 1.2                         | 1.485         | Stable      |
| Field vane shear test| 4.2           | 3.2                         | 1.038         | Unstable    |

From the foundation calculation system calculation results, it can be concluded that the safety factors calculated by the direct shear and the unconsolidated-undrained triaxial UU index are all slope stability, and the stability coefficient calculated by the field vane shear strength estimated shear strength index is lack stable. And the local landslide actually occurred on the site. The stability coefficient calculated by the field vane shear test is the closest to the actual situation. The main reason for the above results is that the marsh phase peat soil has high sensitivity and high plasticity index. It
will disturb the soil sample during the sampling and laboratory test. There is a big gap between the soil index obtained from the laboratory test and the real soil shear strength indicators. The field vane shear test is in-situ test, which can disturb the soil as small as possible, and can more accurately reflect the shear strength index of the soil. In the calculation of the stability of the peat soil foundation slope during construction, it is recommended to use the field vane strength index to estimate the shear strength index of the soil.

6. Conclusions

The main conclusions of the study on marsh soil peat soil in this region are as follows.

(1) The marsh phase peat soil has a high natural moisture content, a large void ratio, and a muddy state, which is a highly sensitive and highly compressible soil. The consolidation coefficient of marsh phase peat soil is small, and the consolidation coefficient decreases significantly with the overburden pressure. The internal friction angle $\phi=3.8^\circ$, the strength growth index is small. The strength of the foundation grows very slowly during the drainage consolidation process.

(2) The shear strength-depth curve of the marsh peat soil field vane shear strength is basically linear. In the stability analysis of the foundation, the shear strength index can be selected directly according to the linear relationship. In the stability analysis of peat soil drainage consolidation foundation, the field vane shear strength index is closer to the actual project.

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