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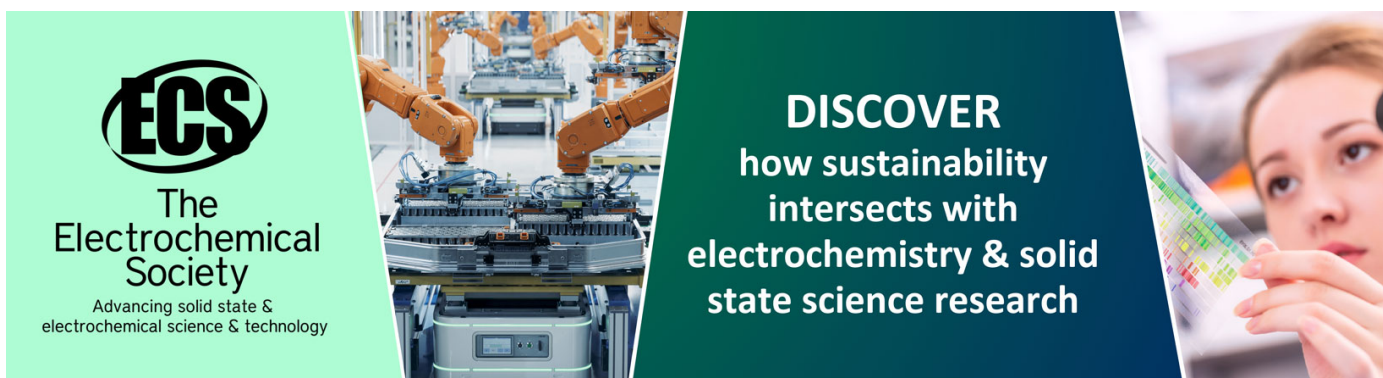
Considering the stress deflection of foundation pit unloading soft soil study on deformation characteristics

To cite this article: Zhou Qiujuan *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **510** 052053

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Considering the stress deflection of foundation pit unloading soft soil study on deformation characteristics

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Abstract. The deflection of the main stress caused by the unloading of the foundation pit is bound to change the stress state of the surrounding soil and produce deformation. By analyzing the stress state of the surrounding soil after the foundation pit excavation and introducing the stress ratio vector, the soil constitutive model considering the stress deflection is derived. The constitutive model shows that: After excavation and unloading of foundation pit, the strain of surrounding soil is not only affected by the change of stress, but also closely related to the deflection of principal stress axis, and then the influence of different azimuth on the deformation characteristics of unloading soil is discussed by static shear test with different azimuth of principal stress axis. The test results show that: When the azimuth Angle of the principal stress is between 0° and 45°, the shear strength of the soil sample decreases with the increase, and the strain increases with the increase. At 45°~75°, the shear strength of soil samples increases with the increase, and the strain decreases with the increase. The variation of the deformation modulus of the soil samples under different azimuths of the principal stress is like a "scoop" curve, which is mainly the reflection of the anisotropy of the soil, and shows strong anisotropy at 0°~15°. By normalizing the stress-strain relationship curves of soil under different azimuth of principal stress, it is found that the strain of soil is not only related to stress, but also affected by the change of principal stress direction. The experimental results are in good agreement with the constitutive model proposed in this paper.

1. Introduction

Foundation pit engineering is very common in infrastructure construction in coastal soft soil areas, and the research on deformation stability caused by foundation pit excavation unloading has been a hot topic in the engineering field^[1-5]. Direction of principal stress deflection is excavation unloading under the action of the surrounding soil is one of the main features of the stress path, which is bound to change the surrounding soil mass stress state and deformation, causing engineering diseases such as cracking of surrounding roads or collapse, cracking and even collapse of adjacent buildings, especially for the remarkable structural and rheological characteristics of soft soil, such as high water content, low permeability, high compression and so on. It makes these engineering diseases caused by soil deformation more prominent in soft soil area. The contribution of stress deflection to the deformation characteristics of soft soil is not clear. Therefore, it is of great theoretical and practical significance to study the soft soil deformation characteristics of foundation pit unloading considering the stress deflection to reduce the engineering disease in the soft soil area.



The soil deformation caused by foundation pit excavation unloading has always been one of the key problems in geotechnical engineering. For this reason, many scholars have carried out abundant research work in such aspects as the rebound deformation of foundation pit unloading soil [6], stress-strain relationship [7], creep characteristics [8] and settlement of surrounding buildings [9]. Peck [10], Blackburn et al. [11] and Wang et al. [12] studied the deformation law and mechanism of surrounding soil after the foundation pit was unloaded. Chen kun et al. [2] studied the deformation law of soil around and at the bottom of deep foundation pit by means of engineering monitoring and numerical simulation. Mu linlong et al. [4] proposed to analyze the soil displacement changes caused by foundation pit unloading by using reverse analysis method. Huang maosong et al. [13] expounded the current research progress of underground engineering and foundation pit engineering in the soft soil area, and focused on the study of the deformation law of soil around the unloading of soft soil. Therefore, scholars at home and abroad have carried out a lot of researches on the deformation characteristics of soil under foundation pit excavation and unloading, but the above researches have not considered the deflection of the principal stress of surrounding soil caused by foundation pit excavation and unloading, so the influence on the stress state and deformation of surrounding soil is not clear. At present, it is more common to consider stress deflection on rock and soil deformation in traffic load [14], tunnel excavation [15] and coal mine [16]. These studies play a positive role in revealing the influence of stress deflection on soil deformation characteristics, but there is no related research on the influence of stress deflection on deformation characteristics of surrounding soil. In view of this, by analyzing the stress field of the surrounding soil after foundation pit excavation, the constitutive relation of soil considering stress deflection is established, the influence of principal stress axis deflection on soil deformation is studied, and the influence mechanism of principal stress deflection on soil deformation characteristics is discussed.

2. Stress field in soil after the excavation of foundation pit

Before the foundation pit is excavated and unloaded, the stress state of the soil around the foundation pit is usually regarded as a semi-infinite space body at the horizontal interface. After the foundation pit is excavated and unloaded, the stress state of surrounding soil changes, and the boundary condition changes from the horizontal interface to the concave surface composed of pit wall and pit bottom. Therefore, in order to simplify the analysis of the semi-infinite plane problem in which the stress state of soil is regarded as a circular notch (as shown in Figure 1), each stress component is calculated [17]:

$$\left. \begin{aligned} \sigma_x &= k_0 \gamma \left(1 - \frac{R^2 x^2}{r^4} \right) \\ \sigma_y &= \gamma \left(1 - \frac{R^2 y^2}{r^4} \right) \\ \tau_{xy} &= \gamma \frac{R^2 xy}{r^4} \end{aligned} \right\} \quad (2-1)$$

In the formula: $r^2 = x^2 + y^2$, γ —The bulk density of soil; k_0 —Lateral pressure coefficient

For the rectangular foundation pit (as shown in Figure 2), the vertical formula (2-1) is rewritten as z-axis, that is, the stress components after unloading of the rectangular foundation pit are rewritten from formula (2-1):

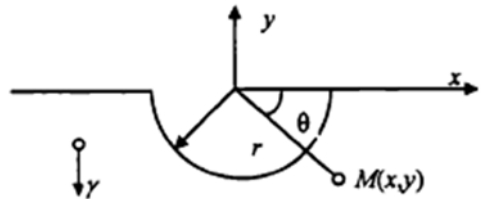
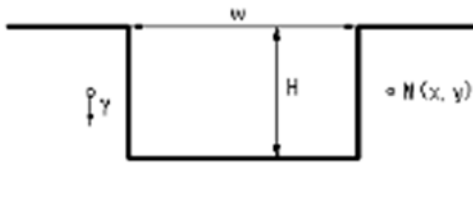
$$\left. \begin{aligned} \sigma_x &= k_0 \gamma \left(1 - \frac{2HW/\pi x^2}{r^4} \right) \\ \sigma_y &= \gamma \left(1 - \frac{2HW/\pi y^2}{r^4} \right) \\ \tau_{xy} &= \gamma \frac{2HW/\pi xy}{r^4} \end{aligned} \right\} \quad (2-2)$$



Figure 1 With semicircular notch half plane

Figure 2 The graphic size of any plane foundation pit

3. Stress Vector Constitutive relation considering deflection of Principal stress Axis

3.1. Introduction of the stress ratio vector

According to the analysis of stress field in soil after foundation pit excavation, the influence of medium principal stress is not considered for plane problem. Suppose that the stress state of a point M in the soil under the unloading action is $\{\sigma_x, \sigma_z, \tau_{xz}, \tau_{zx}\}$, because the shear force is equal to each other, $\{\sigma\} = \{\sigma_x, \sigma_z, \tau_{xz}\}$ is taken.

Set up the magnitude principal stress of point M is σ_1 and σ_3 , and consider the deflection of the direction of the magnitude principal stress under unloading action. Take the Angle between the direction of the large principal stress and the vertical axis as α (positive anti-clockwise), so the Angle between the small principal stress and the vertical axis as: $\alpha + 90^\circ$, then:

$$\sigma_{1,3} = \sigma_m \pm \sigma_m \sqrt{\left[\frac{(\sigma_z - \sigma_x)}{(2\sigma_m)} \right]^2 + (\tau_{xz} / \sigma_m)^2} \quad (3-1)$$

$$\tan 2\alpha = \frac{(\tau_{xz} / \sigma_m)}{(\sigma_z - \sigma_x) / (2\sigma_m)} \quad (3-2)$$

In the formula: σ_m — Mean effective stress (not considering medium principal stress), then:

$$\sigma_m = (\sigma_1 + \sigma_3) / 2 = (\sigma_z + \sigma_x) / 2 \quad (3-3)$$

Form the formula (3-1) ~ (3-3), it can be seen that:

(1) σ_1, σ_3 and α can uniquely determine the action effect of $\{\sigma\}$, and $\sigma_m, (\sigma_z - \sigma_x) / (2\sigma_m)$ and τ_{xz} / σ_m determine and action effect, therefore, these three quantities also determine the action effect;

(2) σ_m as a spherical stress, it is isotropic and will not cause deflection in the direction of the principal stress. Therefore, only $(\sigma_z - \sigma_x) / (2\sigma_m)$ and τ_{xz} / σ_m can cause deflection in the direction of the principal stress axis.

order:

$$\begin{cases} \bar{X} = \frac{\sigma_z - \sigma_x}{2\sigma_m} = \frac{\sigma_z - \sigma_x}{\sigma_z + \sigma_x} \\ \bar{Y} = \frac{\tau_{xz}}{\sigma_m} = \frac{2\tau_{xz}}{\sigma_x + \sigma_z} \end{cases} \quad (3-4)$$

Establish a $O - \bar{X} - \bar{Y}$ coordinate system with O point as the center of the circle, and, $\bar{X}$ 、 $\bar{Y}$ as the horizontal and vertical coordinates (see Figure 3). Suppose that the stress state of a point in the coordinate system is $\{\sigma\}$, and the vector formed by O and M points is $\bar{\eta}_s$, then:

$$\bar{\eta}_s = \bar{X}\bar{i} + \bar{Y}\bar{j} \quad (3-5)$$

In the formula: $\bar{i}$, $\bar{j}$ —— $\bar{X}, \bar{Y}$ axial unit vector.

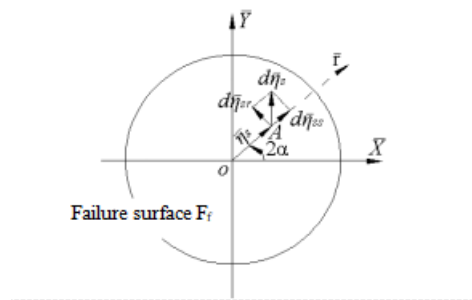


Figure 3 The decomposition of stress vector ratio and its increment

The modulus of $\bar{\eta}_s$ is:

$$\begin{aligned} |\bar{\eta}_s| &= \sqrt{\bar{X}^2 + \bar{Y}^2} = \\ &= \sqrt{\left[\frac{(\sigma_x - \sigma_z)}{(2\sigma_m)}\right]^2 + \left(\tau_{xz} / \sigma_m\right)^2} \end{aligned} \quad (3-6)$$

$\bar{\eta}_s$ is defined as the stress ratio vector and introduced into the constitutive relation considering stress deflection.

From formula (3-4) :

$$\frac{\bar{Y}}{\bar{X}} = \left(\frac{2\tau_{xz}}{\sigma_x + \sigma_z} \right) / \left(\frac{\sigma_z - \sigma_x}{\sigma_z + \sigma_x} \right) = \frac{2\tau_{xz}}{\sigma_z - \sigma_x} \quad (3-7)$$

Compared with equation (3-2), we find that the deflection direction of large principal stress is the direction of $\bar{\eta}_s$. In addition, it can be expressed as:

$$\bar{\eta}_s = |\bar{\eta}_s| \bar{\gamma} \quad (3-8)$$

In the formula: $\bar{\gamma}$ —— unit vector of $\bar{\eta}_s$. That is:

$$\bar{\gamma} = \cos 2\alpha \bar{i} + \sin 2\alpha \bar{j} \quad (3-9)$$

From formula (3-5) ~ (3-9) :

(1) the stress ratio vector $\bar{\eta}_s$ can be completely equivalent to $(\sigma_z - \sigma_x)/(2\sigma_m)$ and τ_{xz}/σ_m .

Therefore, the effect of $\{\sigma\}$ depends on the ball stress σ_m and the stress ratio vector—— $\bar{\eta}_s$. Similarly, only the stress ratio vector can cause the principal stress deflection. On the other hand, before soil failure, each stress state corresponds to a molar stress circle, as shown in Figure 4.

$$\begin{aligned}\sin \phi_{mo} &= \frac{\overline{AB}}{\overline{OA}} = \sqrt{\left(\frac{\sigma_z - \sigma_x}{2}\right)^2 + \tau_{xz}^2} / \sigma_m \\ &= \sqrt{\left(\frac{\sigma_z - \sigma_x}{2\sigma_m}\right)^2 + \left(\frac{\tau_{xz}}{\sigma_m}\right)^2} = \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3}\end{aligned}\quad (3-10)$$

In the formula: ϕ_{mo} ——Flow internal friction Angle or intensity play Angle.

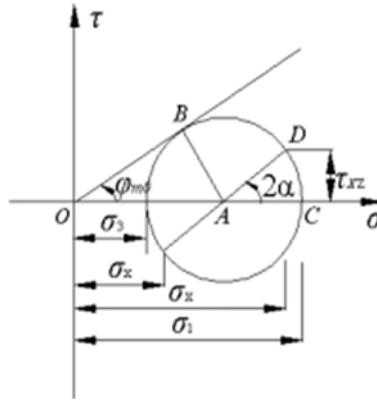


Figure 4 Mohr's stress circle

Comparison with formula (3-6) shows that:

$$|\overline{\eta_s}| = \sin \phi_{mo} = \sqrt{\overline{X}^2 + \overline{Y}^2} \quad (3-11)$$

By differentiating formula (3-8), combining equation (3-5), (3-9) and (3-11), we can get:

$$d\overline{\eta_s} = d|\overline{\eta_s}| \overline{\gamma} + |\overline{\eta_s}| d\overline{\gamma} = d\overline{\eta_{ss}} + d\overline{\eta_{sr}} \quad (3-12)$$

In the formula:

$$d\overline{\eta_{ss}}^V = d|\overline{\eta_s}|^V \overline{\gamma} = \cos \phi_{mo} d\phi_{mo} \overline{\gamma} = \cos 2\alpha d\overline{X} + \sin 2\alpha d\overline{Y} \overline{\gamma} \quad (3-13)$$

or:

$$d\overline{\eta_{ss}}^V = [(\cos 2\alpha d\overline{X} + \sin 2\alpha d\overline{Y}) \cos 2\alpha] \overline{i} + [(\cos 2\alpha d\overline{X} + \sin 2\alpha d\overline{Y}) \sin 2\alpha] \overline{j} \quad (3-14)$$

$$d\overline{\eta_{sr}} = |\overline{\eta_s}| d\overline{\gamma} = [-|\overline{\eta_s}| \sin 2\alpha d(2\alpha)] \overline{i} + [|\overline{\eta_s}| \cos 2\alpha d(2\alpha)] \overline{j} \quad (3-15)$$

or:

$$d\overline{\eta_{sr}} = (-2 \sin \phi_{mo} \sin 2\alpha d\alpha) \overline{i} + [2 \sin \phi_{mo} \cos 2\alpha d\alpha] \overline{j} \quad (3-16)$$

From formula (3-9), the following can be obtained:

$$d\overline{\gamma} = [-\sin(2\alpha) d(2\alpha)] \overline{i} + [\cos 2\alpha d(2\alpha)] \overline{j} \quad (3-17)$$

By comparison with formula (3-16), $d\overline{\eta_{sr}}$ and $d\overline{\gamma}$ are in the same direction.

$$\overline{\gamma} \bullet d\overline{\gamma} = [\cos 2\alpha \times (\sin 2\alpha) + \sin 2\alpha \times \cos 2\alpha] d(2\alpha) = 0$$

Therefore, $\overline{\gamma}$ is perpendicular to $d\overline{\gamma}$. And $d\overline{\eta_{ss}}$ is perpendicular to $d\overline{\eta_{sr}}$ each other, because $d\overline{\eta_{sr}}$ is parallel to $d\overline{\gamma}$ each other and the same as the direction. Based on formula (3-12) ~ (3-16), we can get:

(4) $d\overline{\eta_s}$ can be decomposed into two mutually perpendicular vectors $d\overline{\eta_{ss}}$ and $d\overline{\eta_{sr}}$ (as shown in Figure 3), and the effect can be completely equivalent to $d\overline{\eta_{ss}}$ and $d\overline{\eta_{sr}}$.

(5) Because $|d\overline{\eta_{ss}}| = |d|\overline{\eta_s}|| \overline{\gamma}| = |d|\overline{\eta_s}||$, it reflects the numerical change of, and:

$$\begin{aligned} |d\bar{\eta}_{ss}| &= |d|\bar{\eta}_s|\bar{\gamma}| = |d|\bar{\eta}_s|| = |\cos\phi_{mo}d\phi_{mo}| \\ &= \cos 2\alpha d\bar{X} + \sin 2\alpha d\bar{Y} \end{aligned} \quad (3-18)$$

(6) the component $d\bar{\eta}_{sr}$ reflects the direction change, and:

$$|d\bar{\eta}_{sr}| = |d|\bar{\eta}_s|\bar{\gamma}(2\alpha)| = |2\sin\phi_{mo}d\alpha| \quad (3-19)$$

3.2. The establishment of constitutive relations

Under the action of load, the deformation characteristics of soil are affected by the properties, stress history and stress state of soil. Now defined $\{\varepsilon\} = \{\varepsilon_x, \varepsilon_z, \gamma_{xz}\}$ as the strain of the soil after unloading, $\{\sigma\} = \{\sigma_x, \sigma_z, \tau_{xz}\}$ as stress state. There is:

$$\{\varepsilon\} = F(S_p, S_h, \{\sigma\}) \quad (3-20)$$

In the formula: S_p — Properties of soil; S_h — Stress history.

As $\{\sigma\}$ can be replaced by $\bar{\eta}_s$ equivalent, therefore:

$$\{\varepsilon\} = F(S_p, S_h, \sigma_m, \bar{\eta}_s) \quad (3-21)$$

Differentiate both sides of formula (3-21):

$$\{d\varepsilon\} = \frac{\partial F}{\partial S_p} dS_p + \frac{\partial F}{\partial S_h} dS_h + \frac{\partial F}{\partial \sigma_m} d\sigma_m + \frac{\partial F}{\partial \bar{\eta}_s} d\bar{\eta}_s \quad (3-22)$$

Substitute formula (3-12) into formula (3-22) to get:

$$\{d\varepsilon\} = \frac{\partial F}{\partial S_p} dS_p + \frac{\partial F}{\partial S_h} dS_h + \frac{\partial F}{\partial \sigma_m} d\sigma_m + \frac{\partial F}{\partial \bar{\eta}_s} d\bar{\eta}_{ss} + \frac{\partial F}{\partial \bar{\eta}_s} d\bar{\eta}_{sr} \quad (3-23)$$

It is assumed that soil deformation is less affected by soil property change and stress history in the unloading process, therefore, S_p and S_h are regarded as basically unchanged (it can be implied in the actual soil parameters), as follows:

$$\{d\varepsilon\} = \frac{\partial F}{\partial \sigma_m} d\sigma_m + \frac{\partial F}{\partial \bar{\eta}_s} d\bar{\eta}_{ss} + \frac{\partial F}{\partial \bar{\eta}_s} d\bar{\eta}_{sr} \quad (3-24)$$

The right side of formula (3-24) is represented by $\{d\varepsilon^c\}$, $\{d\varepsilon^s\}$ and $\{d\varepsilon^r\}$ respectively, and the constitutive relation considering stress deflection is obtained:

$$\{d\varepsilon\} = \{d\varepsilon^c\} + \{d\varepsilon^s\} + \{d\varepsilon^r\} \quad (3-25)$$

For this constitutive relation, attention should be paid to:

① $\{d\varepsilon^c\}$ represents the effect of the average effective stress on the strain state, so σ_m should be kept as a constant when calculating $\{d\varepsilon^s\}$ and $\{d\varepsilon^r\}$.

② As a vector, in the process of superposition calculation, $\{d\varepsilon\}$ can only carry out algebraic superposition in the $O - X - Y - Z$ coordinate system, while in other coordinate systems, superposition calculation by vector method is required.

According to the constitutive model of formula (3-25), after the main stress axis is deflected, the strain change of soil mass is related to the change of average effective stress of soil mass, the numerical change of stress ratio and the strain increment caused by the reverse change of main stress. Obviously, the first two terms on the right side of the formula are the change of stress magnitude, while the latter is the change of stress axis direction. Therefore, the constitutive relation not only considers the change of stress magnitude, but also considers the change of stress direction, that is, fully considers the effect of stress vector characteristics on strain, and now the constitutive model is called stress vector constitutive model.

3.3. Constitutive relation of soil around the foundation pit under excavation unloading

According to the stress vector constitutive model and the stress component of the surrounding soil after the foundation pit excavation and unloading, the deformation state of the surrounding soil after the foundation pit excavation and unloading can be analyzed.

The stress component of the surrounding soil after the foundation pit is unloaded (formula (2-2)) is substituted into formula (3-2) to obtain:

$$\alpha = \arctan\left(\frac{4HWxz}{r^4x^2z^2(1-k_0) - 2HW(x^2 - k_0z^2)}\right)/2 \quad (3-26)$$

Then, formula (3-26) is substituted into formula (3-4) to obtain:

$$\left. \begin{aligned} \bar{X} &= \frac{(1-k_0)\pi x^2 z^2 r^4 - 2HW(x^2 - k_0 z^2)}{(1+k_0)\pi x^2 z^2 r^4 - 2HW(x^2 + k_0 z^2)} \\ \bar{Y} &= \frac{2HWxz}{(1+k_0)\pi x^2 z^2 r^4 - 2HW(x^2 + k_0 z^2)} \end{aligned} \right\} \quad (3-27)$$

$\bar{X}, \bar{Y}$ are obtained by formula (3-27), and then the stress ratio vector $\bar{\eta}_s$ is determined. By substituting $\bar{\eta}_s$ into formula (3-14) and (3-15), the expressions of $d\bar{\eta}_{ss}$ and $d\bar{\eta}_{sr}$ can be obtained. Finally, according to formula (3-24), the constitutive relationship of the surrounding soil strain with consideration of stress deflection after excavation and unloading of rectangular foundation pit can be calculated. Because the expression is more complex and has many parameters, it is difficult to calculate in practical application. In order to analyze the influence of the direction change of principal stress deflection on the deformation of surrounding soil after unloading, the stress-strain relationship and deformation modulus of soil after stress deflection are analyzed by the change test of large principal stress azimuth α .

4. Soft soil deformation characteristic test of deflection of main stress axis

4.1. General situation of the test

Shen Yang^[18] took soft clay as the research object to carry out a series of tests considering the change of principal stress axis direction, and studied the influence of the change of principal stress deflection direction on the mechanical properties of soft soil. Based on it, this paper studies the influence of the deflection direction of the principal stress axis on the deformation characteristics of soft soil, reorganizes the test results, and analyzes the influence of the azimuth α of the principal stress on the stress-strain relationship and deformation modulus of soft soil. The conventional physical and mechanical indexes of the test soil samples are shown in Table 1. After the average effective pressure isometric consolidation of 150kPa, the static shear test program with azimuth changes of different principal stress axes is shown in Table 2.

Table 1 Conventional physical and mechanical indexes of test soil samples

Proportion	Void ratio	Water content	Liquid limit	Plastic limit	Triaxial		Direct shear and fast fixation	
G_s	e	$w/\%$	$w_L/\%$	$w_p/\%$	c_{cu}/kPa	$\varphi_{cu}/^\circ$	c/kPa	$\varphi/^\circ$
2.74	1.234	44.3	45.0	18.2	24.8	16.0	5.5	9.0

Table 2 Test scheme

Test number	Change of each parameter when loading			
	p/kPa	b	$\alpha/^\circ$	q/kPa
T101	150	0	0	It increases from 0 until the sample is broken

				broken
T102	150	0	10	broken
T103	150	0	15	broken
T104	150	0	25	broken
T105	150	0	45	broken
T106	150	0	60	broken
T107	150	0	75	broken

In the table: p —Average effective consolidation pressure, $p = (\sigma_1 + \sigma_2 + \sigma_3)/3$;

b —Bishop's constant, $b = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$, If $b=0$ indicates $\sigma_2 = \sigma_3$, the test results can be applied to plane strain; q —Shear stress, $q = (\sigma_1 - \sigma_3)/2$.

4.2. Test results and analysis

1. The stress-strain relationship curve of soil under different principal stress azimuths.

The stress-strain relationship of soft clay samples under different principal stress azimuths α is shown in Figure. 5, where the abscissa is γ_{oct} octahedral shear strain. Figure. 5 shows that the change of azimuth Angle of principal stress has a significant impact on the stress-strain relationship of soil samples. When α is less than 45° , the soil shear stress with the increase of Angle decreases, and when α is greater than 45° , the soil shear stress instead of the rise, it is critical to 45° Angle, shows that when the principal stress azimuth Angle is less than the critical Angle of soil shear capacity decreases with the increase of azimuth Angle, and in $45^\circ \sim 75^\circ$ between soil shear strength increased with the increase of azimuth Angle increased. The reason is that when the principal stress direction is changed, the soil's anisotropy, and a large number of studies have shown that [19], the change of the direction of principal stress of soil pore pressure effect significantly, also exists the critical Angle, within the critical Angle, with the increase of principal stress azimuth, soil pore pressure increase, according to the principle of effective stress, the soil's shear strength decreases, also more than the critical Angle, the pore pressure of soil is less, the shear capacity of soil increased.

At the same time, it can also be seen from Figure. 5 that when the principal stress azimuth Angle is within the range of $0^\circ \sim 45^\circ$, the strain of soil increases with the increase of azimuth under the same condition of shear stress, while the strain decreases with the increase of azimuth between $45^\circ \sim 75^\circ$, which is the same as the change trend of shear resistance. Moreover, the strain of the sample under upward failure basically varies in the range of $9\% \sim 12\%$. When the octahedral strain reaches about 5% , the strength performance of the sample (ratio of shear stress to critical failure shear stress q/q_f) generally reaches over 90% . According to the figure, when $\alpha = 0^\circ$, the soil strain is the smallest, and when $\alpha = 45^\circ$, the soil strain is the largest. This indicates that when the principal stress is not deflected, the soil has the strongest deformation resistance, while when the principal stress is deflected to 45° , the soil has the weakest deformation resistance and is most vulnerable to damage.

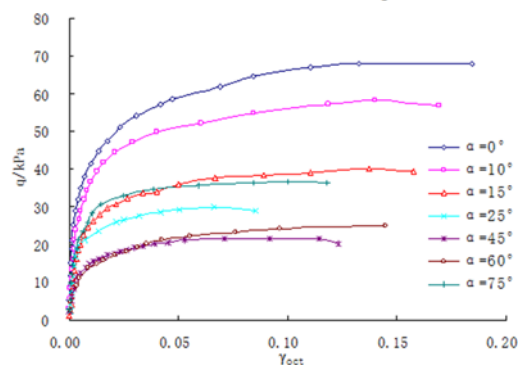


Figure. 5 Stress-strain curve of soil under different azimuth angles

It can be seen from Figure. 5 that the stress-strain curves of soil at different azimuths are hyperbolic, so they can be normalized. Let $\beta = (\sin(\pi(45 + \alpha)/180))^{4.8}$, Figure. 6 is the function of the normalization of the soil stress-strain relation hyperbolic under different azimuth angles. From the figure, the functional relationship between soil shear stress, shear strain and principal stress azimuth under the same confining pressure can be obtained as follows:

$$\frac{\gamma_{oct} \sigma_m}{q\beta} = 7.0541\gamma_{oct} + 0.045 \quad (4-1)$$

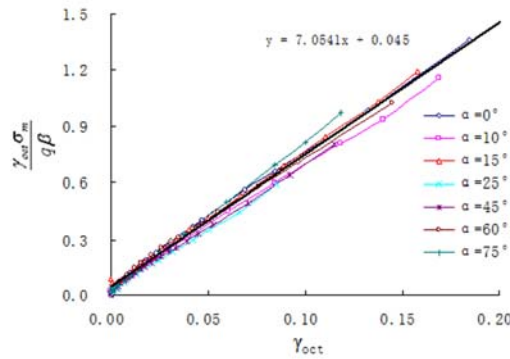


Figure. 6 Normalization function representation of stress-strain curves under different azimuth angles

According to formula (4-1), it can be seen that the soil strain is not only related to stress, but also greatly affected by the change of principal stress direction, which further proves the rationality of the stress vector constitutive model.

2. The change of soil deformation modulus under different principal stress azimuths.

The change rule of the initial deformation modulus of soil under different azimuths is shown in Figure. 7. It can be seen that the deformation modulus is greatly affected by the change of azimuth Angle, which is mainly the reflection of the anisotropy of soil. The change trend is like a "scoop" curve, and the anisotropy is strong at $0^\circ \sim 15^\circ$. In addition, after the curve is normalized by $E_{i(\alpha=0^\circ)} / \beta$ (Figure. 8),

the ratio of E_i to $E_{i(\alpha=0^\circ)} / \beta$ is a constant, and the relation between E_i and α is:

$$E_i = \xi E_{i(\alpha=0^\circ)} / \beta \quad (4-2)$$

Where ξ is the parameter, where $\xi = 0.21$.

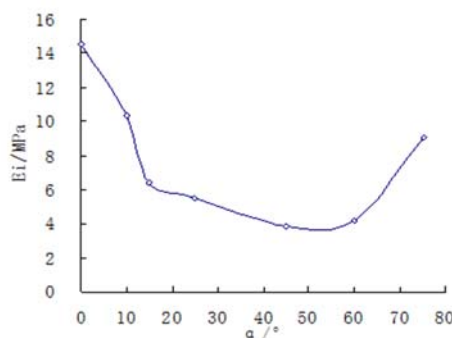


Figure 7 Deformation modulus of soil under different azimuth

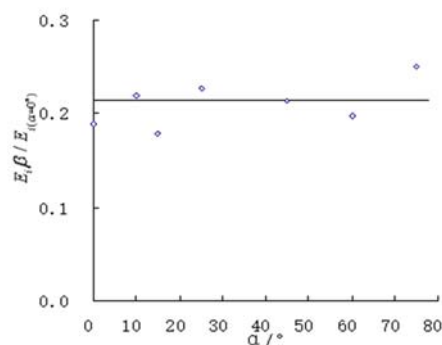


Figure 8 The relationship between $E_i \beta / E_{i(\alpha=0^\circ)}$ and azimuth

5. Conclusions

(1) By analyzing the stress state of the surrounding soil after the foundation pit excavation and introducing the stress vector ratio, the soil constitutive model considering the stress deflection is derived. The constitutive model shows that the soil strain around the foundation pit after unloading is not only affected by the change of the stress, but also closely related to the deflection of the main stress axis.

(2) When the azimuth Angle α of the principal stress is between 0° and 45° , the shear strength of the soil sample decreases with the α increase, and the strain increases with the α increase. At $45^\circ \sim 75^\circ$, the shear strength of soil samples increases with the α increase, and the strain decreases with the α increase. Moreover, the strain of soil sample is the minimum when $\alpha = 0^\circ$, and the strain of soil sample is the maximum when $\alpha = 45^\circ$, indicating that the resistance to deformation of soil is the strongest when the main stress is not deflected, and the resistance to deformation of soil is the weakest when the main stress is deflected 45° .

(3) The variation of the deformation modulus of the soil samples under different azimuths of the principal stress is like a "scoop" curve, which is mainly the reflection of the anisotropy of the soil, and shows strong anisotropy at $0^\circ \sim 15^\circ$.

(4) By normalizing the stress-strain curve of soil under different principal stress azimuths, it is found that the soil strain is not only related to stress, but also significantly affected by the change of principal stress direction. The experimental results are in good agreement with the constitutive model presented in this paper.

References

- [1] Zhou qiujuan, Chen xiaoping, xu guangming. Centrifugal model test and numerical simulation of soft soil foundation pit [J]. Journal of rock mechanics and engineering, 2013,32 (11) : 2342-2348.
- [2] Chen kun, yan shu-wang, sun liqiang, et al. Study on deformation characteristics of deep foundation pit under excavation unloading condition [J]. Rock and soil mechanics, 2016,37 (04) : 1075-1082.
- [3] Zhou qiujuan, Chen xiaoping. Research on the three-axis rheological characteristics of soft soil under the unloading path of typical foundation pit excavation [J]. Rock and soil mechanics, 2013,34 (05) : 1299-1305.
- [4] Mulinlong, huang maopong. Simplified analysis of three-dimensional displacement field of surrounding soil caused by foundation pit excavation [J]. Journal of geotechnical engineering, 2013,35 (05) : 820-827.
- [5] Zhou qiujuan. Experimental study on deformation characteristics of soft soil under different unloading paths [J]. Engineering investigation, 2013,41 (10) : 17-22.
- [6] Li dening, Lou xiaoming, Yang min. Experimental study on elastic deformation of unloaded soil during foundation pit excavation in Shanghai area [J]. Rock and soil mechanics, 2011,32 (S2) : 244-249.
- [7] Liu guobin, hou xueyuan. Unloading stress-strain characteristics of soft soil [J]. Underground engineering and tunnels. 1997, 2:16-23.
- [8] Liu guobin, jia fubo. Experimental study on the rebound time effect of foundation pit [J]. Journal of rock mechanics and engineering. 2007,26 (S1) : 3040-3044.
- [9] Zhang zhi-guo, zhao qi-hua, lu ming-hao. Measured analysis of historical protection building settlement during excavation of adjacent deep foundation pit [J]. Journal of civil engineering, 2015,48 (S2) : 137-142.
- [10] PECK R B. Deep excavations and tunneling in soft ground [C]//Proc 7th ICSMFE, Mexico, 1969:225-290.
- [11] BLACKBURN JT, FINNO R J. Three-Dimensional responses observed in an internally braced excavation in soft clay [J]. Journal of Geotechnical and Geoenvironmental Engineering, 2007,133(11):1364-1373.
- [12] WANG J H, XU Z H, WANG W D. Wall and ground movements due to deep excavations in

- Shanghai soft soils[J].Journal of Geotechnical and Geoenvironmental Engineering,2010,136(7):985-994.
- [13] Huang maosong, wang weidong, zheng gang. Research progress of soft soil engineering and deep foundation pit [J]. Journal of civil engineering, 2012,45 (06) : 146-161.
- [14] Shen Yang, zhou jian, zhang jin-liang, et al. Study on the critical behavior of undisturbed soft clay under cyclic rotation of principal stress axis [J]. Journal of zhejiang university (engineering & engineering edition), 2008 (01) : 77-82.
- [15] Wang dingjian, tang huiming, li changdong, et al. Study on supporting pressure of shallow buried tunnel with consideration of principal stress deflection [J]. Journal of geotechnical engineering, 2016,38 (05) : 804-810.
- [16] Zhao yixin, lu zhiguo, zhu guangpei, et al. Mechanism of mining-induced fault activation considering principal stress deflection [J]. Journal of China university of mining and technology, 2008,47 (01) : 73-80.
- [17] Ma shicheng. Elastic-plastic and rheological analysis of foundation pit excavation and its application [D]. Hunan university, 2001.
- [18] Shen Yang. Experimental study of undisturbed soft clay considering the change of principal stress direction [D]. Zhejiang university, 2007.
- [19] Shen Yang, zhou jian, gong xiaonan. Experimental progress on the influence of principal stress axis rotation on soil properties [J]. Journal of rock mechanics and engineering, 2006 (07) : 1408-1416.